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Abstract

Granular Dynamics in Pebble Bed Reactor Cores

by

Michael Robert Laufer

Doctor of Philosophy in Engineering – Nuclear Engineering

University of California, Berkeley

Professor Per F. Peterson, Chair

This study focused on developing a better understanding of granular dynamics in pebble bed reactor cores through experimental work and computer simulations. The work completed includes analysis of pebble motion data from three scaled experiments based on the annular core of the Pebble Bed Fluoride Salt-Cooled High-Temperature Reactor (PB-FHR). The experiments are accompanied by the development of a new discrete element simulation code, GRECO, which is designed to offer a simple user interface and simplified two-dimensional system that can be used for iterative purposes in the preliminary phases of core design. The results of this study are focused on the PB-FHR, but can easily be extended for gas-cooled reactor designs.

Experimental results are presented for three Pebble Recirculation Experiments (PREX). PREX 2 and 3.0 are conventional gravity-dominated granular systems based on the annular PB-FHR core design for a 900 MWth commercial prototype plant and a 16 MWth test reactor, respectively. Detailed results are presented for the pebble velocity field, mixing at the radial zone interfaces, and pebble residence times. A new Monte Carlo algorithm was developed to study the residence time distributions of pebbles in different radial zones. These dry experiments demonstrated the basic viability of radial pebble zoning in cores with diverging geometry before pebbles reach the active core.

Results are also presented from PREX 3.1, a scaled facility that uses simulant materials to evaluate the impact of coupled fluid drag forces on the granular dynamics in the PB-FHR core. PREX 3.1 was used to collect first of a kind pebble motion data in a multidimensional porous media flow field. Pebble motion data were collected for a range of axial and cross fluid flow configurations where the drag forces range from half the buoyancy force up to ten times greater than the buoyancy force. Detailed analysis is presented for the pebble velocity field, mixing behavior, and residence time distributions for each fluid flow configuration.
The axial flow configurations in PREX 3.1 showed small changes in pebble motion compared to a reference case with no fluid flow and showed similar overall behavior to PREX 3.0. This suggests that dry experiments can be used for core designs with uniform one-dimensional coolant flow early in the design process at greatly reduced cost. Significant differences in pebble residence times were observed in the cross fluid flow configurations, but these were not accompanied by an overall horizontal diffusion bias. Radial zones showed only a small shift in position due to mixing in the diverging region and remained stable in the active core. The results from this study support the overall viability of the annular PB-FHR core by demonstrating consistent granular flow behavior in the presence of complex reflector geometries and multidimensional fluid flow fields.

GRECO simulations were performed for each of the experiments in this study in order to develop a preliminary validation basis and to understand for which applications the code can provide useful analysis. Overall, the GRECO simulation results showed excellent agreement with the gravity-dominated PREX experiments. Local velocity errors were found to be generally within 10-15% of the experimental data. Average radial zone interface positions were predicted within two pebble diameters. GRECO simulations over predicted the amount of mixing around the average radial zone interface position and therefore can be treated as a conservative upper bound when used in neutronics analysis. Residence time distributions from the GRECO velocity data based on the Monte Carlo algorithm closely matched those derived from the experiment velocity statistics. GRECO simulation results for PREX 3.1 with coupled drag forces showed larger errors compared to the experimental data, particularly in the cases with cross fluid flow. The large discrepancies suggest that GRECO results in systems with coupled fluid drag forces cannot be used with high confidence at this point and future development work on coupled pebble and fluid dynamics with multidimensional fluid flow fields is required.
To my wife, Carolyn.
You are the most caring and dedicated person that I know.
Your support and encouragement made this possible.
I love you with all of my heart.

To my parents, Henry and Marsha.
You inspire me to take on the big problems in the world.
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Jeff Bickel has been invaluable throughout this process and the experimental components of this project would not have been possible without his help. Jeff built PREX 3.0 as part of his master’s project in 2010 and it was the first experiment that I used to produce data on the motion of pebbles at the visible surface. As a research engineer in our laboratory, Jeff is responsible for most of the detailed design and fabrication of PREX 3.1.

A number of graduate students at U.C. Berkeley made valuable contributions to this project and have been a source of support through this process. I owe a great deal of gratitude to Ed Blandford, who provided me with great advice throughout my graduate studies and who I view as an important mentor. Jeff Powers, Raluca (Scarlat) Merric de Bellefon, and Tommy Cisneros all started with me in the same year and we have each studied different aspects of pebble fuel. Jeff and I had regular coffee outings that were a staple of my graduate school experience. I must also thank David Krumwiede for his help in keeping our exciting new granular flow projects in the Thermal-Hydraulics laboratory moving forward while I have been working hard to wrap up this thesis. Lisa Zemelman, the Graduate Student Affairs Officer for the
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## Nomenclature

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<th>Description</th>
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<td>AHTR</td>
<td>Advanced High-Temperature Reactor</td>
</tr>
<tr>
<td>AVR</td>
<td>Arbeitsgemeinschaft Versuchsreaktor (German Reactor)</td>
</tr>
<tr>
<td>DEM</td>
<td>Discrete Element Method</td>
</tr>
<tr>
<td>FHR</td>
<td>Fluoride Salt-Cooled High-Temperature Reactor</td>
</tr>
<tr>
<td>GDC</td>
<td>General Design Criteria</td>
</tr>
<tr>
<td>GRECO</td>
<td>Granular Recirculation Code</td>
</tr>
<tr>
<td>HDPE</td>
<td>High-Density Polyethylene</td>
</tr>
<tr>
<td>HTR</td>
<td>High-Temperature Reactor</td>
</tr>
<tr>
<td>NRC</td>
<td>Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>PB-FHR</td>
<td>Pebble Bed Fluoride Salt-Cooled High-Temperature Reactor</td>
</tr>
<tr>
<td>PBMR</td>
<td>Pebble Bed Modular Reactor</td>
</tr>
<tr>
<td>PREX</td>
<td>Pebble Recirculation Experiment</td>
</tr>
<tr>
<td>RAI</td>
<td>Request for Additional Information</td>
</tr>
<tr>
<td>THTR</td>
<td>Thorium High-Temperature Reactor</td>
</tr>
<tr>
<td>TRISO</td>
<td>Tristructural Isotropic</td>
</tr>
</tbody>
</table>
Nomenclature

Symbols

\( A \) Normal viscoelastic damping coefficient [s]
\( d \) Pebble diameter [m]
\( m \) Pebble mass [kg]
\( P \) Fluid pressure [Pa]
\( r \) Radial coordinate [m]
\( R \) Pebble radius [m]
\( r \) Pebble position vector [m]
\( u \) Velocity [m/s]
\( Y \) Young's modulus [Pa]
\( z \) Axial coordinate [m]
\( \gamma \) Tangential kinetic friction damping coefficient [Ns/m]
\( \mu \) Friction coefficient
\( v \) Poisson’s ratio
\( \xi \) Mutual compression between two pebbles [m]
\( \rho \) Density [kg/m\(^3\)]

Subscripts and Superscripts

\( c \) Coulomb friction
\( f \) Fluid
\( i, j \) Pebble indexes
\( k \) Kinetic friction (GRECO hybrid friction model)
\( n \) Normal direction
\( p \) Pebble
\( t \) Tangential direction
\( s \) Static friction (GRECO hybrid friction model)
\( w \) Wall or reflector surface
Chapter 1

Introduction

Energy is central to economic activity in both the developed and developing worlds. Available and affordable electricity increases the range of possible economic options and can play a large role in the improved life quality in poor regions of the world [1]. While electricity production is important for forward economic progress in the world, the current distribution of energy generation technologies also creates significant environmental risks that are likely to be magnified in the future. Fossil fuels dominate the energy mix and are directly linked to two of the major environmental challenges to be faced this century: climate change and air pollution. Energy demand is expected to increase by more than 100% by 2050, which will continue to increase the rate of carbon dioxide emissions to the atmosphere and air pollution in the developing world that could lead to millions of premature deaths on an annual basis [2].

The expansion of nuclear energy capacity in the world has the potential to reduce the negative impacts of climate change and air pollution, while providing a consistent supply of base-load electricity. The current generation of light water reactors (LWRs) are operated consistently at high capacity factors and low operating costs, and generate 12.9% of the world electricity supply [3]. The primary barriers to the expansion of nuclear generating capacity are the high capital costs required to license and build new reactors [4]-[6]. The final disposal methods for radioactive waste are currently unresolved in most nations and remain an important issue to address for future of nuclear power. Concerns over safety have also been a central part of the nuclear debate for many years and continue to be significant following the accident at Fukushima Daiichi in March 2011. A strong case can be made that the overall health and environmental benefits from the current fleet of nuclear reactors far outweigh the consequences of its largest accidents [7]. However, the most promising reactor technologies for the future will be those that have the potential to reduce both the costs and risks relative to existing LWR designs and competing energy sources.

Pebble bed reactors as defined by the use of spherical fuel pebbles, and could potentially lead to a fleet of reactors with several advantages relative to the current LWR technology. These reactors slowly recirculate pebbles through the core while the reactor is operating at power so that high capacity factors might be achieved.
Chapter 1. Introduction

There are two major design variations for pebble bed reactors that use either helium gas or liquid fluoride salt as the primary coolant. Both designs use a large number of coated tristructural isotropic (TRISO) fuel particles in each fuel pebble, which is a robust fuel form and can contain fission produces to high operating temperatures and large discharge burnup [8]-[11]. High temperature reactors have the potential to serve process heat markets for a wide variety for chemical processes [12]. Designs with both coolants use passive safety systems for the long-term removal of decay heat, which do not require AC electrical power. Despite the potential advantages of pebble bed reactors in the future, there are large development costs for new reactor technologies and the future prospect of these systems is highly uncertain.

This chapter provides background information on the topics of slow, dense granular flows that are relevant to pebble-bed reactor systems. Section 1.1.1 provides background information on the challenges associated with slow, dense granular flow and Section 1.1.2 then introduces the characteristics and granular flow issues for high-temperature gas-cooled pebble bed reactors. The experience with this reactor technology provides the basis for understanding the links between granular flow phenomena and reactor analysis. Section 1.1.3 provides a summary of the motivation for and description of the Pebble Bed Fluoride Salt-Cooled Reactor (PB-FHR), which is the primary technology of interest in this dissertation. Section 1.1.4 gives a review of analysis techniques that are used to study granular dynamics in pebble bed reactors and Section 1.1.5 discusses some of the key regulatory issues for pebble bed core design. Following the descriptions of the relevant reactor technologies and analysis methods, Section 1.2 states the objectives of this dissertation and outlines the content covered in each chapter of this document.

1.1 Background Review

1.1.1 Introduction to Granular Flow

A granular material is comprised of a large number of individual particles where forces are transmitted by contact between individual particles and their surrounding neighbors [13]. This definition covers a large range of materials where there is an extensive amount of everyday experience, yet the behavior of these materials is highly dependent on the specific application of interest and can display a large degree of complex behavior. Granular materials can, in different applications, exhibit behaviors that are characteristic of gases, liquids, and solids [14]. Regimes where the behavior of a granular material can be approximated using one of these phases, such as dilute collisional systems [15] and dense static systems [13], have been relatively successful, but cannot be extrapolated for different systems. The transition between different regimes, such as the initiation of an avalanche [16], can be rapid and dramatic and these transitions are not well understood from a theoretical perspective.
Chapter 1. Introduction

This thesis is focused on the regime of slow flow in dense granular media that is applicable for the recirculation of pebble fuel through the core of a nuclear reactor. This regime includes several common applications, such as sand flowing in an hourglass or the drainage of grains from agricultural hoppers. Energy is efficiently dissipated in these systems through inelastic collisions such that particles form long-lasting contacts with neighbors [17]. The flow features in this regime are primarily based on geometry and packing constraints. These systems are densely packed and can support stresses, like solids, before flow begins. However, as particles flow through the system, the transition between static and kinetic friction for particle-particle and particle-wall contacts allows the material to rearrange local packing configurations and exhibit large-scale flow behaviors that resemble a liquid.

The analysis of the dense granular flow regime of interest is made more complex by the heterogeneous force distribution in the material. Forces in dense granular materials are transmitted along stress chains that are dependent on the local packing configuration and show large discontinuities at the particle length scale [18]-[21]. Figure 1.1 shows an experimental visualization of these stress chains, which is possible though the use of photoelastic discs [19], [22]. The white particles in this image are made visible due to the large contact forces compared to the areas that remain dark. Forces in the packed bed are transmitted along these stress chains before they are transmitted to the container wall. During flow, these stress chains are in constant flux as forces redistribute throughout the packed bed [23], [24]. The most common practical concern around these stress chains is the highly non-uniform distribution of wall forces in silos. In the analysis of flow in this regime, the presence of such heterogeneous force distributions suggests that it would be challenging for continuum models to approximate the bulk behavior.
Even with the presence of force heterogeneities, the large-scale flow patterns in dense granular materials tend to exhibit smooth behavior in a time-averaged sense. The particle velocity profiles for applications including silo drainage [13], [25]-[28], rotating Couette shear cells [29], [30], and flow down an inclined plane [31]-[33] can each be approximated by relatively simple functions and have generated a large amount of interest in developing a unified theoretical basis. This effort, however, has not yet been successful and established understanding of system behavior is highly geometry specific. The lack of a general theory for the regime of dense granular flow implies that the behavior in novel systems requires investigation as existing theories have limited predictive capabilities.

1.1.2 Pebble Bed Gas Cooled Reactor

The complete operating experience for pebble bed reactors comes from three gas-cooled systems, which serves as the foundation for understanding the issues with pebble recirculation through the core. These reactors all use helium as the primary coolant and a packed bed of 6 cm diameter spherical graphite pebbles, each loaded with a large number of TRISO fuel particles. Figure 1.2 shows a drawing of a pebble packed with TRISO particles and pebbles in a packed core with control elements visible in the bed. These reactors have moving fuel elements that are slowly recirculated while the reactor is at operating power. This characteristic allows for high capacity factors because refueling outages are not required and for excellent fuel
utilization because the core can run with low excess reactivity and optimal moderation [34]-[36]. The recirculation of fuel through the core, however, adds a significant degree of complexity to the core geometry that introduces uncertainties due to the stochastic variability of the granular flow [37], [38].

Gas cooled pebble bed reactors were originally developed in Germany in the 1950s. The Arbeitsgemeinschaft Versuchsreaktor (AVR) was a 15 MWe demonstration reactor that was built in Julich and commissioned in 1967. The facility performed a large number of experiments and tests over 21 years of operation before it was shut down in 1988. The AVR demonstrated the basic technological viability and safety performance of the pebble bed reactor, including the passive removal of decay heat after depressurization [39], [40]. Approximately 150,000 fuel pebbles were used during the lifetime of the reactor with no significant problems reported in the pebble handling system.

The German program continued with the construction of the 300 MWe Thorium High Temperature Reactor (THTR), which was commissioned in 1985. The reactor experienced significant mechanical difficulties and was shut down a few years later in 1988. The pebble bed core for the THTR was made up of approximately 675,000 pebbles. During its three-year operating lifetime, the total number of pebbles recirculated was that of approximately two full core loadings [41], [42].

Figure 1.2: Pictures of 6 cm diameter fuel spheres compared to a tennis ball (left) and an image of fuel pebbles packed in a reactor bed (right) with control devices in the bed.
There were a number of issues with the pebble recirculation system in the THTR, which demonstrate the importance of understanding the basic behavior of granular materials in reactor cores. The first major issue was the mechanical difficulties of handling broken fuel pebbles in the defueling machine at the bottom of the reactor. A surprisingly large number of broken fuel pebbles were found during the early operation that are believed to be due to the frequent and deep insertion of control elements directly into the bed [42]. Pebble flow around control elements is beyond the scope of this dissertation, but merits further study if this design option is to be pursued.

The second major issue for the THTR was a large discrepancy between the predicted and observed pebble burnup distributions. A complete analysis of the discrepancy was not possible due to the short operating lifetime of the reactor, but a preliminary review suggests that the temperature-dependence of the graphite friction coefficient in helium led to additional hold up of pebbles along the outer reflector surfaces [43]. The distortion led to errors in analysis for operational and safety-related core characteristics including power and temperature distributions and nuclear shutdown margins [44], [45]. The THTR experience is directly relevant to the need to understand granular flow phenomenology in the core in order to have a design that is properly characterized and is in the expected configuration for design and safety analysis.

The only operating pebble bed reactor in the world today is the 10 MWth High Temperature Reactor (HTR-10), located at Tsinghua University in China. This reactor reached criticality in 2000. The Chinese program is currently developing a 250 MWth prototype plant (HTR-PM), derived from the HTR-10 experience base [46]. No results on the pebble recirculation experience at HTR-10 have been published.

1.1.3 Pebble Bed Fluoride Salt Cooled Reactor

The PB-FHR, developed at U.C. Berkeley in collaboration with Oak Ridge National Laboratory, is the most recent design based on the Advanced High Temperature Reactor (AHTR) concept [47] to use liquid fluoride salt to cool coated particle high temperature reactor fuel. The PB-FHR combines the robust fuel form of high-temperature gas reactors with the effective heat transfer of a molten salt coolant and the passive natural circulation safety systems of sodium fast reactors. The baseline primary coolant for the PB-FHR is flibe (LiF-BeF₂), which has a melting temperature of 459° C and a boiling temperature of 1430° C. The primary system of the PB-FHR operates at low pressure and at much higher power densities than gas-cooled reactors, which could present both economic and safety advantages.
Chapter 1. Introduction

Two PB-FHR designs will be used as references throughout this dissertation: the modular 900 MWth PB-FHR [48] and the 16 MWth FHR (FHR-16) test reactor [49]. Figure 1.3 shows a simplified schematic of the primary loop for the 900 MWth PB-FHR. The primary loop is important for the design of the pebble bed core because it establishes the boundary conditions for the coolant flow, although it is most practical to study the core pebble dynamics independently. The nominal core inlet and outlet temperature for the PB-FHR are 600° C and 700° C, respectively. Primary coolant flow is primarily upward through the core with outward radial flow components, see below, form the inner reflector to the outer reflector. It is expected that the design of the PB-FHR will continue to evolve with additional study, but insights gained from these two systems will be useful to inform how changes in the core geometry will be relevant for the pebble recirculation through the core.

One of the main differences between the PB-FHR and gas-cooled systems is that pebbles in the liquid salt will float due to buoyancy forces and therefore recirculation will be opposite that in gravity-dominated system. The reduction in body forces on the pebbles due to buoyancy also means that pebbles in the salt coolant will be subject to smaller forces than those in gas-cooled systems, which should have important implications on pebble surface wear and dust generation. Both designs of interest use an annular fuel pebble design, which includes a low-density inert graphite kernel surrounded by a layer of packed TRISO fuel particles and a 2.5 mm outer shell. The fuel design is shown in Figure 1.4. Fuel pebbles in the PB-FHR system are 3 cm in diameter, half that of the typical gas-cooled pebble bed reactors.
Figure 1.3: Schematic diagram of PB-FHR primary system.

Figure 1.4: Schematic drawing of the annular PB-FHR 3 cm diameter fuel design.
Figure 1.5 shows simplified schematic drawings for the 900 MWth and 16 MWth PB-FHR core designs. Both systems have an axisymmetric annular core configuration with a solid central reflector. The orientations of pebble recirculation are reversed in the PB-FHR compared to gas-cooled reactors because the pebbles are positively buoyant in the liquid coolant. Pebbles are advected with the coolant and injected at the bottom of the core and slowly flow up as pebbles are removed from the top of the defueling chute. This configuration is a significant advantage for the pool configuration of the PB-FHR because access to a defueling machine at the bottom of the primary vessel would be extremely difficult for maintenance. Also, defueling at the bottom of the core could require a primary vessel penetration that could be a potential break point for a loss of coolant accident.

Figure 1.5: Schematic drawings of the 900 MWth PB-FHR (left) and FHR-16 (right) annular core designs. Drawings are not to scale.

The core geometry of the PB-FHR introduces some changes compared to that of the gas-cooled reactors. Both designs include a diverging region at the bottom of the core, which is designed to provide shielding to structures at the bottom of the primary vessel and to reduce the total amount of primary coolant in the system in order to reduce capital costs. Dense granular flow in the diverging region is unique to the PB-FHR application and has no analogous geometry that has been studied in the granular flow literature. The design basis for the PB-FHR core requires that this
region remain densely packed at all times during reactor operation in order to establish confidence in the core configuration. Above the diverging region, the PB-FHR has a constant area region, which has the highest power density and is interchangeably referred to as the active core region. At the top of the core is a converging geometry that resembles the bottom of gas-cooled reactors as pebbles are channeled into defueling chutes.

One design option for the PB-FHR core is the use of radial zones that are established by divider plates in several inlet hoppers at the bottom of the core. The use of radial zones allows an additional degree of freedom for neutronics design as the path of different pebbles can be influenced to further optimize burnup levels of recirculated fuel pebbles. An alternative use of radial zoning in the PB-FHR could be to use an inert layer of graphite pebbles at the outer reflector surface that would shield the graphite reflector blocks and could be replaced after receiving large neutron irradiation doses. Radial zoning has been proposed for gas-cooled reactors where inert graphite pebbles could be used in place of a solid central reflector, which would be difficult to replace and exposed to a large neutron dose [50], [51]. However, the use of a solid reflector in place of inert pebbles is helpful to establish dedicated channels for control rods so they have sufficient reactivity worth and do not need to be inserted directly into the packed bed.

The coolant flow in the annular PB-FHR core is more complex than the helium flow in gas reactors. The primary coolant flow through the core has both axial and radial components as flibe is injected at the bottom of the core and along the lower region of the inside reflector and removed through outlet plena along the top region of the outer reflector and through the defueling chute. This radial flow configuration is designed to reduce the total pressure drop across the core [48], [52]. Reducing the pressure drop in the core will help to establish natural circulation for the removal of decay heat and reduces the required height of standpipes used for pebble injection that will be at the core inlet pressure and therefore will have free surfaces that rise several meters above that of the pool. The multi-dimensional coolant flow path will create drag forces on pebbles in the packed bed that do not align with the buoyancy force. The interest in the coupled fluid drag on the granular pebble flow is unique to the PB-FHR design and is one major motivation of this dissertation.

1.1.4 Analysis Methods for Dense Granular Flow

The use of pebble fuel presents a number of advantages, but is an issue of concern for reactor designers and regulators because the behavior of such systems lacks a general theory and the basic physics is not well understood. Further, the challenges in collecting experimental data for these systems places severe limits on the validation of models and analysis methods. The diverging region geometry and the coupled fluid flow in the PB-FHR adds an additional layer of complexity that pushes the capabilities of current tools.
Chapter 1. Introduction

As discussed in Section 1.1.1, the heterogeneous nature of pebble-scale force distributions creates a significant challenge for the development of continuum models for dense granular flow. No reliable method has been identified to predict the mean velocity in different silo shapes, which include geometries that are most relevant to reactor cores. Two models that have been applied to dense granular flow with mixed success include critical state theory and the kinematic model. Critical state theory comes from soil mechanics and relates stress and density to velocity and mass flow rate. It has been used to study the flow distributions in silos, but the theory creates shock-like discontinuities that are not observed in experimental studies [53]. The kinematic model is a different approach that eliminates the stress-dependence on the velocity field and creates a diffusion-type problem [54]. It provides a reasonable approximation for flow near an orifice [27], [28], but cannot account for the impact of hold up due to wall friction and does not accurately model the flow transition from constant area to converging regions [55].

Continuum models have several other weaknesses in the application to the PB-FHR core. They cannot account for the stochastic nature of dense granular flow and therefore provide no useful insights into the phenomenology of mixing at radial zone interfaces and only a limited assessment of residence time distributions based on the mean velocity field. Finally, no models for granular flow have studied the drag forces from a coupled fluid flow field to assess the impact on pebble motion. This could be done in some cases by introducing a body force or changing the effective direction of the gravity vector, but this effort is not viewed to be worthwhile because the models have limited predictive capabilities.

Discrete Element Method (DEM) simulations are well suited to the study of dense granular flow of spherical particles in pebble bed reactor cores because they allow for realistic packing geometry and tracking of all pebbles in the system. DEM simulations have also shown excellent qualitative and quantitative agreement with fundamental flow behavior in the regime of interest [32], [56]-[58]. With advances in parallel computing, large-scale three-dimensional simulations have been performed to evaluate pebble bed reactor cores to investigate the flow properties [51], [55], [59], [60], forces on the reflectors [61], and dust production [62]. These simulations include on the order of 105 pebbles and are extremely computationally intensive, taking approximately several weeks to complete on large clusters or supercomputers. This makes simulation of systems like the PB-FHR, which has many more pebbles, impractical to complete during the design phase. The use of DEM results is also limited due to the fact that no experimental data are available that describes the motion of all the pebbles in a packed bed and match the fidelity of the simulation results and all simulation methods use highly empirical models for pebble friction. This poses a challenge for model validation and is discussed further in the following section.
Chapter 1. Introduction

The analysis of granular dynamics in the PB-FHR is further complicated by the consideration of coupled fluid drag forces on the pebble motion. Some research is currently underway to develop a coupled DEM and porous media fluid dynamics model for salt-cooled reactors [63], [64]. This approach uses the packing information from the DEM model to develop local porosities that are used for the porous media solver. This coupling strategy can be used for small systems (e.g. test reactor scale), but are likely to remain too computationally expensive for large power reactors. Strategies that use the relative velocity of the pebble and the coolant are of limited use for the reactor application because the pebble velocities in the core are low compared to the coolant and the fluid passes through an essentially static bed.

Due to the fact that dense granular flow behavior is highly geometry dependent, experiments provide valuable insights into the behavior in these systems. Silo drainage experiments have been performed for gravity-dominated systems where pebbles are tracked at a transparent wall [28]. Several proof of principle experiments have also been performed to demonstrate the viability of a central pebble reflector in gas cooled reactor geometries [50], [51] and the maintenance of radial zones through a diverging region [48], [49]. The first Pebble Recirculation Experiment (PREX), shown in Figure 1.6, was built at U.C. Berkeley in 2006 to demonstrate the recirculation of pebbles in a cylindrical test section with fluid flow based on a salt-cooled reactor design [65]. This experiment also provided useful insights on the behavior of pebbles as they land at the free surface at the bottom of bed, but did not provide data on the pebble motion through the core. A more detailed understanding of granular flow in complex core geometries is required to evaluate models so that the impact of pebble dynamics can be integrated into the neutronics design of the reactor. The need for additional experimental data relevant for reactor geometries is a major motivation behind the work in this dissertation.
1.1.5 Regulatory Issues

In addition to meeting the requirements for the design process, the analysis methods for granular dynamics in pebble bed reactors must meet the approval of regulators in order to be a viable reactor technology. In the United States, the Nuclear Regulatory Commission (NRC) has the primary responsibility to license commercial nuclear reactors and ensure their safe operation to protect the health and welfare of workers and the general population and to protect the environment. The fundamental requirement to understand the phenomena associated with granular dynamics in pebble bed reactor core stems from the need to understand the configuration of the reactor system.

The licensing requirements for commercial reactors are based largely on the experience base with LWRs and the their applicability to non-LWR designs varies. The General Design Criteria (GDC) in 10 CFR 50 Appendix A [66] include a number of high-level safety requirements that would be applicable to pebble bed reactors.
Chapter 1. Introduction

GDC 10 states that the reactor core “shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation.” The precise configuration of pebble bed cores cannot be determined. Therefore, adequate methods to appropriately characterize the core pebble distributions must be developed and proven to evaluate whether the system can meet its performance and safety requirements. Further, the Safety Analysis Report for a reactor design must provide information “relative to materials of construction, general arrangement, and approximate dimensions, sufficient to provide reasonable assurance that the final design will conform to the design bases with adequate margin for safety” [67]. This requires that the understanding of granular dynamics must be sufficient to ensure that the core maintains an acceptable pebble configuration throughout the lifetime of the reactor. These questions of core geometry and composition are unique to pebble bed reactors and are difficult to characterize given the current analysis tools for dense granular flow.

The most important experience with regulatory issues for pebble bed reactor cores comes from the NRC pre-application review of the Pebble Bed Modular Reactor (PBMR), which was a gas cooled reactor under development in South Africa through 2010. The PBMR is a “modular” helium-cooled reactor that was heavily influenced by the early development program in Germany. The major change in design for the PBMR, compared to earlier commercial pebble bed reactors, was to configure the pebble core to be tall and annular to allow decay heat to be removed by conduction under depressurized cool-down conditions, rather than relying on active decay heat removal systems. The 400 MWth (165 MWe) PBMR Pilot Plant design includes a 10 m tall annular core with a solid central reflector, where pebbles circulate from the top to the bottom under gravity [68]. This core design has many similarities to the PB-FHR, the major exceptions being that it lacks radial pebble zoning, a diverging inlet region to the active core, and cross flow of the primary coolant.

In response of the PBMR pre-application review process, the NRC staff identified key safety-related issues of concern, including several regarding pebble bed dynamics, in a Request for Additional Information (RAI) that would need to be addressed in the licensing process [69]. This RAI was in response to the preliminary PBMR core design, which included a central reflector of inert graphite pebbles instead of the later solid graphite structure. Table 1.1 details the parts of the RAI that are related to pebble dynamics in the core. Issues of concern include the residence time distribution of the pebbles and their impact on neutronic analyses, the impact of porosity variations in the packed bed near the reflector walls, and the ability to validate computer simulations with experimental data. The RAI also refers to the computational demands of large-scale DEM simulations and their limited use for design and parametric analysis. These questions do not, by any means, form a comprehensive list of issues to complete the licensing process, but they do serve as a useful starting point as to what issues the NRC staff will expect to see addressed in
any new application for a pebble bed reactor. Unfortunately, PBMR did not provide a detailed response to the RAIs and will not complete the licensing process so we cannot infer what level of detail would be required to satisfy the NRC for these issues.

Of particular interest in the RAI from the NRC staff are the questions regarding analysis capabilities and model validation for granular dynamics, because these are very significant challenges for the current analysis capabilities. The primary means to develop confidence in simulation results is through validation experiments that are conducted for the purpose of determining the predictive accuracy of a computational model for the intended purposes [70]. Continuum models for granular flow have shown poor predictive capability beyond the specific systems they were derived from and large-scale DEM simulations produce high-fidelity results that match qualitative observations, but do not have any comparable experimental data for true model validation.
6.2.6 Provide detailed quantitative information on the predicted spectrum of pebble transit times through the reactor. Of particular interest is the statistical characterization of maximum transit times (i.e. the upper tail of the spectrum). Describe in detail the technical basis (e.g. test data, code models) for the predicted spectrum. Describe the in-plant testing and monitoring that will be performed in the demonstration module and subsequent modules to validated or correct the predicted transit-time spectra and associated pebble flow profiles and to detect pebble flow aberrations.

6.2.25 Pebble flow was evaluated by comparing German experiments and South African computer experiments. It is stated that agreement is within 10%. What parameters were compared? What is their safety significance?

6.2.26 Please justify why the German pebble flow experiments are applicable to PBMR computer simulation assessment. What are the figures of merit? How will the biases and uncertainties be estimated and how will they ultimately be incorporated into the code prediction of pebble flow?

6.2.27 Porosity distribution variations in the pebble bed of up to 10% have been reported.

(a) What is the radial and axial variation in the porosity in the PBMR core?

(b) What is the variation in the porosity inward from the wall to two pebble diameters? What effect if any does this have on the estimated rod worth?

(c) At the wall the porosity goes to unity. Are transport corrections necessary and used at the wall to compute rod worth?

(d) Is the porosity variation taken into account in computing the fuel temperature distributions and its uncertainty?

6.2.28 Since the size of the central [inert pebble] reflector, and the mixing zone, are strongly defined by the manner in which pebbles are loaded, how do you benchmark the computation?

(a) Since one simulation takes ~4 months, parametric studies appear to be limited. So which calculations/simulations are the defining computations?

(b) Does the ANNABEK experiment (to which the PFC3D simulation was compared) contain a central reflector column? Please describe the experiment in detail, provide the experimental results, and describe its relevance to the PFC3D simulation.

6.2.29 What is the correlation between the local pebble flow velocity and the local porosity?

Table 1.1: Relevant safety and technical RAIs from the NRC staff identified during the pre-application review of the PBMR [69].
Blandford [71] makes the important distinction between exploratory and confirmatory validation experiments that is particularly important for the current state of knowledge about granular dynamics in pebble bed reactor cores. Exploratory research is primarily concerned with establishing the potential value and viability of a technology and experiments in this scope must meet reasonable quality standards to meet the ‘proof of principle’ objectives. The main objective of confirmatory research is to prove that the physical behavior of a specific system is understood to an acceptable degree. Confirmatory validation experiments would be required for the analysis of any safety-related phenomena under NRC review. These experiments must be completed with strict nuclear quality assurance standards (NQA-1) and typically require significant resources. Because the PB-FHR is in the early stages of development and there is limited knowledge of granular dynamics in these systems, the key research needs addressed in the scope of this dissertation fall into the exploratory category. Future confirmatory research for granular dynamics in pebble bed reactor cores will present significant additional challenges for model validation given the limited predictive capabilities of analysis tools and the difficulty of experiment design.

One major challenge for reactor designers in developing a validation basis is to establish that components of the technology are sufficiently well understood to meet both the performance metrics for economic viability and the safety requirements for licensing. Table 1.2 presents a set of development objectives for new reactor technologies that is applicable to the design of pebble bed reactor cores and other systems that include complex phenomena and are important to the design basis. The phased approach is based on the Generation IV Roadmap [72] and the FHR experimental validation program proposed by Blandford [71] as part of the overall FHR development effort at U.C. Berkeley. The development includes viability, performance, and demonstration phases that represent increasing levels of design maturity and financial commitment. The PB-FHR is currently in the viability phase where fundamental questions of the system potential remain open and need to be addressed before proceeding with additional development.

Table 1.2 is important to define the requirements at the current stage of design and to identify gaps that could impact the future viability of a reactor technology. For the application of granular dynamics in the pebble bed core, basic viability questions need to be addressed for the PB-FHR based on a preliminary evaluation of what the licensing requirements will be. These requirements are based on existing documentation from regulators, such as the GDCs and PBMR RAIIs. These include the ability to maintain radial zoning through diverging core geometries and the impact of coupled fluid flow on the pebble flow. These high level issues also lead to a set of more detailed questions around the physics of these granular systems such as the stochastic variation in pebble motion and its impact on mixing and residence time distributions. Experiments using simulant materials provide a useful means to assess
the importance of the key phenomena in question at greatly reduced cost. Finally, an assessment of the currently available simulation capabilities is required early in the process to determine what code development might be required and to identify the crucial validation data that will be required in the future. This logic outlines the work required for the viability phases, which is the main focus of this dissertation, but can also be applied to future development phases.

<table>
<thead>
<tr>
<th>Viability Phase</th>
<th>Performance Phase</th>
<th>Demonstration Phase</th>
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<tbody>
<tr>
<td>Regulation</td>
<td>Safety Requirements</td>
<td>Safety Demonstration</td>
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<tr>
<td>Knowledge Base</td>
<td>Fundamental Physics</td>
<td>Failure Modes</td>
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<tr>
<td>Experience Base</td>
<td>Simulant Experiments</td>
<td>Prototypical Experiments</td>
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<tr>
<td>Analysis Tools</td>
<td>Simulation Capabilities</td>
<td>Validation Basis</td>
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<td>Simulation Confirmation</td>
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Table 1.2: Technology development objectives for different stages in reactor licensing.

The key conclusion to draw from this discussion of the regulatory issues for pebble bed cores is that there is a wide array of operational and safety-related issues around granular phenomena that will need to be addressed in the licensing process. In order to accomplish this objective, there are two phases of analysis that are required. The first stage is to develop a strong fundamental understanding of granular flow phenomena in the reactor system. This is the fundamental objective that this dissertation attempts to address. The second stage in the process is to evaluate what the impacts of these phenomena are on key figures of merit for the system performance and safety objectives. These questions are beyond the scope of work presented here, but will become essential for the future development of pebble bed reactor technology.
1.2 Scope of Study

This study is focused on the development of a fundamental understanding of granular dynamics behavior in pebble bed reactor cores through experimental work and computational analysis. The work is focused on the PB-FHR system, but can easily be extended for gas-cooled designs. The experimental data presented in this dissertation attempts to address basic viability questions on the behavior of granular material in reactor core geometries, including the use of radial zoning and diverging regions before pebbles enter the active core region. The experimental results of this thesis will also provide first of a kind data to evaluate the impact of coupled fluid drag forces on the pebble dynamics, which is a critical viability question in the design of the PB-FHR. This experimental work is accompanied by the development of a new DEM simulation tool, which is designed to offer a simple user interface, and model simplifications that can be used for iterative purposes in the design process. The experimental data collected for this study are intended to serve as a preliminary validation basis for the DEM code.

The scope of work completed for this dissertation can be divided into four major areas of effort. The first major effort was the development of the Granular REcirculation COde (GRECO), which is a simplified two-dimensional DEM simulation tool that is much faster than full three-dimensional codes and was conceived to be useful in the design process. GRECO was developed in MATLAB and is implemented in a parallel form using the MATLAB Parallel Computing Toolbox. MATLAB was selected for code prototyping due to the ease of debugging using its data storage, the ease of date input and output, and its robust visualization capabilities. GRECO uses conventional DEM simulation techniques, but includes two key developments that make it more useful for reactor core problems. These include a new friction model, which can better capture some of the key static phenomena of interest, and the implementation of a loose fluid flow coupling scheme that approximates the drag forces as a modified field of body forces in the core domain. GRECO includes separate modules for initial pebble packing, pebble recirculation, and post-processing.

The second major area of contribution of this dissertation is new experimental data that provide key insights into the basic phenomena of granular dynamics in pebble bed reactor core geometry. The results presented in this area are obtained from two gravity-dominated systems, the Pebble Recirculation Experiment (PREX) 2 and 3.0. PREX 2 and 3.0 use simulant pebbles to study the core geometry effects on pebble motion for the PB-FHR and FHR-16 test reactor. These facilities were previously built at U.C. Berkeley for proof of principle type experiments. The data collected for this dissertation include the tracking of pebbles at the visible surface to generate detailed local velocity statistics. This data also provide a number of important results that inform the basic understanding of the mixing behavior at radial
zone interfaces and pebble residence time distributions. A set of image processing tools was developed and verified using MATLAB to detect pebble positions in a large number of time step images and to track pebbles between sequential frames.

The third area of work for this study is experimental results for a coupled system, PREX 3.1, where the impact of fluid drag forces on pebble dynamics can be evaluated. This experiment is scaled based on the FHR-16 test reactor and uses simulant materials. The analysis of pebble motion data from this system was completed using the post-processing tools developed for the gravity-dominated experiments. An additional set of tools was also developed to process the pressure data from this experiment, which was collected directly by a set of manometer taps on the surface of the test section.

The final work in the scope of this dissertation is the comparison of the GRECO simulation results to the data from all three scaled experiments. This provides an initial validation basis for GRECO and informs what design applications it will be most useful for. GRECO is based on a simplified model of the granular system and therefore cannot capture all of the physics of interest for these systems, but it does provide a tool that can be used practically to gain insights about the impact of container geometry and fluid drag forces on the pebble velocity distribution, mixing phenomena, and residence time distributions.

This manuscript is organized into five chapters. The first chapter presented the motivation for this study based on the unique application of granular dynamics in pebble bed reactor cores and relevant background information on the design and licensing issues associated with these systems. Chapter 2 details the development and model assumptions in the GRECO simulation tool, including the new friction model, which is designed to study the recirculation of fuel pebbles through reactor cores with and without coupled fluid drag forces. The experimental results for the gravity-dominated PREX 2 and 3.0 facilities are presented in Chapter 3, while those for the scaled PREX 3.1 facility are presented in Chapter 4. Both Chapters 3 and 4 include direct comparisons of key data from the experiments and GRECO simulations. Chapter 5 discusses the key findings and conclusions of this research and identifies important gaps that merit future study.
Chapter 2

Development of GRECO for Reactor Core Design

This chapter documents the assumptions and methods of a new design-oriented discrete element method (DEM) analysis tool named GRECO (Granular REcirculation COde). GRECO incorporates the basic approaches used in other DEM codes used to study granular flow, such as LAMMPS [73] and PEBBLES [60], but includes a set of modeling assumptions and methodologies that allow the use of a simplified two-dimensional pebble bed geometry that can be simulated on time-scales that are useful for reactor design efforts. The main features that distinguish GRECO from previous DEM codes used to study pebble bed reactor cores include a novel formulation for pebble-wall friction interactions, the ability to loosely couple fluid and pebble dynamics with little additional computation time, and the estimation of uncertainty based on GRECO results and several experiments performed as part of this study. This modeling approach allows GRECO to be used for a wide variety of reactor core geometries and can generate useful results that should inform the design and licensing process. GRECO is implemented as a parallel program in MATLAB.

2.1 Overview of GRECO Motivation

The discrete element method (DEM) is based on techniques employed for molecular dynamics and is a powerful tool for the analysis of dynamic granular systems. It was proposed as a methodology to study granular flow by Cundall and Strack [74], who developed a contact model for cohesionless particles. For granular systems with short-range forces, analysis methods can be parallelized to take advantage of the current computational power of large clusters and supercomputers. These advances allow for the study of pebble bed reactor systems that include on the order of 105 pebbles.

Despite the recent advancements in parallel computing, large granular systems remain highly computationally expensive and full-scale simulations remain impractical to integrate into the design process for pebble bed core geometries. This fundamental challenge is based on the fact that the study of pebble bed cores benefit from at least one recirculation of the entire pebble bed, and preferably more than one, in order to quantify the distributions in pebble residence times. Thus, efficient DEM codes that scale the computational time for each time step with the number of
particles in the system, \( N_p \), will scale at order \( N_p^2 \) for the circulation of the entire bed. This scaling of simulation time implies that while a small number of full-scale three-dimensional simulations may be possible to study cores with order \( 10^3 \) - \( 10^6 \) pebbles, alternative analysis methods will be needed for the design process.

In order to overcome the computational scaling challenges for full-scale DEM simulations, GRECO is based on the analysis of a two-dimensional pebble system in which the motion of a single layer of pebbles is modeled. This assumption dramatically reduces the total number of pebbles in the system and allows for study of large systems with computation time on the order of several hours to days. An extreme example of this benefit can be seen for the 900 MWth PB-AHTR, where the core has about \( 3 \times 10^6 \) pebbles, compared to just 8,500 pebbles in the GRECO model. For codes of similar computational efficiency, this reduction in the number of pebbles by a factor of about 350 translates into a factor of about 125,000 in total CPU time for the code to complete one bed recirculation. Parallelization can help to reduce this gap in real time, but the speed advantages for systems with many fewer pebbles remain dramatic.

The reduction of the system from a full three-dimensional axisymmetric geometry to the simplified two-dimensional configuration in GRECO is a major assumption and will impact the usefulness of results generated from this kind of analysis. Further, the use of this kind of assumption may have different implications for cylindrical versus annular core geometries. A detailed review of these considerations will be covered in Chapter 3, where GRECO results are compared to experimental results for axisymmetric gravity-dominated systems of two different scales.

### 2.1.1 Equations of Motion and Time Integration

GRECO tracks the position vector \( \mathbf{r} \) of each pebble in a granular system based on the two-dimensional form of Newton’s equation of motion, where the angular orientation \( \theta \) is reduced to a scalar quantity. The governing equations of motion for the center of mass coordinates of pebble \( i \) in a system of pebbles (\( i = 1, \ldots, N \)) are

\[
\frac{\partial^2 \mathbf{r}_i}{\partial t^2} = \frac{1}{m_i} \left( \mathbf{F}_{\text{Buoyancy}} + \sum_{j \neq i} \mathbf{F}_{ij} + \mathbf{F}_{\text{Wall}} + \mathbf{F}_{\text{Drag}} \right)
\]

\[
\frac{\partial^2 \theta_i}{\partial t^2} = \frac{1}{J_i} \left( \sum_{j \neq i} T_{ij} + T_{\text{Wall}} \right)
\]

where \( m_i \) is the pebble mass and \( J_i \) is the pebble moment of inertia, which reduces to \( 2/5 \ m_i \ R_i^2 \) for spheres of uniform density and radius \( R_i \) used in the GRECO models. Alternative formulations for the moment of inertia could be used in GRECO for non-uniform spheres, such as the PB-FHR fuel pebbles. The body forces acting on
Chapter 2. Development of GRECO for Reactor Core Design

the center of mass of pebble \( i \) in Equation (2.1) include buoyancy \( F_{Buoyancy} \), contact forces with other pebbles \( F_{ij} \), contact forces with wall surfaces \( F_{Wall} \) and the combination of viscous and inertia fluid drag \( F_{Drag} \). Torques in the GRECO model are applied to pebble \( i \) in Equation (2.2) as a result of tangential forces from pebble-pebble contacts \( T_{ij} \) and pebble-wall contacts \( T_{Wall} \).

In the simple case of gravity drainage in air, the buoyancy force will be simply the force due to gravity \( F_{Buoyancy} = m \mathbf{g} \) and there will be no drag forces present due to the interstitial fluid \( F_{Drag} = 0 \). Rotational moments in GRECO are based only on torques applied for pebble-pebble and pebble-wall contacts. Torques due to viscous drag are neglected in all of the GRECO analysis in this study. This is thought to be a reasonable approximation for dense granular flow, in which pebble velocities are small, but can be added in the future with minor modifications.

GRECO was developed for the specific granular systems of uniform spherical pebbles, which is characteristic of pebble bed reactor cores and is a case that is very efficient to manage using the discrete element method. For the simple case of spherical particles, two pebbles \( i \) and \( j \) are in mechanical contact if the mutual compression between them \( \xi_{ij} \) between them satisfies to condition

\[
\xi_{ij} = R_i + R_j - |\mathbf{r}_i - \mathbf{r}_j| > 0
\]

where \( R_i \) and \( R_j \) are the radii and \( \mathbf{r}_i \) and \( \mathbf{r}_j \) are the position vectors of the pebbles. Figure 2.1 shows a schematic drawing of the interaction model and the mutual compression between two pebbles. GRECO evaluates the force vector \( F_{ij} \) and torque \( T_{ij} \) on pebble \( i \) due to contact with pebble \( j \) by

\[
\begin{align*}
F_{ij} &= F_{ij}^n \hat{e}_{ij}^n + F_{ij}^t \hat{e}_{ij}^t \\
T_{ij} &= F_{ij}^t R_i
\end{align*}
\]

where \( F_{ij}^n \) and \( F_{ij}^t \) are the magnitudes of the normal and tangential (i.e. friction) forces and \( \hat{e}_{ij}^n \) and \( \hat{e}_{ij}^t \) are the unit vectors that define the geometry of the pebble interaction. Similar formulations can be developed for the pebble-wall contacts where \( R_j = 0 \) and the local geometry is determined by the shortest distance between the pebble position and the wall. The magnitudes of the force components are functions of the relative position of the pebbles and their relative velocities. The details of the force models used in GRECO are given in Sections 2.1.2 and 2.1.3.
Chapter 2. Development of GRECO for Reactor Core Design

Figure 2.1: GRECO pebble contact model based on the interaction of two spheres.

GRECO performs the integration of Equations (2.1) and (2.2) using a fifth order predictor-corrector algorithm developed by Gear as applied to granular systems in Ref. [75]. The Gear predictor-corrector algorithm is an especially useful method to manage the extremely large dynamic force gradients in the pebble contract forces. The Gear algorithm is commonly used and well suited to DEM simulations because it maintains a high degree of numerical stability and only requires one force evaluation for each time step [75]. The stability of the Gear algorithm is also advantageous for intensive DEM simulations because it allows larger time steps to be used and reduce the total computation time required. This characteristic is consistent with the intent to make GRECO a fast code that can be used for design purposes.

The Gear algorithm is implemented in GRECO for a two-dimensional system of spheres with three degrees of freedom. The positions of all active pebbles in the simulation domain are tracked between each time step along with all time derivatives up to $d^4/dt^4$. GRECO tracks this data using a pebble position matrix variable $X_i$ defined as

$$X_i(t) = \begin{bmatrix} \mathbf{r}_i(t) & \mathbf{v}_i(t) & \mathbf{a}_i(t) & \mathbf{r}_i^{(3)}(t) & \mathbf{r}_i^{(4)}(t) \\ \mathbf{\theta}_i(t) & \omega_i(t) & \dot{\mathbf{\theta}}_i(t) & \theta_i^{(3)}(t) & \theta_i^{(4)}(t) \end{bmatrix}$$

(2.6)
Chapter 2. Development of GRECO for Reactor Core Design

The pebble position and its derivatives are used at the beginning of each GRECO micro time step to predict the new values at time $t+\Delta t$ using the matrix equation

$$X_i^{pr}(t + \Delta t) = X_i(t) C^{pr}$$  \hspace{1cm} (2.7)

where $C^{pr}$ is a coefficient matrix based on the Taylor expansion series. For the fifth order Gear scheme implemented in GRECO, $C^{pr}$ is defined as

$$C^{pr} = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
\Delta t & 1 & 0 & 0 & 0 \\
\frac{1}{2} \Delta t^2 & \Delta t & 1 & 0 & 0 \\
\frac{1}{6} \Delta t^3 & \frac{1}{2} \Delta t^2 & \Delta t & 1 & 0 \\
\frac{1}{24} \Delta t^4 & \frac{1}{6} \Delta t^3 & \frac{1}{2} \Delta t^2 & \Delta t & 1
\end{bmatrix}$$  \hspace{1cm} (2.8)

Following the predictor step, $X_i^{pr}$ is used to evaluate the forces acting on each pebble, which can be used to generate a corrected pebble acceleration $a_i^{co}$. The difference between the predicted and corrected acceleration $\Delta a_i = a_i^{co} - a_i^{pr}$ is then used to update $X_i$ using

$$X_i(t + \Delta t) = X_i^{pr}(t + \Delta t) + \Delta a_i C^{co}$$  \hspace{1cm} (2.9)

where $C^{co}$ is a matrix of the corrector weights that are specific to the order of the algorithm and the type of differential equation. For the GRECO implementation of the fifth order algorithm, the corrector weight vector is given by

$$C^{co} = \begin{bmatrix}
c_0 \frac{\Delta t^2}{2} & c_1 \frac{\Delta t}{2} & c_2 & c_3 \frac{3}{\Delta t} & c_4 \frac{12}{\Delta t^2}
\end{bmatrix}$$  \hspace{1cm} (2.10)

with

$$c_0 = \frac{11}{90}, \quad c_1 = \frac{3}{4}, \quad c_2 = 1, \quad c_3 = \frac{1}{2}, \quad c_4 = \frac{1}{12}$$

The corrector step is completed for all pebbles before GRECO continues to the next time step where the algorithm is repeated.
Because small time steps are required for the stiff contact force interactions in GRECO (see Section 2.1.2), it is not necessary to store the pebble position data after completing the corrector step in the Gear integration scheme. Instead, GRECO implements a two-tiered time step methodology (see Figure 2.2) that reduces the data storage requirements and better represents the overall pebble motion for the regime of dense granular flow. In this structure, the time steps of the predictor-corrector algorithm are referred to as micro time steps, which are completed for each macro time step where position data is stored and other code functions, such as pebble recirculation, can be completed. The user determines the number of micro time steps $N_{Micro}$ based on the simulation requirements. For example, the study of expansion waves or elastic vibration behavior might require fine temporal resolution and a small number of micro time steps. Typical recirculation problems for reactor systems do not require fine data on pebble motion and use $N_{Micro} \sim 1,000$.

![Figure 2.2: Sketch of GRECO algorithm for time integration showing the macro and micro time step loops.](image-url)
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2.1.2 Pebble Contact Normal Forces

GRECO computes normal contact forces for pebble-pebble $F_{ij}^n$ and pebble-wall interactions $F_{i-Wall}^n$ as damped collisions between viscoelastic materials. The force magnitudes for pebble-pebble and pebble-wall contacts are determined based on the general form for the collision of two materials used in [75] with the material parameters $Y$ (Young modulus) and $\nu$ (Poisson ratio)

$$F_{ij}^n = \frac{4\sqrt{R_{ij}^e}}{3} \left( \frac{1-v_i^2}{Y_i} + \frac{1-v_j^2}{Y_j} \right) \left( \frac{\xi_{ij}^{3/2}}{\xi_{ij}} + \frac{A_i + A_j}{2} \sqrt{\xi_{ij}} \frac{d\xi_{ij}}{dt} \right) \tag{2.11}$$

where $A$ is a dissipative constant that is a function of the material viscosity and can be determined empirically from the coefficient of restitution. $R_{ij}^e$ is the effective radius of the colliding spheres defined as

$$R_{ij}^e = \left( \frac{1}{R_i} + \frac{1}{R_j} \right)^{-1} \tag{2.12}$$

For colliding spheres of the same material and dimension, the normal force interaction between pebbles reduces to the form

$$F_{ij}^n = \frac{Y_i \sqrt{2R_i}}{3(1-v_i^2)} \left( \frac{\xi_{ij}^{3/2}}{\xi_{ij}} + \frac{A_i}{\sqrt{\xi_{ij}}} \frac{d\xi_{ij}}{dt} \right) \tag{2.13}$$

and for spheres colliding with a flat wall surface of a different material, the normal force relationship reduces to

$$F_{i-Wall}^n = \frac{4\sqrt{R_i}}{3} \left( \frac{1-v_i^2}{Y_i} + \frac{1-v_{Wall}^2}{Y_{Wall}} \right) \left( \frac{\xi_{i-Wall}^{3/2}}{\xi_{i-Wall}} + \frac{A_i + A_{Wall}}{2} \sqrt{\xi_{i-Wall}} \frac{d\xi_{i-Wall}}{dt} \right) \tag{2.14}$$

Equations (2.13) and (2.14) are used in GRECO to compute the magnitude of the normal forces acting on the pebble center of mass. They are combined into Equation (2.4) with the unit normal vector $\hat{e}_{ij}^n$ to compute the normal force vector acting on pebble $i$.

One of the challenges for DEM simulations is the small time steps required to manage the stiffness of pebble interactions based on physical values of Young’s modulus on the order of $10^9$ N/m. In order to relax the time step requirements, GRECO uses effectively softer materials where the effective Young’s modulus is one-hundredth the physical value for the material. This allows the use of larger time steps that greatly speed up the computation time. This approach is standard to many
DEM codes and does not significantly impact the pebble motion for slow, dense granular flows where the small time scale dynamics of pebble interactions are less important than local geometry constraints. The GRECO results shown in the following chapters use Young’s moduli of $1.75 \times 10^7$ Pa and $2.30 \times 10^7$ Pa, which are reduced by a factor of 100, for pebble-pebble and pebble-wall contacts, respectively.

The value of the damping coefficient $A$ can be determined empirically based on the coefficient of restitution for pebble-pebble and pebble-wall collisions. The experiments included in this study use high-density polyethylene (HDPE) pebbles in test sections with acrylic wall surfaces. Simple pebble drop tests were performed to measure the coefficient of restitution using a hard surface (granite) for pebble-pebble contact and a clamped acrylic sheet for pebble-wall contact. These tests found the coefficients of restitution to be 0.86 and 0.37 for pebble-pebble and pebble-wall contacts, respectively. The low coefficient measured for the HDPE-acrylic contact is likely due to additional damping between the acrylic sheet and granite surface. Distortions from additional damping have very little impact in the GRECO output results because the regime of dense granular flow is highly effective in distributing energy from inelastic collisions. The corresponding values of the damping coefficient $A$ in the GRECO normal force model to match the measured coefficients of restitution are $5.7 \times 10^{-5}$ s and $10.3 \times 10^{-5}$ s. These values are used in all of the GRECO simulation cases in this dissertation.

### 2.1.3 Hybrid Friction Model

The primary innovative feature in GRECO is the development of a novel pebble-wall friction model that handles kinetic and static friction in two distinct steps. The method is considered to be a hybrid method because it combines the Haff and Werner friction model for kinetic friction [76] with a new tangential displacement condition to better capture static friction between pebble and smooth wall surface. The hybrid friction model is only applied to pebble-wall contacts based on the assumption that static wall friction is more important for the overall velocity field of the pebble bed. This assumption is supported by previous work in the literature that shows for static beds, the pebbles at the walls are loaded close to the Coulomb static friction limit, while pebbles in the bed have much lower friction loadings [77]. Large-scale DEM simulations also show that pebble wall friction is one of the dominant factors in the overall system behavior [55].
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The GRECO friction model uses the Haff and Werner friction model to treat kinetic friction for all of the pebble-pebble and pebble-wall contacts. The model is based on the assumption that friction is a proportional control law that opposes the relative velocity between two surfaces at the point of contact. This control law for the magnitude of the kinetic friction tangential force $F_{k_t}$ is formulated as

$$F_{k_t} = -\text{sign}(v'_{rel}) \cdot \min \left( \gamma' |v'_{rel}|, \mu_k |F_n| \right)$$

(2.15)

where $v'_{rel}$ is the relative tangential velocity, $\gamma'$ is an empirical damping constant, $\mu_k$ is the kinetic component of the friction coefficient and $F_n$ is the magnitude of the normal contact force.

The Haff and Werner model has been used successfully in many DEM simulations and is relatively simple to implement because it requires only the position and velocity data for the pebbles in the current time step. The model, however, is best suited for dynamic systems because it cannot handle true static contacts – as the relative velocity approaches zero, so does the tangential force. Thus, slow-moving or static systems will decompose in a non-physical manner.

In order to better accommodate static friction for the pebble-wall contacts, GRECO implements a new zero-displacement constraint on the tangential motion of the pebbles. The hybrid static friction force is calculated after all of the other forces have been evaluated, including the kinetic friction term. For each pebble-wall contact GRECO evaluates the critical static force $F_s^*$ which is required to enforce zero tangential displacement for the pebble center of mass. For the fifth order Gear predictor-corrector time integration scheme used in GRECO, this critical force is determined by

$$F_s^* = m_p \left[ \frac{2}{c_0 \Delta t^2} \left( r_i - r_i^{pr} \right) + r_i^{pr} \right] \cdot \mathbf{e}^t - \mathbf{F}_{\text{net}} \cdot \mathbf{e}^t$$

(2.16)

where $m_p$ is the pebble mass, $c_0$ is a coefficient from the Gear time integration ($c_0 = 11/19$ for fifth order Gear scheme), $\Delta t$ is the integration time step, $r_i$ is the pebble position, $r_i^{pr}$ is the predicted pebble position, $\mathbf{e}^t$ is the tangential unit vector, and $\mathbf{F}_{\text{net}}$ is the net force from all other interactions. Note that the exact formulation of $F_s^*$ is dependent on the time integration scheme used in order to enforce the zero tangential displacement requirement. Simply setting the critical force to oppose the net tangential force on the pebble is sufficient only to maintain a constant velocity. If this condition were used, true static contacts could not be established, as pebbles would move slowly at constant speed across the walls.
The magnitude of the hybrid static friction force $F_{st}$ is limited in GRECO based on the relationship

$$F_{st} = \min(F^*, \mu_s |F^*|)$$

(2.17)

where $\mu_s$ is the hybrid static friction coefficient. In order to remain consistent with the Coulomb friction coefficient $\mu_c$, the sum of the kinetic and hybrid static friction coefficients in GRECO is constrained by

$$\mu_c = (1 - \lambda)\mu_k + \lambda\mu_s$$

(2.18)

where $\lambda$ ranges from zero to one and is a GRECO model parameter determined by the user. This constraint enforces the Coulomb friction limit and allows the user to adjust the degree to which static friction influences the system behavior. All of the GRECO results presented in this study were performed with $\lambda = 0.1$.

After the hybrid static friction force is determined, it is added to the net force for all pebbles in the current time step and the Gear corrector step is performed to complete the time integration.

One major assumption of the GRECO hybrid friction model is that the static friction component only applies a linear force on the pebble center of mass. The static friction component does not impose any torques on the pebbles and does not directly impact the rotational motion of the system. This is a non-physical assumption because static friction plays a role in opposing both linear and rotational motion in true granular systems.

The most reasonable physical interpretation of this assumption is that the hybrid friction force behaves like a rolling friction force in which small deformation of the pebble imposes a net normal force on the center of mass. This interpretation is particularly important because it allows GRECO to handle circumstances where pebbles may be stuck at a wall in the reactor where drag forces may impose a large normal force that is large enough to prevent the pebble from rolling. Typical DEM friction models based on controlling the relativize velocity at the point of contact cannot handle this physical situation due to the limitation that no friction force can be applied when a pebble is rolling along the reflector with no slippage. This limitation applies not only to the Haff and Werner model described above, but also to the Cundall and Stack model [74], which implements both proportional and integral (P-I) control terms and is much more capable of modeling static systems.

The GRECO hybrid friction model can also be viewed as an analogous model assumption to the common DEM practice of using smaller particles at the wall boundaries to approximate surface roughness. The GRECO implementation is more flexible than the small pebble approximation because wall surfaces are described as straight-line segments that can accommodate a wide variety of geometries. In
addition, GRECO can handle the equivalent of very small surface roughness features with no additional computational cost. This is due to the fact that the normal forces acting on a pebble due to surface roughness are approximated by the hybrid static friction coefficient and do not require a large number of small boundary pebbles to approximate these forces. For system boundaries assembled from small pebbles, the number of additional pebble contact scans can increase dramatically and increase the total computation time.

The value of the GRECO friction model for reactor cores can be seen with the consideration of a few simple pebble motion scenarios. Figure 2.3 shows three useful test cases of pebble motion, including a static pyramid, a pebble rolling on an inclined plane, and a pebble at a wall surface with fluid flow normal to the surface. The static pyramid (Figure 2.3a) is a particularly challenging case for all DEM friction models because all the surfaces are smooth and large friction coefficients are required to maintain the static configuration. The Haff and Werner friction model will simply decompose for all friction coefficients. The P-I controller of the Cundall and Stack model will maintain a static condition after a short settling phase where slip occurs at the points of contact. The GRECO friction model can also establish a static configuration because static friction forces at the wall do not apply any torques on the pebble. With no static pebble-pebble friction, this case give an analytical solution of the critical static friction coefficient \( \mu_s = 0.19245 \), which was matched by simple GRECO tests. A critical value for pebble friction coefficients can also be derived for this system, with \( \mu_{\text{critical}} = 0.2679 \), but this benchmark is less relevant for GRECO because the hybrid friction model does not consider static friction for pebble-pebble contacts. While useful as a model problem for a friction model, this configuration is not directly applicable to the dense packing of pebble bed reactor cores.

Two other cases of interest are that of a pebble rolling on an inclined plane under gravity forces (Figure 2.3b) and with a fluid velocity normal to the wall surface (Figure 2.3c). Pebbles in these configurations may or may not be subject to additional contact forces from other pebbles in a packed bed configuration. As mentioned earlier, when subject to only gravity forces, the pebble will roll down the plane subject to rolling friction forces. Control-style friction laws cannot account for rolling friction due to the fact that no torques may act on the pebble if there is no slip at the point of contact. The GRECO hybrid friction model can account for rolling friction in a more physically realistic manner.

The case with fluid flow normal to the surface (Figure 2.3c) is particularly important for reactor core analysis because some critical fluid flow velocity will exist so that static friction will be enough to prevent pebbles from rolling down the wall surface. The GRECO friction model can model this static behavior, while control-style friction models cannot due to the same limitations as the gravity-dominated inclined plane. While the hybrid friction model includes some non-physical
assumptions, especially the lack of static friction for pebble-pebble contacts, this simple case demonstrates that the selection of a particular friction model can have a large impact on the types of phenomena that one will be able to evaluate in simulations. In nuclear applications, this can have a large impact on the suitability of model because there is a high standard for validation for safety-related phenomena.

Figure 2.3: Simple test cases for DEM friction models.

2.1.4 Pebble Contact Scanning Algorithm

GRECO uses an efficient scheme to scan for pebble-pebble contacts so that the computation time for each time step scales with the total number of pebbles in the system. The method for contact scanning in GRECO uses two methods described in Ref. [75]: the Verlet algorithm and the link cell algorithm. These methods are extremely efficient for codes like GRECO, which include spherical pebbles with short-range force interactions.

The Verlet algorithm is based on the simple observation of granular dynamics that pebbles will remain in close proximity to each other, at least over the course of several time steps, and therefore only a small subset of pebbles in the system need to be tested for contacts. For each pebble, there is a Verlet list in which all close neighbors of that pebble are recorded and must be evaluated to detect any pebble-pebble contacts. The Verlet lists are generated at the start of each micro time step in GRECO by sorting pebbles into a grid of Verlet cells in which the mesh size is equal to the diameter of the largest pebbles in the simulation to guarantee the detection of all close pairs (Figure 2.4). All pebble contacts in the system can be found by testing for mutual compression between a pebble with all the pebbles listed in its assigned Verlet cell and with those in the eight surrounding cells. Some efficiency could be gained by selectively updating the Verlet lists only for time steps where pebbles cross over the Verlet cell boundaries. However, this produces limited benefit because Verlet lists can be generated quickly compared to the evaluation of the pebble forces.

The Verlet algorithm is supported by the link cell algorithm, which reduces the number of contact tests and force computations by a factor of two. In this method, the Verlet lists are created at the beginning of each micro time step and the Verlet
cells are scanned in a sequential fashion. Starting in the lower left region of the simulation domain, collision detection is only required for the current Verlet cell and the four neighboring cells above and to the right (Figure 2.4). The computational efficiency of this scanning method is gained through the fact that pebbles in contact will exert equal and opposite forces. Forces due to pebble-pebble contacts are therefore computed only once and applied to both pebbles.

![Image of Verlet cells in a GRECO simulation. For the cell marked with dashed lines, the other highlighted cells require scanning for pebble-pebble contacts using the link cell algorithm.](image)

Figure 2.4: Image of Verlet cells in a GRECO simulation. For the cell marked with dashed lines, the other highlighted cells require scanning for pebble-pebble contacts using the link cell algorithm.

### 2.1.5 Wall Boundaries

The input of wall boundaries in GRECO is designed to be simple and to accommodate a wide variety of possible container geometries. The two-dimensional analysis in GRECO requires the definition of wall boundaries approximated as short linear segments that are defined by the user in the loose packing module. Analysis of pebble-wall interactions on curved surfaces is not implemented in GRECO, but could be added with relatively modest effort.

Wall boundaries are defined in GRECO as linear segments that connect a series of points (i.e. corners) specified by the user. These line segments must be defined in a counterclockwise look around the packed bed. The user may define the type of surface for each segment of the boundary in order to use different friction coefficients in different regions. Curved surfaces are not implemented in GRECO in its current version. Therefore wall contacts are limited to the region normal to the wall surface.
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The process of searching for pebble-wall contacts is handled in a similar fashion to the scan for pebble-pebble contacts by using Verlet cells. This methodology has not been used in existing DEM codes, but is extremely efficient and can be extended to the analysis of large three-dimensional systems. During the initialization phase of the loose packing module, an algorithm is completed to evaluate which wall segments, if any, a pebble in each Verlet cell might contact. The resulting Verlet list for each cell includes the nearby boundary and wall segment indexes, which are the only segments that need to be tested for pebbles in that cell. Figure 2.5 shows the Verlet cell boundaries for the GRECO model of the Pebble Recirculation Experiment (PREX) 3.0 experiment, which is detailed in Chapter 3. The highlighted cells are the ones that may have pebble-wall contacts and require evaluation to determine if such contacts exist. This method for pebble-wall contact scanning is especially efficient for GRECO models that include many short wall segments and allows for more complex geometries to be considered with negligible additional computation time.

External corners require special treatment in DEM simulations because pebbles can contact these corners without entering the projected contact region for a given line segment. Interior corners do not require such consideration due to the fact that any pebble nearby would contact one or both of the adjacent wall segments before the corner. Exterior corners are treated in GRECO with the same force relationship as pebble-wall contacts with the normal force interaction acting along the direction from the corner to the center of the pebble. Pebble-corner contacts occur if there is interference between the pebble and the corner position and if the pebble is in the angular range between the two adjacent wall segments. The second condition is required to prevent a pebble from having contact with both a wall and a corner, which would provide additional tangential forces and artificially hold up the pebble.

During the loose packing module initialization, GRECO automatically scans the boundary inputs for external corners and, similar to the method of testing pebble-wall contacts, generates Verlet lists for cells that might have pebble-corner contacts. GRECO includes external corners between two adjacent boundary segments and at the endpoints of boundaries, such as inlet hoppers. The latter capability allows for the use of thin divider plates to be used without having a very short wall segment at the end. Figure 2.5 shows the Verlet cell boundaries for the GRECO model of the PREX 3.0 experiment with those cells that require pebble-corner contact scanning. The efficiency benefit is similar to that for pebble-wall scanning and is especially useful for the GRECO approximation of convex boundary features.
Figure 2.5: Image of Verlet cells for the PREX 3.0 GRECO simulation. Highlighted cells require scanning for pebble-wall (left) and pebble-corner (right) contacts.

2.1.6 Polydisperse Pebble Packing

GRECO includes the capability to simulate granular flow in monodisperse or random polydisperse spherical pebble beds. Monodisperse pebble beds include particles of one diameter, while polydisperse pebble beds include particles with a variation of different diameters around a nominal average particle size. Polydisperse beds are recommended for two-dimensional DEM simulations in order to reduce crystallization effects and to decrease the probability of jamming in narrow channels, such as those in the pebble loading hopper regions of the PB-FHR.

In the loose packing module of GRECO, the pebble radius is randomly selected from a uniform distribution between $R \pm \delta R$. Based on the analysis in [77], the recommended polydispersion factor $\delta R / R$ is 0.1. Figure 2.6 shows the decrease crystallization observed in the constant area and converging regions of PREX 3.0 for $\delta R / R = 0$ and $\delta R / R = 0.1$. It is important to note that the polydisperse packing in
two-dimensional DEM simulations exhibit stress chains over longer distances than three-dimensional cases, which reflects the limited degrees of freedom in the system. In three-dimensions, stress chains occur over the length of a few pebble diameters before the forces are distributed more broadly [78].

Figure 2.6: Pebbles packed in the constant area and converging region of PREX 3.0 with $\delta R / R = 0$ (left) and $\delta R / R = 0.1$ (right). Ordered hexagonal packing is clearly visible in the monodisperse bed.

### 2.2 GRECO Simulation Methods

#### 2.2.1 Initial Pebble Loading Methodology

A loose pebble packing method has been developed as part of GRECO to decrease the time required to set up initial loading configurations for simulation runs. This module is also where the initial geometry analysis is completed to develop the wall and corner contact lists for all Verlet cells in the simulation domain.

The loose packing algorithm initializes by scanning all Verlet cells in the simulation domain and applies a set of logic requirements that identifies the cell as a valid or invalid box to insert a new pebble. All cells outside the boundary walls are automatically excluded, as are cells where pebble-wall or pebble-corner contacts may exist. An initial layer of pebbles is loaded at the system outlet. Pebbles are then inserted individually several pebble diameters above the highest ($g < 0$) or below the lowest ($g > 0$) pebble in the system and allowed to settle until a stable position is established with two contacts. Small gaps are left between pebbles in the loose packing so that large initial forces can be avoided when the normal GRECO mechanics model is used for additional settling. The algorithm is extremely efficient.
for the two-dimensional GRECO systems because integration and contact scanning is only required for one pebble.

After the loose pebble packing is completed, the main GRECO program is used to simulate the dynamic settling of all the pebbles in the system and to create an initial tight packing configuration that is used for any subsequent recirculation analysis. GRECO includes an option to add pebbles to the inlet hoppers so that the bed remains completely packed while completing the settling. This mode is active when the user input variable FillHoppers is set to one. Another useful option for settling is SettleMode, which sets all pebble velocity and higher derivative data to zero at the end of each macro time step. When activated, this mode reduces the accumulation of kinetic energy for tall systems as pebbles fall to close the small gaps left from the loose packing. Figure 2.7 shows the loose configuration with 1,150 pebbles and the tight configuration with 1,373 pebbles for the PREX 3.0 GRECO model. Full settling is typically achieved in about 20 Macro Time Steps using 2000-4000 Micro Time Steps.

![Figure 2.7: GRECO simulation loose packing of 1150 pebbles (left) and tight packing of 1373 pebbles (right) for PREX 3.0.](image)
2.2.2 Pebble Recirculation Modes

GRECO features several recirculation modes that are listed in Table 2.1. The basic options include the ability to turn recirculation on or off and to define the velocity for pebbles in the discharge region. For the free discharge modes (Modes 1 and 3), pebbles recirculate under gravity forces. This approach is commonly used for large three-dimensional DEM simulations because it would be too computationally expensive to run with a controlled slow pebble discharge. This method leads to low pebble packing in the defueling chute, which is not characteristic of the true system where dense packing is maintained everywhere in the system. As a benefit of the reduced computation demand for the two-dimensional system, GRECO offers several discharge modes that preserve dense packing configurations in the defueling region.

For the GRECO modes that include pebble recirculation (Modes 3-5), pebbles are removed from the simulation domain when they reach the lowest \((g < 0)\) or highest \((g > 0)\) Verlet cells in the geometry on a continuous basis. At the end of each macro time step, all pebbles removed from the system are reinserted into the inlet hoppers if there is enough space at the free surface. If the hoppers are full, the pebble is removed from the simulation for the next macro time step. When there is excess volume in the hoppers, inactive pebbles are reinserted into the simulation. Recirculated pebbles are distributed and allowed to quickly settle to the free surface in the hoppers to maintain dense packing in each of the inlet hoppers.

<table>
<thead>
<tr>
<th>Mode ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Pebble Discharge, No Recirculation</td>
</tr>
<tr>
<td>1</td>
<td>Free Discharge, No Recirculation</td>
</tr>
<tr>
<td>2</td>
<td>Fixed Velocity Discharge, No Recirculation</td>
</tr>
<tr>
<td>3</td>
<td>Free Discharge with Pebble Recirculation</td>
</tr>
<tr>
<td>4</td>
<td>Fixed Velocity Discharge with Pebble Recirculation</td>
</tr>
<tr>
<td>5</td>
<td>Parabolic Velocity Discharge with Pebble Recirculation</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of GRECO recirculation modes.
Mode 4, which includes a fixed velocity discharge in the outlet region and pebble recirculation to one or more inlet hoppers, is the most useful GRECO recirculation mode to capture the behavior of pebble dynamics in reactor core geometries. For this mode, plug flow in the constant-area defueling chute is assumed and the discharge velocity \( v_{\text{Outlet}} \) is established based on the user-defined number of micro time steps such that,

\[
v_{\text{Outlet}} = \begin{bmatrix} 0 \\ \text{sign}(g) \frac{r}{N_{\text{Micro}} \Delta t} \\ 0 \end{bmatrix}
\]  

The formulation of the outlet velocity in Equation (2.19) establishes that pebbles in the defueling chute will be displaced by one pebble radius between each macro time step where position data is recorded. There is no built-in limit on the magnitude for \( v_{\text{Outlet}} \), so GRECO simulations with recirculation and small numbers of micro time steps will produce nonphysical velocities for the discharge region. The GRECO user should verify that the discharge velocity is reasonable based on the pebble discharge rate observed for a free discharge before running in a controlled discharge velocity mode. Due to the fact that dense granular flows in converging geometries will have near-constant discharge rates, a large outlet velocity would effectively turn the simulation into a free discharge run and would have no impact on the stability of GRECO to perform the computation.

An alternative discharge mode for GRECO is Mode 5, which uses a parabolic velocity profile in the discharge region. For this mode, the user sets either the ratio of the discharge velocities at the walls and the center of the defueling region or the coefficients of a parabolic fit for the discharge velocity (e.g. from experimental data). The average discharge velocity is set using the same formulation in Equation (2.19). This mode gives the ability to test different velocity profiles where pebble hold-up at the walls in the defueling region may be an important factor. However, Mode 4 is recommended for most applications because it does not require pre-existing knowledge of the discharge velocity profile.

### 2.2.3 Post Processing Module

The GRECO post-processing module was developed to extract a wide range of statistics from the stored pebble position data at each macro time step in the simulation that can be compared directly to the experimental data accumulated from the PREX facilities. Additional results on the pebble forces can also be studied with GRECO using with post-processing module, but this data should be treated with some caution because the mode of force transmission will be significantly different in the constrained two-dimensional GRECO simulation compared to the true three-dimensional.
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dimensional system. The GRECO post-processing module includes five modes that are briefly described in this section.

**Mode 1 – Pebble Velocity Statistics**

This is the primary data extraction mode for the GRECO simulation results that evaluates the local mean and variance for pebble velocities in each Verlet cell in the simulation domain. Pebble motion steps are assigned to a Verlet cell based on the average position between the initial and final position. The displacement data from the simulation are normalized by the average pebble displacement in the constant area or active core region of the domain. This normalization allows for the results to be scaled by reactor neutronics designers as needed based on the desired residence time of fuel pebbles in the active core region.

Statistics on pebble motion are compiled using two coordinate bases. Cartesian coordinates (x-y) provide a useful common reference frame to evaluate the vertical and horizontal velocity components. It is important to note that for annular core geometries, the Cartesian coordinates in GRECO are described using the cylindrical coordinate terms (r-z) but the simulation geometry does not change.

The second coordinate bases used for the GRECO statistics are based on the displacement components normal to and tangential to the average local velocity vector in each Verlet cell. In this orientation, the mean tangential velocity is equal to the magnitude of the mean velocity vector in Cartesian coordinates and the mean normal velocity is equal to zero. The value of these results comes from the variance data. The standard deviation of the tangential velocity component is a useful measure of the stochastic variation of pebbles along the average streamline path. The standard deviation of the normal velocity component is a useful measure of stochastic pebble mixing and how likely pebbles are to move off of their current streamline.

**Mode 2 – Residence Time Distributions**

Mode 2 in the GRECO post-processing module extracts the pebble paths from the stored position data. The pebble paths can be used to evaluate the residence time distributions for pebbles as they recirculate through the entire core or between two elevations of interest. The user can specify whether to include path data from all pebbles in the system or from one of the radial pebble zones.

**Mode 3 – Pebble Force Analysis**

Statistics on pebble forces from the GRECO simulation can be extracted from the stored position and velocity data using Mode 3 of the post-processing module. This mode is the most computationally intensive because it requires the evaluation of all forces for each macro time step. Tallies are compiled for the mean and variance of the normal and tangential forces for pebble-pebble and pebble-wall contacts. The
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latter data can be used to estimate the force loading on reflector surfaces, although these will have some distortions due to the two-dimensional modeling assumption in the GRECO model.

Mode 4 – Pebble Recirculation Rates

This post-processing module extracts the overall pebble recirculation rates for radial pebble zones. This method simply tallies the number of pebble loaded into each radial zone inlet hopper and determines the relative fractions of each type.

Mode 5 – Radial Zone Statistics

Mode 5 in the GRECO post-processing module generates tallies and gives the probabilities of finding pebbles from each of the radial zones in each of the Verlet cells in the simulation domain. This module provides useful insights into the amount of mixing at the radial zone interfaces in different regions of the core.

2.3 Fluid Dynamics Coupling Methods

GRECO includes a loose coupling methodology to evaluate the impact of fluid drag forces on the granular dynamics. This method approximates the fluid drag forces as a body force that is independent of the pebble velocity. A loose coupling strategy is determined to be appropriate for GRECO due to the non-physical two-dimensional geometry approximation and the motivation to produce results as quickly as possible during preliminary core design efforts. Three-dimensional DEM simulations at later stages in the design process can use realistic pebble bed configurations to use in porous media equations with moderate increases in the computational costs [64].

In simulations that include fluid drag, the GRECO simulation domain is divided into a square mesh where each cell is assigned a constant drag force. This force vector acts as a spatial-dependent body force on pebbles in the simulation and does not apply any torques on the pebbles. For convenience purposes, the dimensions of the drag force mesh are selected to align with those for the Verlet cells, but other cell dimensions can be used depending on the fidelity for the drag force data. The assumption that the drag forces are constant is true in the case of static beds and is extrapolated to the conditions of slow dense granular flow in which the pebble velocity is small compared to that of the fluid, which applies for the slow recirculation of pebbles in reactor cores.

One useful physical interpretation of this coupling strategy is that the fluid drag forces act as a kind of modified multi-dimensional gravity field. This assumption is useful in the case of DEM simulation tools, including GRECO, which must accelerate the timescales of granular dynamics relative to the prototypical system in order complete simulations in a reasonable amount of computation time. The acceleration of dynamics in the simulation may introduce distortions if velocity-
dependent drag correlations are used because the pebble velocity in the simulation time scale may not be small compared to that of the fluid flow.

The most practical method to determine the local drag forces in each Verlet cell is to use the pressure data from experimental or numerical results from the analysis of porous media flow. Based on the pressure data from porous media flow, the net drag force $F_{\text{drag}}$ on a stationary sphere in a linear pressure field can be approximated as

$$F_{\text{drag}} = -V_p \frac{dP}{dx}$$  \hfill (2.20)

where $V_p$ is the pebble volume and $P$ is the fluid pressure. Appendix A gives a derivation for Equation (2.20) based on the integration of a linear pressure field on the surface of sphere. This approximation is most appropriate for systems with very small pebble velocities. In systems with larger pebble velocities, the momentum transfer from the fluid to the pebbles will result in a decrease in pressure and this formulation will no longer hold. Equation (2.20) is used as the basis to determine the coupled fluid drag forces for the experimental data presented in Chapter 4 of this dissertation. This coupling method is particularly convenient for this study because it allows for direct experimental pressure data to be used to determine the fluid drag forces and does not rely on the use of a porous media flow pressure correlation.

### 2.4 Code Parallelization

GRECO is implemented as a parallel code using the MATLAB Parallel Computing Toolbox in order to decrease the total clock time required to generate pebble recirculation results. This allows for analysis of systems up to about 10,000 pebbles on an 8-core desktop in about two days. Depending on the data required, shorter or longer studies may be needed. Preliminary velocity data for systems of this size can be generated in about 12 hours, while more detailed data on pebble recirculation can take up to a week to complete. The ability to generate results on these time scales is much more useful for design efforts than the use of full three-dimensional DEM analysis.

The GRECO parallelization methodology is based on the domain decomposition strategy described by Pöschel and Schwager [75]. The simulation domain is divided into horizontal regions that have approximately the same number of pebbles. The boundaries for the domain decomposition are required to align with the boundaries of the Verlet cells, which can account for some differences in the number of pebbles in each zone. Load balancing between the horizontal regions is accomplished by checking the number of pebbles in each zone at the end of each macro time step and redistributing the zone boundaries if any one zone exceeds its expected pebble count by some user-defined threshold (typically 10%). This redistribution is important for cases of free drainage with no recirculation, but is not a large concern for typical
recirculation studies because the bed should remain fully packed with approximately equal number of pebbles through the entire simulation.

After the domain decomposition is established, each core is tasked with performing all steps in the GRECO time integration and force analysis for the assigned pebbles. The predictor step is performed for all pebbles, followed by scans for pebbles that need to be transferred between the domain partitions. Data packages are assembled and passed to the destination lab, if required. Message passing is also used following the predictor step to update the positions of pebbles located immediately above and below the current lab. Due to the fact that only the predictor position is used in the force evaluation, no other message passing is required during the evaluation of the micro time step. After the force computation and corrector step are completed, GRECO moves on to evaluate the next micro time step. After evaluating all micro time steps, GRECO stores the pebble position data for each lab and recirculates pebbles, as required, at the start of the next macro time step.

The parallel version of GRECO greatly improves the ability of the user to produce useful results for different core geometries using conventional multi-core desktop computers. Table 2.2 shows the computation time and speed up factor compared to the serial code for 100 GRECO time steps from one core to eight cores. These results are for PREX 2 and PREX 3.0, which contain 8,436 and 1,373 pebbles, respectively, and are the two experimental geometries that are covered in Chapter 3. The results in Table 2.2 show excellent speed up efficiency moving from one to eight cores. The efficiency of the parallel algorithm decreases with additional cores because of the increase message passing demands, but still shows an improvement in the wall clock time. This is seen particularly in the smaller PREX 3.0 system where fewer forces are evaluated by each processor.
Table 2.2: Clock times and speed up factors of parallel GRECO code for PREX 2 and 3.0 simulations with 8,436 and 1,373 pebbles, respectively. The results are given to complete 100 micro time steps.

Verification of the parallel GRECO implementation was performed by comparing the results for the updated parallel code to a serial version of the code to evaluate any differences in the key simulation parameters over a small number of time steps (10-100). Key figures of merit for this verification process were pebble forces and the average overlap of pebble contacts. These values are very sensitive to the divergence between the serial and parallel version and were useful to detect and correct coding errors during the development of GRECO. For the final version of GRECO, differences in the forces between the serial and parallel code were less than $10^{-12}$ N, which is many orders of magnitude lower than the typical pebble contact forces. Differences in the average pebble overlap in the GRECO results from one processor and from twelve processors were found to match to within ten significant figures after 100 time steps. In summary, there is a high level of confidence that the parallel version of GRECO introduces no significant differences from serial version of the algorithm.
Chapter 3

Conventional Gravity-Dominated Systems

This chapter presents a detailed analysis of flow in “dry” granular systems, where the consideration of coupled drag forces from fluid flowing through the packed bed is not needed. There are two primary objectives in the results and discussion covered here. The first objective is to present experimental data for new annular core geometries. These results are intended to provide a fundamental understanding of granular flow in these geometries and how they relate to core design efforts. The second objective is to provide an initial validation basis for GRECO and to quantify the errors associated with the two-dimensional geometry assumption.

3.1 Experimental Methods

The Pebble Recirculation Experiment (PREX) 2 and 3.0 facilities are scaled experimental facilities that were built at U.C. Berkeley to demonstrate the fundamental behavior of dense granular flow in complex core geometry designs for the pebble-bed fluoride salt-cooled high temperature reactor (PB-FHR). These facilities use high-density polyethylene (HDPE) spheres to simulate fuel pebbles and recirculation is done under gravity drainage. Therefore, they cannot account for any impact of coupled fluid drag forces on the granular dynamics.

Previous experiments with PREX 2 [48] and PREX 3.0 [49] were motivated to address basic viability questions around radial zoning and a description of qualitative behavior of granular flow in diverging regions. The results presented in this dissertation for each facility include a detailed new quantitative analysis of the motion of pebbles that is intended to serve as an initial validation database for granular flow models, such as GRECO. The following sections provide a brief description of the PREX facilities, as well as the data collection and processing methods used for the results presented later in this chapter.
3.1.1 Facility Descriptions

PREX 2 is a gravity-dominated experiment based on the annular core geometry for the 900 MWth PB-FHR [48]. The axisymmetric core design is approximated as a 15° wedge, which is intended to capture the impact of radial expansion and contraction in the geometry of the prototypical system. Figure 3.1 shows a front view of the facility loaded with approximately 130,000 pebbles, along with labels of the important axial regions of the core. The dotted black line at the left side of the image is the centerline \(r = 0 \text{ m}\) for the test section wedge. The core geometry region is 2.85 m high and the inner and outer radii for the wedge are 0.37 m and 0.97 m.

Figure 3.1: PREX 2 test section loaded with approximately 130,000 pebbles after complete bed recirculation. Different regions of the test section are labeled.
PREX 2 includes six radial zones that are established by the presence of five steel divider plats that extend down to a height of 2.475 m at the top of the test section. The width of each inlet hopper is on the order of $3d$. The radial zones in PREX 2 are intended for demonstration purposes only and are not based on a specify PB-FHR core design.

For reference purposes, the wall boundaries at the left and right side of the test section will be described as the inner and outer reflectors, respectively. These descriptions are used throughout the discussion in this chapter and are useful for thinking about the experimental results in terms of the actual PB-FHR core geometry. In addition, the wedge geometry of the PREX 2 facility will be treated in cylindrical coordinates where the visible surface of pebbles will be considered to be the $r$-$z$ plane.

The PREX 2 facility has geometric scaling at 42% of the prototypical system based on the commercial availability of 1.26 cm diameter HDPE spheres and their suitability for experiments with coupled drag forces using water as a simulant fluid [65]. The front and rear walls ($r$-$z$ plane) of the test section wedge are flat acrylic sheets, while the inner and outer reflector are fabricated from thermoformed acrylic in order to eliminate any sharp corner along these surfaces. The complete surface geometry for PREX 2 is included in Appendix B.

PREX 3.0 is also a gravity-dominated experiment and is based on the annular core geometry of a 16MWth PB-FHR test reactor design [49]. PREX 3.0 is constructed from the same materials as PREX 2 and has the same geometric scaling factor, but is built as a $30^\circ$ wedge. Figure 3.2 shows the front view of the facility loaded with approximately 18,000 pebbles, along with an image of the empty test section showing the curved inner and outer reflector surfaces. PREX 3.0 has a more complex reflector geometry design that is motivated by the desire to develop more uniform pebble flow profiles based on the results from PREX 2. The core geometry region is 1.2 m high and the inner and outer radii of the wedge are 0.17 m and 0.43 m in the constant area region. PREX 3.0 includes three radial zones with divider plates that extend to a height of 1.07 m. The complete surface geometry for PREX 3.0 is included in Appendix C.
Figure 3.2: PREX 3.0 test section loaded with approximately 18,000 pebbles (left) and empty (right). The empty test section shows the curved surfaces on the inner and outer reflector.

3.1.2 Data Collection Procedures

The primary data collected for the two gravity-dominated systems consist of sequences of high-resolution images with a small number of pebbles recirculated between each step. For PREX 2, we recorded a sequence of 618 high-resolution still images with 200-250 pebbles (0.15 – 0.17% of the total) removed from the bottom of the test section between each frame. A similar sequence of 360 images was also collected for PREX 3.0 with 50-100 pebbles (0.28 – 0.56% of the total) removed between each image. Pebbles were added to the inlet hoppers at the top of the test section as needed in order to maintain pebble packing in each radial zone above the divider plates. The stepwise nature of data collection is appropriate for the regime of slow, dense granular flow in pebble bed reactor cores. For these granular flow conditions, pebbles form long-lasting contacts with neighbors and they are largely insensitive to short time-scale phenomena associated with pebble collisions [79].
During the data collection runs, the mass of pebbles added to each of the inlet hoppers was also recorded in order to generate overall recirculation rates for each of the different radial zones. These measurements were collected by filling each of the radial hoppers to a marked height in order to maintain pebble packing above the hopper dividers and to record the recirculation mass for the bed at its original configuration.

### 3.1.3 Data Processing Methods

For each of the sequences of images from the PREX experiments, the process of extracting data on the pebble motion is divided into two components: the detection of pebble positions in each image and the tracking of pebbles between two sequential images.

For the detection of pebbles in an image, a MATLAB script is used to determine the positions of all the pebbles at the surface of the experiment. The script compares the region surrounding each pixel in the frame to a reference pebble image, which is used to calculate a local differential between the local region and the reference image. Figure 3.3 shows several sample reference pebble images for the PREX 2 analysis. Reference pebble images are automatically generated for different regions of an image based on the observation that the precise center position is sensitive to local lighting conditions and reflections from the pebble surface. Figure 3.4 shows a small region of an image from the PREX 2 data set marked with the detected pebble positions. Analysis of randomly selected images shows accuracy on the order of 1 pixel (~0.05$d$) for the pebble center position. Because position errors are caused primarily by variations in local lighting conditions, errors will tend to be correlated and the resulting uncertainties in the difference in pebble positions between two images will be reduced.

![Sample reference pebble images for PREX 2 position scanning algorithm. The pebble images have a diameter of 25 pixels.](image-url)
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Figure 3.4: Crop of PREX 2 data image with marked yellow pebble center positions.

Verification of the pebble detection algorithm is performed by three methods. First, the separation distance of all pebbles is compared to the pebble diameter. This sets a minimum distance that two pebbles at the surface can be separated by and pebbles found to be closer than this distance to two neighboring pebbles are removed as false positives at the pebble surface. Visual inspection of these false positives reveals in almost all cases that they are, in reality, accurate center positions of pebbles detected in the layer behind the surface layer.

The second method of verification is based on visual inspection of a random set of images from each data set. This method allows for quick inspection of images to determine that the threshold limits are appropriate to prevent false positives for pebble detection. False positives for pebble position are of greater concern because the algorithm for pebble tracking can generate errors if pebbles are detected where no pebble is located. In contrast, the impact of false negative pebble detection is primarily to reduce the sample set of pebble motion data, but has little impact on the accuracy of the tracking algorithm, described below.

The third method of verification is based on visual analysis of the time sequence from reconstructed images based on the pebble position data. Figure 3.5 shows an example of a reconstructed bed from one frame of the PREX 3.0 data set compared to the original image. The combined movie of these image sequences provides a simple means to show where large concentrations of false positives or false negatives might be located. These can then be corrected by adjusting the threshold values used to confirm that pebbles have been detected.
Pebble motion between sequential images is tracked using a MATLAB script that is based on an insight from the Spot Model [80] that dense granular flows should exhibit spatial velocity correlations over length scales on the order of a few pebble diameters. This observation can be used to track pebble motion in regions with large displacements of several pebble diameters between time steps, such as near the defueling chutes in PREX 2 and PREX 3.0.

The tracking algorithm initially tracks pebbles in the constant area region, which have the smallest displacements, based on the nearest pebble position in the next image. Tracking is limited to pebbles located below the initial position (i.e. pebbles cannot flow “up”) and have a limited horizontal displacement of 0.25d in order to prevent non-physical tracking for pebbles that are not detected in the scanning
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algorithm. This scanning method is accurate as long as the displacements in the constant area region are less than one pebble diameter.

From the constant area region, the algorithm sequentially scans pebbles above and below the constant area region in ascending and descending order, respectively. The new position of each untracked pebble is predicted based on the average displacement of neighboring pebbles within a distance of $3d$ that already have tracking assignments. The closest pebble position to the predicted location in the second image, within a scanning distance of $1.5d$, is assigned as the new position. Pebbles in the second image may only have one pebble assigned. In addition, the method will rescan for a new pebble position in the second frame if the original tracking is closer to the predicted new position of a different pebble. Figure 3.6 shows a sample of the pebble tracking for PREX 2 near the top of the defueling chute. Regions of the test section, like this, with large displacements are the most challenging for the tracking algorithm.

Figure 3.6: Sample image of pebble tracking near the top of the defueling chute for PREX 2. Solid and open markers show the positions of pebbles for the first and second time steps, respectively, with lines between them for the assigned tracking. The ‘+’ markers show the predicted positions with thin lines connected to the nearest pebble position in the second time step.
Verification of the tracking algorithm was performed by visual inspection of a randomly selected set of 20 time steps. This process was repeated following all updates to the code and changes to the scanning parameters. Several challenging cases of pebble tracking were discovered that led to additional refinement of the decision logic to assign new pebble positions. After several iterations, the MATLAB script was found to have no erroneous tracking assignments and therefore the pebble tracking between frames has a confidence level greater than 95%.

3.2 GRECO Model Parameters

GRECO models were developed for the PREX 2 and PREX 3.0 reflector geometry that can be directly compared to the velocity data obtained from the experiments. The wall boundary geometry in GRECO, described in Section 2.1.5, approximates the surfaces of the inner and outer reflector as a series of linear segments. Figure 3.7 shows the wall boundaries used in the GRECO simulations for PREX 2 and PREX 3.0. The simplified GRECO models study a two-dimensional layer of polydisperse pebbles with average diameter $d = 1.26$ cm and a uniform random dispersion distribution from $0.90d$ to $1.10d$. All pebbles in the system have a mass of 0.994 g to match the mass of the HDPE spheres used in the experiments. The system is subject to gravity drainage under the acceleration due to gravity $g = -9.81$ m/s$^2$. After the initial settling period, the PREX 2 and PREX 3.0 GRECO models filled the containers with 8,436 and 1,373 pebbles, respectively. Figure 3.8 shows the packed pebble bed from the GRECO simulation after complete recirculation. The GRECO model reduces the total number of pebbles in the systems to about 7% of those in the experiments, which allows for simulation results to be generated in reasonable time scales for design efforts.
Figure 3.7: GRECO model wall geometry for PREX 2 (left) and PREX 3.0 (right).
Figure 3.8: Packed pebble beds after recirculation for PREX 2 with 8,436 pebbles (left) and PREX 3.0 with 1,373 pebbles (right).
A parametric study with GRECO was completed for the PREX 3.0 geometry in order to determine appropriate friction coefficients for the hybrid friction model that could be used for pre-predictions for PREX 2 when compared to the experimental velocity data. The simulation results presented in this chapter use an interpebble kinetic friction coefficient $\mu_p = 0.2$ and a tangential damping constant $\gamma_p = 1 \text{ Ns/m}$. The pebble-wall Coulomb friction coefficients $\mu_w = 0.5$ is used. This friction coefficient has been used in other DEM studies that show excellent qualitative and quantitative agreement with experimental data [55], [58], and is therefore viewed as a reasonable value for the scope of this study.

The GRECO models for the gravity dominated experiments described here use a hybrid static friction coefficient for the wall surfaces $\mu_s = 0.05$, $10\%$ of the Coulomb limit. The kinetic friction coefficient $\mu_k = 0.45$ is also used. These values ensure that the combination of static and kinetic friction cannot exceed the Coulomb limit. Tangential damping for the wall contacts matched that for pebble-pebble friction with $\gamma_w = 1 \text{ Ns/m}$. Normal forces in the GRECO simulations are handled using the material properties for HDPE-HDPE and HDPE-acrylic contacts described in Section 2.1.2 for the contact with viscoelastic damping.

Pebble motion data for each PREX facility were compiled from three complete bed recirculations. This required 4,800 macro time steps for the PREX 2 model and 1,800 macro time steps for PREX 3.0 model. The number of micro time steps for required to keep a densely packed bed in the inlet hopper region was 200 for PREX 2 and 1,000 for PREX 3.0. GRECO uses the number of micro time steps to set the discharge pebble velocity in the defueling chute. The additional micro time steps for PREX 3.0 were required to ensure that no gaps developed in the angled section at the bottom of the inlet hopper divider plates. A time step $\Delta t = 3.6 \times 10^{-5} \text{ s}$ was used for all simulations and demonstrated excellent stability. All velocity data presented from the GRECO simulations are normalized by the average displacement in the constant area region at heights between $80d$ and $150d$ for PREX 2 and between $40d$ and $50d$ for PREX 3.0.

### 3.3 General Flow Characteristics

The design options for pebble bed reactor cores include several geometry characteristics that are different from the standard problems in granular dynamics. Besides having cylindrical symmetry, the geometry options for pebble reactor cores include annular geometries where granular flow occurs between a center reflector and an outer reflector, the presence of dividers at the core inlet to establish radial zones in the annular core, and a diverging region from the pebble inlet to the active core region as well as a converging section at the exit. The granular flow behavior in these novel geometric configurations associated with pebble bed cores merit a general...
introduction and qualitative discussion of the experimental results before a detailed quantitative analysis is presented in the following sections.

Figure 3.9 shows several selected images from PREX 2 that can be used to discuss the large-scale flow behaviors in annular pebble cores, in this case for a potential PB-FHR core. Approximately 17,600 pebbles (~14% of the bed volume) were removed from the bottom of the test section and added to the inlet hoppers at the top between each frame in Figure 3.9. The pebble colors in the photos are especially helpful for flow visualization as different colors are used to fill each of the small radial hoppers that extend just above the start of the diverging region. The horizontal layer of dark green pebbles near the top of the test section at the start of the cycle is used as a divider between two different color zoning configurations. The bottom and top edges of this divider layer were originally level with the bottom of the hopper dividers and therefore are approximate isochrones, layers of pebbles that have the same residence time. This also applies for the horizontal bands below (light and dark green) and above (gray) the thick divider layer. The change in the height-dependent profile of the isochrones between successive time steps, which leads to increases or decreases in the spacing between the isochrones, is also a simple way to visualize the local flow velocity.

Following the pebbles as they enter the top of PREX 2 in Figure 3.9, we observe that the pebbles on the right side near the outer reflector move more quickly than those located near the inner reflector. Physically, this is due to the motion of pebbles into free volume from the radial expansion that pebbles can move towards as they move lower in the diverging region. There is also some observable hold up of pebbles at the outer reflector wall in the diverging region due to wall friction effects. As a result, pebbles in the fifth radial zone (light green) are the first to reach the constant area region. Pebbles located in the first radial zone (dark green next to inner reflector) show some outward diffusion as the layer expands in the diverging region, but remains smaller than the other layers and are the last to reach the constant area region. The profile of isochrones leaving the diverging region can be seen to be very similar, implying that the slow drainage of pebbles in packed expansion regions demonstrate consistent time-averaged behavior. This result is a significant finding and suggests that expansion geometries are a viable option for reactor core design.

Once the pebbles reach the constant area region, there are no significant observable changes in the profile of the isochrones and the structure of the radial zone interfaces. This profile demonstrates plug flow behavior in this region of constant-area flow, where the pebbles move with constant velocity and minimal shearing or mixing. Plug flow can be observed through nearly all of the constant area section until the pebbles descend just above the converging region at the bottom of the test section. Plug flow behavior has been commonly observed for constant area regions in cylindrical silo drainage [28], [50]. The results from PREX 2 confirm that
uniform plug flow in silo drainage also applies to annular packed beds with inner wall boundaries such as the PB-FHR and PBMR.

In the converging region, significant channeling can be observed in Figure 3.9g where pebbles in the center of the bed move much more quickly towards the defueling chute than pebbles located near the inner and outer reflector. Observed hold up was much more significant at the outer reflector wall and these pebbles have the longest average residence time for one circulation through the reactor core. Several light green pebbles from the initial loading in Figure 3.9a are present at the outer reflector wall after the recirculation in Figure 3.9h. During the data collection, no pebbles were permanently held up at the outer reflector and approximately 20,000 pebbles (~15% of the total bed) would need to be circulated to remove the last remaining pebbles from the initial loading.

The observations from the converging region in PREX 2 are consistent with the standard engineering understanding of cylindrical silo drainage geometries [25], [28]. However, previous studies do not capture the effects of wall friction at an inner reflector surface. The large-scale flow structures in PREX 2 show that even though pebbles in the radial zone adjacent to the inner reflector are located directly above the defueling region, the fastest moving zone in the converging region is the third zone (white). Neutronic studies of pebble bed cores may need to consider this hold up at the central reflector in the converging region, in addition to effects of the longest residence times at the outer reflector surface.

The selected images from pebble recirculation in PREX 3.0 in Figure 3.10 show that the packed bed behaviors from PREX 2 also apply to smaller systems that may include more complex geometry. Accelerated pebble motion can be observed in the expansion region and a more centered residence time profile can be seen as pebbles in the radial zone next to the inner reflector pass through the narrow throat then expand into the constant area region. Plug flow is seen in the constant area region, followed by the channeling of pebbles in the central radial zone in the converging region and into the defueling chute. Radial zones are maintained in this complex core geometry with small mixing and diffusion effects.
Figure 3.9: Selected images from PREX 2 stepwise drainage. Approximately 17,600 pebbles were recirculated between each image. The colored pebbles are used to help flow visualization and tracking of the radial zone interfaces. The horizontal bands show approximate residence times for pebbles inserted at the same time.
Figure 3.10: Selected images from PREX 3.0 stepwise drainage. The colored pebbles are used to help flow visualization and tracking of the radial zone interfaces. The horizontal bands show approximate residence times.
3.4 Mean Velocity Fields

3.4.1 Experimental Results

The local mean velocity fields for PREX 2 and 3.0 were determined based on the displacement of pebbles tracked between two sequential images. The displacements for each time step were normalized based on the mean displacement $\Delta z_{plug}$ of pebbles for the current time step in the constant area region of the experiment where plug flow was observed, $50d < z < 80d$ and $40d < z < 50d$ for PREX 2 and 3.0, respectively. This normalization corrects for the small variation in the number of pebbles removed between each time step. This scaling is also useful in reporting pebble velocity data for the purpose of reactor design because the constant area section corresponds to the active core region and pebble velocities and residence times can be scaled based on the specified design parameters for fuel residence time in this region.

The tracking data for each time step was averaged over square cells of dimension $d$ over the visible surface. Results were compiled such that a pebble at position $r^n$ at the $k$th time step and at position $r^{k+1}$ at the $(k+1)$th time step is recorded for the bin that contains the average position $(r^k + r^{k+1})/2$ between the two steps. The normalized velocity data $(r^k + r^{k+1})/ \Delta z_{plug}$ are recorded for the purposes of computing the average values and distribution curves for all cells in the test section geometry.

The average horizontal and vertical components of the velocity field for the PREX 2 experiment are shown in Figure 3.11 and for the PREX 3.0 experiment in Figure 3.12. Figure 3.13 shows the magnitude of the velocity for both test sections. The experimental velocity data show the extent of the plug flow region with very small horizontal components in the active core region above the converging region and below the diverging region. The vertical velocity component shows that there are subtle variations that extend above the converging region to an elevation of $80d$, including channeling effects above the defueling chute and hold up at the outer wall. These results are consistent with the previously observed behavior at the outer wall for dense granular flow [43], [50]. The axisymmetric geometry and the presence of an inner reflector results in some additional hold up at the inner wall, which results in a slight offset for the channeling of pebbles in the converging region.

The streamlines for the mean velocity field for the PREX 2 and PREX 3.0 geometries are shown in Figure 3.14. The streamlines are computed by integrating the motion from equally spaced material points at the top of the test sections using the experimental mean velocity field. The streamlines in both experiments show smooth pebble motion through the entire test section that follow the contours of the container geometry. Except in the case of the outer reflector in PREX 3.0, the
streamlines at the edges of the inlet regions separate from the wall surface through the diverging region and establish a gap on the order of a few pebble diameters from the reflector in the constant area region. This implies that pebbles that are inserted in contact with the reflector surfaces will, in general, not remain in contact with the reflector as they pass through the diverging region. This would not be expected in cylindrical core geometries because plug flow will be established before the pebbles circulate out of the inlet hoppers.

PREX 2 and 3.0 are the first experiments known to the author to report the behavior of dense granular flow in packed expansion regions, as this feature is unique to the application of reactor cores. Figure 3.11 shows the streamlines and velocity vectors for the diverging regions of each test section. This style of surface plot, along with others presented in this dissertation, are useful for visualizing the general trends and large-scale granular flow patterns at the visible surfaces. In PREX 2, the motion of pebbles towards the outer reflector is observed to be faster than the primarily downward motion of pebbles located near the inside reflector. The complex reflector geometry of PREX 3.0 also shows that pebbles accelerate towards both reflectors after then enter the diverging region below \( z = 65d \). Most importantly, the velocity components and streamlines in the expansion regions show smooth time-averaged behavior.

![Figure 3.11: Mean experimental horizontal (left) and vertical (right) velocity components for PREX 2. All values are local displacements relative to the mean displacement magnitude in the plug flow region \((80d < z < 150d)\).](image)

Figure 3.12: Mean experimental horizontal (left) and vertical (right) velocity components for PREX 3.0. All values are local displacements relative to the mean displacement magnitude in the plug flow region ($40d < z < 50d$).

Figure 3.13: Experimental magnitude of the average local velocity relative to the average plug region displacement for PREX 2 (left) and PREX 3.0 (right).
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Figure 3.14: Streamlines for PREX 2 (left) and PREX 3.0 (right) computed based on the mean experimental local velocity data. Arrows show the relative magnitude of the local velocity for several horizontal cross sections.

Figure 3.15: Streamlines in the diverging regions of PREX 2 (left) and PREX 3.0 (right) computed from experimental pebble motion data. Arrows show the relative magnitude of the local velocity for several horizontal cross sections.
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It is also worthwhile to take a closer look at the vertical velocity profiles in the diverging and converging regions, which help to give a better understanding of pebble fluxes in different regions of the core. Figure 3.16 shows the normalized profiles for the converging region of PREX 2. These show, as expected, broad velocity profiles observed well above the defueling chute and the extreme channeling effects observed near the exit, closer to the defueling chute entrance. In contrast to previous results for cylindrical geometries, the profiles show some slowing of pebble motion at the inside reflector wall and peak velocities are observed several pebble diameters from the wall. The peak velocity also shifts outward at higher elevations.

Figure 3.17 shows the vertical velocity profiles in the diverging region of the PREX 2 experiment at the top of the test section. These profiles show smooth, time-averaged behavior in this region with peak downward velocities observed at increasing radial positions. There is also observable slowing of pebbles directly in contact with the outer reflector wall in the profiles. These results show that pebbles move preferentially outward towards free volume that becomes available due to the radial expansion of the container geometry. Pebbles close to the inner reflector wall therefore start to move at close to the plug flow velocity at elevations well above the end of the diverging region.

![Figure 3.16: Vertical velocity profiles at several elevations in the converging region of PREX 2. The profiles are normalized by the average plug region velocity.](image-url)
3.4.2 Comparison to GRECO Results

Local velocity fields are one of the primary outputs from GRECO simulations and comparison to dry experiments, such as PREX 2 and 3.0, provide an excellent test basis for code validation and to understand the limits of the two-dimensional simplifying assumption. This section compares details of the local velocity data for GRECO runs using the model parameters outlined in Section 3.2. Pebble motion data were recorded for 4,800 and 1,800 time steps for PREX 2 and 3.0, respectively, which corresponds to three complete bed recirculation cycles.

Figure 3.18 compares the mean velocity results from GRECO with the experimental data for pebbles at the visible surface in PREX 2. The relative error (left side) shows that the GRECO velocity field accurately captures the plug flow behavior with small discrepancies in the constant area section, while errors in the diverging and converging regions are typically within 20%. Errors from 20% to 40% are observed in several regions and merit further discussion. The magnitudes of the local error in units of pebble diameters per pebble diameter of plug region displacement (right side) show excellent agreement between the two results. Errors less than 0.25$d$ are observed throughout the core except for the areas in and above the defueling chute and at the outer reflector wall in the diverging region. These
errors are best explained by the two-dimensional GRECO modeling assumption, which is discussed in more detail below.

The simulation results significantly under predict the velocity in and around the defueling region and at the outer reflector wall in the diverging section. These distortions are likely due to the two-dimensional simplification in the GRECO model. The area ratio for the defueling chute compared to the active core region is much lower for the three-dimensional geometry due to the radial contraction and pebble velocities must be larger to maintain conservation mass flux at each cross section. The impact of larger velocities in the defueling chute extends upward into the inner section of the converging region due to the fact that these pebbles see the greatest acceleration due to the channeling effects. The larger errors at the outer wall are likely also due to the two-dimensional assumption because the true radial expansion would open a much larger free volume for pebbles to migrate towards.

The local velocity is over-predicted at the inner radii in the diverging region and around the corner at the outer reflector wall at the top of the converging region. The first result is likely related to the errors observed at the outer reflector in this region because the lack of a true radial expansion shifts the maximum downward velocity towards the center towards the inner radii, where smaller velocities are observed in the experimental data. The errors at the outer corner above the converging region are, however, not a result of the two-dimensional model assumption. These distortions are likely the result of some shortcomings in the GRECO hybrid friction model and are sensitive to small error magnitude because this location has the lowest observed pebble average velocities.
Figure 3.18: Errors from the PREX 2 average velocity field for GRECO simulation results compared to experimental surface velocity data. The figure on the left gives the relative error of the simulation results and the figure on the right gives the error normalized by the average plug displacement. Positive values indicate that GRECO results over-estimate the velocity compared to the experimental results.

The results for PREX 3.0 also show excellent agreement with the measured local velocity field. Figure 3.19 shows the relative error in the test section geometry, where errors of less than 10% are observed in most locations. The largest errors of up to 25% are observed in the inlet region, the outer reflector wall in the converging region, and the defueling chute. The distortions at the inlet and defueling chute are logical based on the translation from a three-dimensional axisymmetric geometry to the two-dimensional GRECO approximation, similar to the results observed in PREX 2.

The larger errors observed at the outer reflector wall in the converging region cannot be simply explained due to the GRECO dimensional assumption. GRECO over predicts the velocity in this region relative to the experimental results. This
distortion could be a reflection of possible shortcomings in the hybrid friction model or a distortion based on the high friction forces for pebbles with two wall contacts in the corners. It is important to note that this region has the smallest local pebble velocities and therefore will generate high relative errors. The magnitude of the horizontal and vertical velocity component errors, shown in Figure 3.20, show that the difference in pebble displacements in this region are on the order of 10-20% of a pebble diameter per pebble diameter of plug displacement. The pebble residence times should show some sensitivity to these errors for the longest residence time pebbles in the system. This is discussed further in Section 3.6.

Figure 3.19: Relative error of GRECO simulation results compared to the experimental surface velocity data in PREX 3.0. Positive values indicate GRECO values larger than observed in the experiment.
Figure 3.20: Magnitude in units of pebble diameters for plug displacement of one pebble diameter of the horizontal (left) and vertical (right) error of GRECO simulation results compared to the experimental surface velocity data for PREX 3.0. Positive values indicate GRECO values higher than observed in the experiment.

The vertical velocity profiles are a useful means of evaluating the distortions from the two-dimensional assumption in GRECO. Figure 3.21 to Figure 3.24 show the downward velocity profiles in the different regions of the PREX 3.0 geometry, including the inlet, diverging, converging, and defueling regions. In the inlet region profiles (Figure 3.21) it is clear that there are significant differences in the GRECO and experimental results from the geometry change, as discussed above. The resulting velocity profiles, however, have extremely similar shapes to those seen in the experimental data. The same is also true in the defueling region (Figure 3.24), which has the largest area distortion relative to the plug flow region. The similarity in the velocity profiles suggest that GRECO results may be used as an approximation for the full three-dimensional geometry using a scaling factor based on the local cross-sectional area compared to the plug flow region. In the case of PREX 3.0, the area ratio of the defueling chute compared to the plug flow region in the two-dimensional GRECO model is 4.50 compared to 6.73 in the true cylindrical geometry. This
would give a correction factor of 1.5, which would bring the GRECO results much closer to those from the experimental defueling chute.

The profiles in the diverging (Figure 3.22) and converging (Figure 3.23) regions show that the GRECO velocity data closely match the experimental results both in shape and magnitude, consistent with the errors reported above. GRECO accurately captures the transition to plug flow near the end of the diverging region to the constant area section at a height of $z = 54d$, although there is some additional hold up at the reflector walls in the upper core region in the GRECO data. The converging region has excellent agreement in the velocity profiles, even with the higher relative errors discussed earlier. Hold up at both reflector walls is observed as well as channeling of pebbles in the center region located above the shift to the defueling region.

Figure 3.21: Vertical velocity profiles for several elevations in the PREX 3.0 inlet region from experimental data (left) and GRECO simulation (right).
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Figure 3.22: Vertical velocity profiles for several elevations in the PREX 3.0 diverging region from experimental data (left) and GRECO simulation (right).

Figure 3.23: Vertical velocity profiles for several elevations in the PREX 3.0 converging region from experimental data (left) and GRECO simulation (right).
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Figure 3.24: Vertical velocity profiles for several elevations in the PREX 3.0 defueling region from experimental data (left) and GRECO simulation (right).

Overall, the GRECO velocity results demonstrate a reasonable approximation for the mean pebble velocity distributions in both PREX 2 and PREX 3.0. This is achieved with the simplified two-dimensional DEM model that is significantly less computationally expensive than analysis of the full three-dimensional system. Relative errors for the GRECO results are generally observed to be within 10-15% of the experimental data. The largest errors for the GRECO results are found in the defueling region where conservation of pebble mass flow requires that GRECO will significantly under predict the mean velocity. This error is likely not significant because the defueling chute is a low power region that should have a small impact on the overall core neutronics performance. The GRECO average velocity data are therefore found to be acceptable for the purposes of preliminary core design efforts before design-specific scaled experiments can be built. The neutronic efforts of the GRECO errors will require additional study and is beyond the scope of this dissertation.

3.5 Radial Zoning and Pebble Mixing

3.5.1 Experimental Results

The use of radial zoning in core gives designers an additional degree of freedom to optimize the reactor neutronic performance. However, the stochastic nature of pebble dynamics requires that mixing at radial zone interfaces is well characterized so
that appropriate pebble allocations are used to determine the point design and
sensitivity studies to determine the impact of less distinct zone interfaces.

The experimental results from PREX 2 and 3.0 demonstrate that radial zoning is
possible in complex reactor core geometries that include expansion regions. Figure
3.25 shows the average position of the zone interfaces for the two test sections. The
think lines in the figures are based on statistics of pebble colors in different regions of
the test section and the thin lines are the computed streamlines from the lowest point
of the inlet hopper divider plates. These boundaries are the nominal interface
position, but do display some mixing behavior, as they are not perfectly distinct. The
interface positions for PREX 2 are shown only for the upper active core and
diverging regions because the presence of different zoning colors from the initial
loading prohibits accurate tallies below the thick dark green horizontal divider layer.
These results shows that the computed streamlines show excellent agreement with
the observed average interface position and can be used during the reactor design
phase a reasonable approximation.

One important question during the core design process is where to place the inlet
hopper divider plates to achieve a desired radial zone width in the active core region.
This problem is relatively simple for cylindrical core because plug flow is established
in the hoppers and there is minimal radial motion through the constant area region.
For the PB-FHR, which includes a diverging region, the radial motion of the fuel
pebbles before reaching the active core is more complicated. One reasonable
approximation for the zone width in the inlet region might be to maintain the desired
area fractions for the active core. Table 3.1 and Table 3.2 show the area fractions for
the active core region and inlet hoppers for the radial zones in PREX 2 and 3.0,
respectively. The differences in the area fraction are typically within 3%. The inlet
area fractions tend to be higher for the inner zones and lower for the outer zones.
This is not surprising because the outer hoppers experience the largest radial
translation before they reach the active core. These results suggest that, to first order,
preserving the area ration for the inlet hoppers and active core is a valid method for
the initial design of pebble bed reactor cores with radial zones before scaled
experimental data can be obtained.
Figure 3.25: Position of the radial zone interfaces for PREX 2 (left) and PREX 3.0 (right) based on local tallies of different color pebbles. The thin lines show the computed streamlines from the end of the inlet hoppers.
Figure 3.26 shows the width of the radial zone interfaces for PREX 3.0. The zone widths associated with the 90th, 95th, and 99th percentile are shown to demonstrate how the mixing interface tails off away from the nominal position. These results show that pebble interfaces remain extremely distinct in the initial expansion region above \( z = 70d \) with the 99th percentile within one pebble diameter from the nominal position. In the diverging region between the inlet and the active core \( (50d < z < 70d) \), there is a dramatic increase in the interface width due to pebble mixing. The 99th percentile at the top of the active core region is at a distance of \( 2d \) to \( 2.5d \) from the nominal interface position. Through the active core, where plug flow is observed, the interface width remains reasonably constant. Finally, for the converging region, there is a contraction of the interface width as the pebbles channel
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towards the lower throat area for the yellow-light green interface while the light green-dark green interface width remains roughly constant. The results of the zone interface widths for the upper core and diverging region in PREX 2, shown in Figure 3.27, follow the same general trends observed for PREX 3.0.

Figure 3.26: Radial zone interface widths between the yellow and light green pebbles (top) and light green and dark green pebbles (bottom) in PREX 3.0. The zone widths are given for the 90%, 95%, and 99% pebble probabilities.
Figure 3.27: Radial zone interface widths for PREX 2. Results are presented for the 90th (left), 95th (center), and 99th (right) percentile. The interfaces are indexed from the inner reflector to the outer reflector.

The statistics on interface mixing rates are useful for core neutronics design, but do not capture the correlated local packing effects that might also merit consideration from a design perspective. In both PREX 2 and PREX 3.0, it was observed that mixing at the radial zone interfaces often occurs in what can be described as an interlocking finger structure, rather than the migration of single pebbles in a diffusion-type process. Figure 3.28 shows an example of this packing in which several pebbles of each color extend as a short chain on either side of the nominal interface position. While the basis for this patterning is not totally clear, from visual observations, it appears to develop as the result of small overlaps that occur in the initial loading region that broaden into wide overlap structures in the diverging region. This result suggests that stochastic distributions of local pebble packing in the diverging region will play a dominant role in the mixing that occurs before the plug flow region.
In order to gain a better understanding of the mixing behavior in the diverging and converging regions, it is useful to consider how pebble motion distributions vary based on the average local velocity. This data will inform how the stochastic variation in pebble displacement is likely to impact the residence time and the radial mixing of pebbles. Figure 3.29 shows the standard deviation normal and tangential to the average velocity for each data cell in PREX 2. These results were obtained using the direction of the mean local velocity vector to calculate the normal and tangential components for every tracked pebble motion. Using these bases, the average tangential component of the velocity is equal to the magnitude of the average velocity vector and the average normal component is equal to zero.

The results in the converging region in Figure 3.29 show that the local variance in pebble displacements is dominant for the tangential component, which is on the order of 20% of the average displacement vector. In contrast, the normal component is significantly smaller and on the order of 5% away from the wall and converging to zero close to the outer reflector. This result shows that the reduction in degrees of freedom for pebble motion at the outer reflector permeate into the bed and pebbles are unlikely to diverge from their existing streamline. This is consistent with both experimental [79], [81] and DEM simulation [55], [59] results that show low levels of mixing and diffusion in converging hopper geometries.

In contrast to the small variance for the normal displacement, there is a significant amount of variance in the normal velocity data in the converging region. This result matches the physical intuition that as volume becomes constrained, pebbles are more likely to be held up as other pebbles move ahead into free volume. This suggests that there would be large variations in residence time for pebbles in this region of the core.
However, the low level of anticipated normal displacement means that pebbles located on faster moving streamlines closer to the region above the defueling chute where channeling occurs are unlikely to diffuse to the slower moving streamlines near the outer reflector wall.

The variance for the normal and tangential components in the diverging region at the top of PREX 2 also reveal significant insight into the nature of the stochastic behavior in packed expansion. The behavior in this region is largely the opposite of what is observed in the converging region. We find that there are relatively large variances normal to the average displacement vector compared to the tangential component. This behavior implies that pebbles in the expanding region will tend to mix more and move to different streamlines with greater frequency than in other core regions, but that there will be small differences in the residence time along those streamlines.

The nature of stochastic behavior in the diverging region is particularly important for the application of pebble bed reactor cores because the mixing that occurs between radial zones establishes both the positions of the radial zone interfaces in the active core region and the degree of mixing around the interface. The results from PREX 2 suggest that while the average flow behavior in the bed expansion appears to be smooth, this is the primary region where mixing occurs and pebbles will shift between streamlines.

The observed variance in the constant area region of PREX 2 reconfirms the consistent plug flow behavior that should be expected in the active core. Relative standard deviations of less that 5% were observed and it is important to note that the absolute value of these variations are extremely small because this region has the largest cross sectional area and the smallest pebble velocities. Figure 3.29 shows a band in the center of the constant area section with higher standard deviations. This is an artifact from the difficulty associated with finding the precise center location for the white pebbles in this radial zone. The large relative standard deviations are easy to generate because the motion is small and offsets of one or two pixels can have a significant effect.

Figure 3.30 shows the variance for the normal and tangential velocity components in PREX 3.0. These results show that the general trends observed in PREX 2 can also be seen in the smaller and more complex geometry of PREX 3.0. In general, larger variances are observed for the normal velocity component as pebbles move to outer radial positions while larger variances are observed in the tangential velocity component as pebbles move to inner radial positions. The most interesting finding here is that this trend hold true for both the diverging and converging regions, which include pebbles moving in both radial directions. This result suggests that the stochastic variability of pebble motion in complex container geometries shows general behavior that is predictable and can be quantified using scaled experiments.
Figure 3.29: Standard deviation for the normal (left) and tangential (right) velocity components normalized by the local velocity magnitude in PREX 2.

Figure 3.30: Standard deviation for the normal (left) and tangential (right) velocity components normalized by the local velocity magnitude in PREX 3.0.
3.5.2 Comparison to GRECO Results

The GRECO simulations results for the mean radial zone interface position and pebble mixing can be directly compared to the experimental pebble motion data for the visible surfaces of PREX 2 and 3.0. Figure 3.31 shows the computed streamlines from the lower limit of the inlet hoppers in PREX 2 using the experimental velocity field (thick lines) and the GRECO simulation velocity (thin lines). It was previously shown in Section 3.5.1 that these streamlines closely match the 50% probability interface from tallies of different color pebbles. Figure 3.31 also includes the error between the GRECO and experimental results in units of \( d \). The errors increase through the diverging region to a maximum value of \( 2d \) and remain roughly constant through the constant area region, where plug flow is established. The errors becoming smaller in the converging region as the pebbles are constrained into a smaller cross sectional area near the defueling chute.

Figure 3.31: Computer interface streamlines (left) and interface position errors (right) for PREX 2. Thick streamlines are derived from the experimental velocity data and
thin streamlines are derived from the GRECO velocity data. The interfaces are indexed from inner to outer radial positions.

The comparison of the GRECO average interface positions to the experimental results for PREX 3.0 (Figure 3.32) follows the same trends observed in PREX 2. GRECO interfaces show very small errors through the inlet region above \( z = 65d \) before some error is introduced through the diverging region. As the pebbles reach the constant area region, the errors remain relatively constant before they get smaller through the converging region above the defueling chute. Maximum errors of \( 1.5d \) were found for Interface 1 (yellow-light green), while Interface 2 (light green-dark green) showed smaller errors less than \( 0.5d \).

The interface position results for PREX 2 and 3.0 suggest that GRECO simulations can be useful for preliminary core design efforts. Both cases show that the GRECO tends to under estimate the radial position of the interface for zones near the inner reflector and, in the case of PREX 2, tends to over estimate the radial position for zones near the outer reflector. These distortions may be the result of the two-dimensional GRECO geometry, which cannot account for the radial expansion in the diverging region.

Mixing at the radial zone interfaces is also a key phenomena of interest to core designers because it may limit the performance benefits of using radial pebble zoning. Figure 3.33 shows the probability distributions as a function of radius for each of the different radial zones in PREX 3.0. The think lines are the probabilities from the experimental tallies at the visible surface and the thin lines are from tallies of GRECO simulation results. The errors in the average interface positions discussed above are clear in Figure 3.33 as GRECO under predicts radial position near the inner reflector and over predicts the radial position near the outer reflector. The results also show that there is much more dispersion in the pebbles in the GRECO results compared to the more distinct interfaces observed in the experiment. Similar results were also found for PREX 2. This distortion appears to be due to how pebble motion is constrained in in the diverging region in the two-dimensional GRECO model. Based on this result, the dispersion of radial zone interfaces from GRECO simulation results can be assumed to show more mixing than the prototypical system. Therefore, preliminary analysis of the core neutronics performance using perfectly distinct interfaces and GRECO mixing results should bound the expected behavior of the physical system.
Figure 3.32: Computed interface streamlines (left) and interface position errors (right) for PREX 3.0. Thick streamlines are derived from the experimental velocity data and thin streamlines are derived from the GRECO velocity data. The interfaces are indexed from inner to outer radial positions.
Figure 3.33: Probabilities distributions of pebbles for each radial zone at a height of \( z = 45d \) in the constant area region of PREX 3.0. The thick lines show the results from experimental tallies and the thin lines show the results from GRECO.

Figure 3.34 and Figure 3.35 show the relative standard deviations for the normal and tangential velocity components for PREX 2 and 3.0, respectively. These results differ significantly from the experimental surface data presented in Section 3.6.1. The first key observation is that the relative variances are much larger than the experimental results, ranging up to 80% of the local velocity magnitude. This wider distribution of pebble motion in the GRECO simulations is an important distortion from the two-dimensional geometric simplification. In the three-dimensional system, pebbles will have additional degrees of freedom to move in regions of changing cross sectional area and therefore pebbles have a greater tendency to stall locally as pebbles around them move. The two-dimensional system is more constrained and there are fewer local pebbles to move into free volume. Pebbles therefore have a greater tendency to move around each other as they circulated through the test section. This is especially evident with the large variances observed in the plug flow region of PREX 3.0 in Figure 3.35.
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Figure 3.34: Standard deviation for the normal (left) and tangential (right) velocity components normalized by the local velocity magnitude from GRECO simulation results of PREX 2.
Figure 3.35: Standard deviation for the normal (left) and tangential (right) velocity components normalized by the local velocity magnitude from GRECO simulation results of PREX 3.0.

The GRECO results also do not show some of the key qualitative findings from the experimental results. In the diverging areas of the test sections, the simulations show significant tangential variations throughout the region. The normal standard deviations for PREX 2 have similar large-scales structures to the experimental results. However, the PREX 3.0 results show significant mixing only in the center section away from the walls and do not capture the variations between the inner and outer sections of the diverging region after the inlet.

The pebble mixing behavior in the converging region also appears different between the simulation and experimental results. GRECO distributions show significantly larger normal standard deviations in lower section of PREX 2, which is due to the requirement for pebbles in the two-dimensional system to move around one another, discussed earlier. Smaller normal variances, and less mixing, are only observed close to the wall where the mixing is physically constrained by the boundary.

Overall, the GRECO results for the pebble radial zone interface position show reasonable agreement with the gravity dominated PREX results while the stochastic pebble motion displays some significant distortions in the constrained two-dimensional simulation. Based on this finding, it is recommended that GRECO be
used to predict the radial zone interface positions when accompanied by a neutronics sensitivity study to determine the impact of errors up to about $2d$. The level of mixing at the interfaces observed in the GRECO results is significantly larger than that from the experiments. Therefore, the diffusion of pebbles from the average interface position in the GRECO results should be treated as a conservative upper bound and should be compared to the case of a perfectly distinct interface to evaluate the impact on core performance. This results in this section show some of the important distortions introduced in GRECO because of the two-dimensional geometry simplification.

### 3.6 Recirculation Rates and Residence Time Distributions

The probabilistic distribution of pebble residence times to complete one recirculation through the core of a pebble bed reactor is one of the main factors, along with the core flux distribution, in determining the expected burnup distribution of the fuel. The ability to accurately assess the residence time distributions is essential to establish the average core composition and confidence that the pebbles with the longest residence times do not exceed their allowable burnup. This section covers several direct and indirect methods used to study the residence time distributions from the PREX experimental results in comparison to GRECO DEM simulations and analytic kinematic model results.

#### 3.6.1 Direct Experimental Results

For PREX 3.0, it is practical to obtain direct residence time distributions for the pebbles in each radial zone due to the relatively small number of pebbles in the system. Thin layers of 100 pebbles in each radial zone circulated through the test section in discrete time steps where the mass of pebbles removed from the test section was recorded. For each time step, the number of tracked pebbles was tallied to assemble a cumulative probability distribution of pebble residence times for each radial zone.

Figure 3.36 shows the cumulative probability distributions for eight tracked layers. The results are normalized by the median residence time for the central (light green) radial zone and offset by a correction for the average residence time for pebbles to circulate from the bottom of the visible region out of the system. The results show that pebbles in the central (light green) radial zone have the shortest average residence time, which is expected due to the fact that these pebbles are both the least affected by the wall friction effects, have the shortest average streamline through the core, and circulate through the region with the most significant channeling effects in the converging region.

The comparison of the residence time distributions for the other two radial zones in Figure 3.36 show that those pebbles near the inner reflector have longer average
residence times than those near the outer reflector. This result is somewhat surprising because those pebbles along the outer reflector wall in the converging region have the smallest average velocities and appear to have the longest residence times based on visual observations at the surface. This result is likely due to the complex geometry of PREX 3.0 where pebbles near the inner reflector are held up through the inlet region, while pebbles in the outer region move at higher velocities along their average streamlines. In addition, the converging region in PREX 3.0 forces pebbles in the inner zone to move towards the center region before the defueling chute.

Figure 3.36: Experimental residence time cumulative distributions for the time it takes for a pebble in each radial zone to recirculate through PREX 3.0.
3.6.2 Comparison to Monte Carlo Algorithm for PREX 3.0

Monte Carlo methods to determine the residence time distribution present a useful basis to estimate residence time distributions when direct measurements are impractical. This applies to both large experiments such as PREX 2 and full three-dimensional DEM simulations where it would take too long to track pebbles that recirculate through the entire bed for design purposes. This section presents a description of the Monte Carlo algorithm used to analyze the residence time distributions based on the mean and variance of the observable surface velocity fields for PREX 2 and 3.0. This method is extended in the following section to the GRECO DEM simulation results.
The residence time distributions are tallied based on a user-defined number of pebbles that are recirculated between two specified heights in the test section geometry. The initial pebble position is selected randomly based on a weighted cumulative distribution function of the local downward velocities to account for the different pebble mass flux in different parts of the inlet region. For each time step, the new pebble position \( \mathbf{r}_{k+1} \) is determined randomly based on the normal distribution and the local velocity variance at the original position \( \mathbf{r}_k \) such that

\[
\mathbf{r}_{k+1} = \mathbf{r}_k + \left[ \mathbf{v}_{av}(\mathbf{r}_k) + \sigma_{av}(\mathbf{r}_k) \sqrt{2} \text{erfinv}(2\text{rand}-1) \right] \Delta z_{\text{plug}}
\]  

(3.1)

where \( \mathbf{v}_{av} \) and \( \sigma_{av} \) are the average velocity and standard deviation based on the pebble position at time \( k \) and \( \Delta z_{\text{plug}} \) is the user-defined time step interval based on the vertical displacement in the plug flow region. An alternative method to randomly generate the new pebble positions based on the actual cumulative distribution functions was also developed, but the results showed only small discrepancies from those using the normal distribution. In order to accurately account for correlated velocity components, Equation (3.1) is implemented so that it uses the velocity statistics normal and tangential to the average velocity data compiled for each Verlet cell.

Figure 3.38 shows the cumulative distribution functions for the radial zones in PREX 3.0 using the probabilistic Monte Carlo method. It is readily apparent that these results differ significantly from those in the direct measurement of pebbles presented in Section 3.6.1 above. From the Monte Carlo results, we see that the dark green pebbles have both the longest residence time and also the largest variance. This matches the expectations based on results from cylindrical core geometries where pebbles at the outer reflector have the smallest local velocities. One possible explanation for the discrepancy could be distortion effects of pebbles observed at the outer wall compared to the bulk behavior. In this case, yellow pebbles away from the wall in the packed bed must be moving more slowly than those at the wall and dark green pebbles must be moving more quickly to account for the different behavior. The front wall surface adds additional friction forces on the pebbles and those pebbles at the corners should be most impacted. However, there is no clear physical explanation of why the yellow pebbles would be impacted so differently from pebbles in the dark green zone.
Figure 3.38: Monte Carlo generated residence time distributions based on the experimental velocity field mean and variance data for the time it takes a pebble to circulate through PREX 3.0 in each of the radial zones.

To further investigate the potential discrepancy between the internal bed behavior and the pebble motion observed at the exterior surface, it is worthwhile to evaluate the overall pebble recirculation rates. Table 3.3 shows the measured recirculation rates of each radial pebble zone in PREX 3.0 as the fraction of pebbles recirculated. These results are compared to the numerical estimate based on integration of the surface velocity data in the inlet region at height $z = 82d$ and for the plug flow region at $z = 45d$. The direct data were obtained from the recirculation of approximately 10,000 pebbles. The integrals give the recirculation fraction of each radial pebble zone when normalized by the integral of the mean velocity across the entire width of the test section. This data show that the numerical results closely match the direct measurements, which suggests that the surface velocity data are well correlated to the internal velocity field. The largest difference is seen for the yellow pebbles near the inner reflector wall for the inlet region where the numerical results under-predict the yellow recirculation rate by about 2.5%. This difference means that that the pebbles in the bulk are actually moving slightly faster than those observed at the surface. These results based on the plug flow region show closer convergence to the direct measurements of pebble recirculation rates, within about 1%. These results directly contradict the hypothesis that the difference in residence time data in Section 3.6.1 are due to distortions introduced by observations at the wall.
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<table>
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<th>Direct Measurement</th>
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<th>Velocity Integral (z = 45 d)</th>
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<td>18.75 %</td>
<td>16.27 % ( - 2.46 %)</td>
<td>18.76 % ( - 0.10 %)</td>
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<tr>
<td>Zone 2 (Light Green)</td>
<td>36.48 %</td>
<td>37.57 % (+ 1.09 %)</td>
<td>35.49 % ( - 0.99 %)</td>
</tr>
<tr>
<td>Zone 3 (Dark Green)</td>
<td>44.77 %</td>
<td>46.16 % (+ 1.39 %)</td>
<td>45.86 % (+ 1.09 %)</td>
</tr>
</tbody>
</table>

Table 3.3: Relative recirculation rates for PREX 3.0. The direct measurement rates are based on recirculation data for 10,181 pebbles. The surface velocity integrals are based on the area weighted pebble flux between the 50% interface boundaries at elevation $z = 82d$ in the inlet region and $z = 45d$ in the constant area region.

The most plausible explanation for the observed discrepancy between the probabilistic surface data and the direct measurements is that it is the result of variations in pebble flux rates within the width of each of the inlet hoppers. Figure 3.39 shows the probability distributions for the initial radial position for pebbles inserted into each hopper. These results show that pebbles are more likely to be inserted at the outer radii of the hoppers, due to a combination of the radial expansion and the additional friction at the lower walls in the angled hopper inlets. For the direct measurements, pebbles were inserted in horizontal bands in each hopper in numbers proportional to the overall recirculation rates of each zone. Based on the measured probability densities, this horizontal loading would over-represent yellow pebbles close to the inner reflector with longer residence times and under-represent yellow pebbles close to the green pebble interface with shorter residence times. The opposite biases would also be expected for the dark green pebbles.

The bias in data for the pebble residence time distributions in PREX 3.0 demonstrates an important challenge in accurately characterizing the data away from the observable wall, which can be sensitive to both known and unknown distortions. The consistency in the observed pebble flux based on the surface velocity data with the overall bulk recirculation rates implies that Monte Carlo-based residence time distributions may be more reliable than statistics from small sets of tracked pebbles. This effect would be more apparent in larger systems where sampling statistics would be even smaller compared to the total number of pebbles in the system.
Figure 3.39: Inlet hopper probability density normalized by the average probability density for that hopper in PREX 3.0 at $z = 82d$.

3.6.3 PREX 2 Experimental and Monte Carlo Results

For PREX 2, the pebble recirculation rates were measured directly by keeping track of the total mass of pebbles added to each radial zone hopper. Table 3.4 shows the recirculation rates from the direct measurements compared to area-weighted integrals of the pebble velocities at the visible surface. Comparisons are given for the velocity distributions at the end of the inlet hoppers ($z = 195d$) and at the 50% interface positions in the constant area region ($z = 110d$). The results recirculation rates from the constant area region show excellent agreement and are within 3% of the measured results. This supports the assumption that the surface behavior is a reasonable approximation for the bulk behavior of pebbles away from the visible wall. Larger differences are seen for the velocity integrals at $z = 195d$ due to the narrow widths of the radial zones in the inlet hoppers, which are only about $4d$ wide.
### Table 3.4: Relative recirculation rates for PREX 2. The direct measurement rates are based on mass measurements for the recirculation of 108,000 pebbles. The surface velocity integrals are based on the area weighted pebble flux between the 50% interface boundaries at elevation $z = 195d$ in the inlet region and $z = 110d$ in the constant area region.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Direct Measurement</th>
<th>Velocity Integral ($z = 195d$)</th>
<th>Velocity Integral ($z = 110d$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1 (Dark Green)</td>
<td>6.9%</td>
<td>3.6% (-3.3%)</td>
<td>4.4% (-2.5%)</td>
</tr>
<tr>
<td>Zone 2 (Yellow)</td>
<td>13.9%</td>
<td>18.2% (+4.4%)</td>
<td>15.0% (+1.2%)</td>
</tr>
<tr>
<td>Zone 3 (White)</td>
<td>15.3%</td>
<td>14.4% (-0.9%)</td>
<td>15.4% (-0.1%)</td>
</tr>
<tr>
<td>Zone 4 (Yellow)</td>
<td>18.9%</td>
<td>20.3% (+1.4%)</td>
<td>21.8% (+2.9%)</td>
</tr>
<tr>
<td>Zone 5 (Light Green)</td>
<td>21.9%</td>
<td>27.5% (+5.6%)</td>
<td>22.7% (+0.8%)</td>
</tr>
<tr>
<td>Zone 6 (Dark Green)</td>
<td>23.0%</td>
<td>16.0% (-7.0%)</td>
<td>20.7% (-2.3%)</td>
</tr>
</tbody>
</table>

The Monte Carlo method introduced above was used to estimate the residence time distributions in PREX 2 because it was not practical to directly track small layers of pebbles. Figure 3.40 shows the residence time distributions for the six radial zones using the experimental mean velocity field and statistics for normal and tangential motion. The zones are indexed from the inner reflector to the outer reflector. Residence times are given in terms of the total displacement in the constant area region, which can be scaled as required by core neutronics designers based on the desired residence times for fuel pebbles in the active core region. Table 3.5 also gives the average residence times and their standard deviations for each radial zones normalized by the average residence time for all pebbles recirculating through the core.
The results for the residence time distributions in PREX 2 are consistent with the general observations of the local velocity fields. The longest residence times and the largest variances are observed in pebbles in Zone 6 near the outer reflector surface. These pebbles remain in the system about 10% longer than the average residence time because they have longer streamline paths through the system and experience the greatest hold up due to wall friction along the outer reflector in the converging region. Pebbles in Zone 5 also have longer residence times than other zones based on similar logic. Zone 1, which includes pebbles located adjacent to the inner reflector have a comparable average residence time to Zone 5, but show much less variation. These pebbles experience hold up due to the wall friction along the inner reflector surface, but have considerably shorter streamline paths through the core. The central radial zones (2-4) show the shortest residence time distributions, ranging from 4-6% shorter than the overall average. These zones are the least impacted by wall friction and experience the most dramatic channeling towards the defueling chute in the converging region.

Figure 3.40: Monte Carlo generated residence time distributions based on the experimental velocity field mean and variance data for the time it takes a pebble to circulate through PREX 2 in each of the radial zones.
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### Table 3.5: Mean and standard deviation for pebble residence time in each PREX 2 radial zone relative to the average residence time for all zones.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Zone Residence Time Relative Average</th>
<th>Zone Residence Time Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1 (Dark Green)</td>
<td>0.997</td>
<td>0.0060</td>
</tr>
<tr>
<td>Zone 2 (Yellow)</td>
<td>0.960</td>
<td>0.0079</td>
</tr>
<tr>
<td>Zone 3 (White)</td>
<td>0.942</td>
<td>0.0027</td>
</tr>
<tr>
<td>Zone 4 (Yellow)</td>
<td>0.949</td>
<td>0.0063</td>
</tr>
<tr>
<td>Zone 5 (Light Green)</td>
<td>1.008</td>
<td>0.0220</td>
</tr>
<tr>
<td>Zone 6 (Dark Green)</td>
<td>1.102</td>
<td>0.0232</td>
</tr>
</tbody>
</table>

3.6.4 Comparison to GRECO Results

The recirculation rates for each radial zone in PREX 2 and 3.0 can be directly compared to those from the GRECO simulation runs. Table 3.6 and Table 3.7 give the recirculation fractions for PREX 2 and 3.0, respectively, and the errors compared to the direct mass measurements. The results show significant discrepancies up to about 10% for both experiments. The largest errors are found for the outer radial zones, where GRECO under predicts the overall recirculation rate. The GRECO results for the inner radial zones tend to under predict the recirculation rates. This distortion is a result of the simplified two-dimensional GRECO model that cannot account for the radial expansion in the axisymmetric geometry.

A more accurate method to estimate the overall recirculation fraction from the GRECO simulation results would be to use the vertical velocity profiles and pebble probability densities in the constant area region to estimate the relative mass flux of each zone. These results are also included in Table 3.6 and Table 3.7 and are based on area integrals in the cylindrical coordinate base. These results more closely match the direct mass measurements, with typical errors within 3%. Because the GRECO results accurately capture the plug flow in the constant area region, errors from this methodology will be due to distortions in the pebble probability distributions, previously discussed in Section 3.4.2.
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<table>
<thead>
<tr>
<th>Zone 1</th>
<th>GRECO Hopper Loading Recirculation Fraction</th>
<th>GRECO Velocity Integral Recirculation Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Dark Green)</td>
<td>6.2 % (−0.7 %)</td>
<td>3.8 % (−3.1 %)</td>
</tr>
<tr>
<td>Zone 2</td>
<td>18.8 % (+4.9 %)</td>
<td>13.0 % (−0.9 %)</td>
</tr>
<tr>
<td>(Yellow)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 3</td>
<td>21.0 % (+5.7 %)</td>
<td>18.0 % (+2.7 %)</td>
</tr>
<tr>
<td>(White)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 4</td>
<td>21.3 % (+2.4 %)</td>
<td>22.1 % (+3.2 %)</td>
</tr>
<tr>
<td>(Yellow)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 5</td>
<td>20.5 % (−1.4 %)</td>
<td>24.9 % (+3.0 %)</td>
</tr>
<tr>
<td>(Light Green)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 6</td>
<td>12.2 % (−10.8 %)</td>
<td>18.1 % (−4.9 %)</td>
</tr>
<tr>
<td>(Dark Green)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.6: Recirculation rates of radial zones in PREX 2 from GRECO simulations based on hopper loading tallies and velocity integrals in the constant area region \((z = 110d)\). The errors are given in parentheses and show the differences between the simulation and experimental results.

<table>
<thead>
<tr>
<th>Zone 1</th>
<th>GRECO Hopper Loading Recirculation Fraction</th>
<th>GRECO Velocity Integral Recirculation Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Yellow)</td>
<td>26.0 % (+7.2 %)</td>
<td>17.1 % (−1.7 %)</td>
</tr>
<tr>
<td>Zone 2</td>
<td>38.6 % (+2.1 %)</td>
<td>37.2 % (+0.7 %)</td>
</tr>
<tr>
<td>(Light Green)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 3</td>
<td>35.3 % (−9.5 %)</td>
<td>45.7 % (+0.9 %)</td>
</tr>
<tr>
<td>(Dark Green)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.7: Recirculation rates of radial zones in PREX 3.0 from GRECO simulations based on hopper loading tallies and velocity integrals in the constant area region \((z = 45d)\). The errors are given in parentheses and show the differences between the simulation and experimental results.
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The GRECO simulation results for the average velocity field and the statistical distributions of pebble motion can be used to generate residence time distributions for the radial zones using the same Monte Carlo methodology described in Section 3.6.2 using the experimental velocity data. Figure 3.41 shows the residence time distributions for the radial zones in PREX 2, ordered from the inner reflector to the outer reflector. These results match the general trends found from the experimental data, where pebbles in Zones 5 and 6 have the longest residence times distributions and largest variance. The pebbles in Zone 1 along the inner reflector also have longer residence times that are comparable to Zone 5, but with a narrower distribution that was also observed in the experimental results. While the GRECO results match the general trends of the experimental data, they do show residence times that are 5-8% longer when normalized by the constant area region displacement. These discrepancies are probably acceptable for preliminary core design efforts due to the large uncertainties around wall friction in the prototypical system.

Figure 3.41: GRECO simulation results for the cumulative residence time probabilities for the radial zones in PREX 2.
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Figure 3.42 shows the residence time distributions for PREX 3.0 using the Monte Carlo method to incorporate the stochastic variation in pebble motion. The top figure is based on the experimental results normalized by the constant area region displacement and the bottom figure gives the same results using the GRECO mean velocity field and local velocity distributions. The results show excellent qualitative and quantitative agreement. These results suggest that GRECO velocity data can be used with the Monte Carlo algorithm to produce useful residence time distributions even if there are large differences in the variances of the velocity components compared to experimental data. This capability is particularly valuable to core designers who would want to use spatial neutron flux distributions to estimate realistic fuel pebble burnup levels in the radial zones.

![Experimental Velocity Data](image1)

![GRECO Simulation Velocity Data](image2)

Figure 3.42: Experimental and GRECO simulation results for the cumulative residence time probabilities for the radial zones in PREX 3.0.
3.7 Conclusions

This chapter covers experimental and GRECO simulation results for conventional gravity-dominated silo drainage in geometries based on the core design of the PB-FHR. The scaled Pebble Recirculation Experiments (PREX) 2 and 3.0 presented here are based on annular core designs for a 900 MWth PB-FHR commercial pilot plant point design and a 16 MWth PB-FHR test reactor design. The results from the experiments help to build confidence in innovate core geometries that include diverging inlet regions and radial pebble zoning. The results from these experiments were directly compared to GRECO simulation results.

The mean pebble velocity field was analyzed for pebbles at the visible surfaces of PREX 2 and PREX 3.0. The velocity results showed smooth time-averaged behavior in the diverging regions, which is a key experimental finding for this novel core geometry. It is also significant that the diverging region remained densely packed in all of the experiments. The velocity fields also showed smooth transitions to plug flow in the constant area region, which has been observed in other silo drainage experiments. Below the plug flow region, a significant amount of channeling was observed above the defueling chute and pebbles moved more slowly along the inside and outside reflector boundaries. The slowest pebble velocities were observed along the outer reflector in the converging region of the core.

GRECO simulation results showed a good level of agreement with the experimental data. Local GRECO velocities were found to be within 10-15% of the experimental results, with slightly larger errors found for the slowest moving pebbles along the outer reflector and in the defueling chute. The relative errors for the slow moving pebbles were found to be higher because of the smaller experimental velocity magnitudes and the errors were generally much less than one pebble diameter for a displacement of \( d \) in the plug flow region. Large errors in the defueling chute are an expected distortion from the two-dimensional GRECO model and are of little impact on reactor core design because this is a low power density region.

A detailed study of radial pebble zones in PREX 2 and PREX 3.0 was also presented here. Radial zones are established by the use of divider plates to create inlet hoppers for each pebble type. Radial zones created from these hoppers remained in tact through the diverging region where the greatest degree of mixing was observed. The widths of the radial zone interface regions were found to be on the order of a few pebble diameters in both PREX 2 and PREX 3.0. The probabilities of finding pebbles more than 2\( d \) and 3\( d \) from the average interface position were found to be about 5\% and 1\%, respectively. The preservation of radial pebble zones through a diverging region is a key finding of this study. Negligible mixing was observed in the plug flow region. Small mixing effects were also observed in the converging region, where pebbles showed small variances in the stochastic motion normal to the direction of the mean local velocity.
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The experimental results for radial zone interface positions and mixing effects were compared to statistics generated with the GRECO simulation tool. The simulation results showed reasonable accuracy and predicted the position of the radial zone interfaces generally within $2d$. GRECO results showed a tendency to under predict the interface position at inner radial positions and to over predict the interface position at outer radial positions. The GRECO interface boundaries also showed a higher level of mixing, which is due to the constrained two-dimensional system. It is recommended that sensitivity studies be performed to determine the impact of these errors on the core neutronics performance. For preliminary design efforts, the GRECO results are likely sufficient before scaled experimental facilities can be built to evaluate granular flow in specific core designs.

This chapter also presented an analysis of pebble residence times in the gravity-dominated PREX systems. These included direct measurement of residence time distributions for a small layer of pebbles in PREX 3.0 and a new Monte Carlo method to estimate residence times based on the stochastic variation of the pebble velocity data for the visible surface. Significant discrepancies were observed between the direct measurements and the Monte Carlo results. The direct measurements showed that pebbles along the inside reflector had the longest average residence time, while the Monte Carlo method showed that pebbles moving along the outer reflector would have the longest residence times. The source of this discrepancy is thought to be the non-uniform velocity distributions in the inlet hoppers. Tracking flat layers of pebbles was shown to over estimate the residence times along the inner region and under estimate the residence times in the outer regions of the test section. This result suggests that extreme care must be taken when using small sets of pebbles to extrapolate the overall pebble residence time distributions in large granular systems. Stochastic methods, such as the Monte Carlo algorithm developed here, may in fact be more accurate.

The GRECO simulation results showed excellent qualitative and quantitative agreement with the Monte Carlo results from PREX 2 and PREX 3.0. The accuracy of the GRECO results is somewhat surprising given the differences in the standard deviations for the velocity components between the experimental and simulation results. This suggests that the accuracy of the mean velocity field is the primary determinant of the value of the Monte Carlo-derived residence time distributions. The GRECO velocity statistics are therefore determined to be a reasonable method to generate residence time distributions for pebble bed reactor cores during the iterative design phase.
Chapter 4

Coupled Granular and Fluid Dynamics

This chapter presents a detailed analysis of granular flow in “wet” pebble bed systems, where the advection of a fluid through the bed creates drag forces on the pebbles and the coupled pebble and fluid dynamics must be considered. These results are particularly important for reactor core designs such as the PB-FHR, where the effects of potentially complex multidimensional fluid flow fields on the time-averaged pebble motion must be understood in the design process. Fluid drag forces in these systems have the potential to change the granular flow compared to the relatively simple case of gravity drainage and extrapolation of behavior between these systems cannot be assumed. Similar to the results presented in Chapter 3, this chapter presents experimental data from the “wet” Pebble Recirculation Experiment (PREX) 3.1 to develop a basic physical understanding of the phenomenology associated with coupled granular and fluid dynamics. The experimental data can be directly compared to GRECO simulation results in order to determine the applicability of the code and modeling assumptions for such complex systems.

4.1 Experimental Methods

Pebble Recirculation Experiment (PREX) 3.1 is a scaled experimental facility that was built to evaluate the effects of coupled fluid flow fields on pebble recirculation in PB-FHR cores. The facility uses water as a simulant fluid and positively buoyant high-density polyethylene (HDPE) plastic spheres, which have been previously demonstrated to capture the important hydrodynamic phenomena of pebble fuel in the liquid salt flibe [65].

PREX 3.1 is the first experiment known to the author that provides detailed velocity field data for coupled granular and fluid systems with multi-dimensional fluid flow fields. Previous experiments that track detailed local pebble motion at a clear surface have been performed under gravity drainage [50], [51], like the results presented in Chapter 3. The original PREX experiment, build at U.C. Berkeley in 2006 [65], was built to demonstrate the feasibility of pebble recirculation for liquid salt-cooled reactors, but is not able to provide any local data related to the pebble
motion. The results from PREX 3.1, therefore, will provide important insights on the impact of fluid drag forces on granular dynamics in multi-dimensional flow fields.

### 4.1.1 Scaling Analysis

The scaling approach for PREX 3.1 is based on the analysis by Bardet et al. [65] in support of the PB-FHR design effort. This work developed a scaling approach for the original PREX that could use high-density polyethylene pebbles and water as a simulant fluid to match the dynamics of fuel pebbles and flibe in the prototypical conditions if the solid-fluid density ratio, Reynolds number and Froude number are matched. The previous analysis, however, is based on scaling the drag forces on a single pebble in a free velocity stream, which is relevant to demonstrate pebble handling in recirculation. The following discussion establishes that the same scaling parameters can be used for pebbles in a densely packed bed with porous media flow in the pore volume.

The forces acting on a pebble in a densely packed bed can be expressed as,

\[ \sum F_{\text{Pebble}} = F_{\text{Buoyancy}} + F_{\text{Drag}} + F_{\text{Contact}} \]  \hspace{1cm} (4.1)

where \( F_{\text{Buoyancy}} \) is the effective buoyancy force on the pebble, \( F_{\text{Drag}} \) is the effective drag force on the pebble and \( F_{\text{Contact}} \) is the net result of forces due to contact with other pebbles or wall surfaces. The measurement of contact forces is not within the scope of the experimental work completed for this dissertation. It is not expected to impact the coupling of the fluid forces to the pebble motions because contacts in dense granular flows are long lasting and proper scaling is based primarily on matching the coefficients of friction and restitution. It is also important to note that this analysis assumes that buoyancy and drag forces act as body forces through the center of the pebble, which is true for spheres in packed beds, but would not hold true for other grain shapes. With non-spherical particles, drag forces may apply torques that would also need to be considered in analysis.

Based on the substitutions,

\[ \sum F_{\text{Pebble}} = \rho_p V_p \frac{\partial u_p}{\partial t} \]  \hspace{1cm} (4.2)

\[ F_{\text{Buoyancy}} = \frac{\rho_f - \rho_p}{\rho_p} V_p g \]  \hspace{1cm} (4.3)

\[ F_{\text{Drag}} = -\frac{\partial P}{\partial x} V_p \]  \hspace{1cm} (4.4)
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where $\rho_p$ and $\rho_f$ are the pebble and fluid densities, $V_p$ is the pebble volume, $u_p$ is the pebble velocity, and $P$ is the fluid pressure. The approximation of the drag force in Equation (4.4) is based on the integral of the net surface force on a spherical surface in a linear pressure field and is derived in Appendix A.

Incorporating the Ergun correlation for the pressure gradient,

$$\frac{\partial P}{\partial x} = -\frac{\beta \mu_f (1-\varphi)^2 u_f}{d_p \varphi^3} - \frac{\alpha \rho_f (1-\varphi) u_f^2}{d_p \varphi^3}$$

(4.5)

where $\varphi$ is the porosity, $\alpha$ and $\beta$ are constant model fitting parameters, and $u_f$ is the fluid velocity, a modified form of the pebble-fluid forces in a packed bed is given by,

$$\rho_p \frac{\partial u_p}{\partial t} = \left( \rho_f - \rho_p \right) g + \frac{\beta \mu_f (1-\varphi)^2 u_f}{d_p^2 \varphi^3} + \frac{\alpha \rho_f (1-\varphi) u_f^2}{d_p \varphi^3}$$

(1)\hspace{1cm} (2)\hspace{1cm} (3)\hspace{1cm} (4)

(4.6)

From Equation (4.6), we divide all terms by the pebble density and divide each term in the equation by the inertial drag term (4) to find the form,

$$\frac{\rho_p d_p \varphi^3}{\alpha \rho_f (1-\varphi) u_f^2} \frac{\partial u_p}{\partial t} = \frac{\varphi^3}{\alpha (1-\varphi)} \frac{\rho_f - \rho_p}{\rho_f} \frac{d_p g}{u_f^2} + \frac{\beta (1-\varphi)}{\alpha} \frac{\mu_f}{\rho_f u_f d_p} + 1$$

(4.7)

The dimensionless parameters for the pebble velocity and time scales can be expressed as

$$u_p^* = \frac{u_p}{u_f}$$

(4.8)

$$t^* = \frac{u_f}{d_p} t$$

(4.9)

which can be combined into Equation (4.7) along with the definition of the Reynolds and Froude numbers to give the result

$$\frac{1}{\alpha (1-\varphi)} \frac{\varphi^3}{\rho_f} \frac{\partial u_p^*}{\partial t^*} = \frac{1}{\alpha (1-\varphi)} \left( 1 - \frac{\rho_p}{\rho_f} \right) \frac{1}{Fr} + \frac{\beta (1-\varphi)}{\alpha} \frac{1}{Re} + 1$$

(4.10)
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The result found in Equation (4.10) shows that the drag and buoyancy forces for the coupled pebble and fluid dynamics in a packed bed experiment will be properly scaled by matching the geometric configuration, the ratio of the pebble and fluid density, and the Reynolds and Froude numbers.

The dynamics of the pebble motion merits some further discussion because it has important implications on both experiment and simulation methods. Granular systems do not “flow” in the same way as a fluid where reducing the velocity scale will cause a proportional reduction in the velocity of all material points in the system. In granular materials, the bulk flow is governed by the complex transitions between static and kinetic friction that occur at the scale of individual pebble contacts. When pebbles downstream move, stable void space may develop that will reduce the flow of pebbles upstream until static contacts break and the voids are filled. Therefore, an appropriate timescale \( \tau \) for the pebble motion is the time that it takes for a pebble to move, under gravity or buoyancy, a distance comparable to the size of the pebble. Using the pebble radius \( R_p \) as the length scale, this gives \( \tau \) and the corresponding pebble velocity scale as

\[
\tau = \sqrt{\frac{2R_p}{g_{\text{eff}}}} \quad (4.11)
\]

and

\[
u_p \sim \sqrt{\frac{R_p g_{\text{eff}}}{2}} \quad (4.12)
\]

where \( g_{\text{eff}} = g \left( \rho_f / \rho_p - 1 \right) \) is the effective acceleration due to gravity or buoyancy. Due to the fact that the pebble velocity is small compared to the fluid velocity in the systems of interest, the inertia terms in Equation (4.10) can be neglected with minimal distortion.

Using water at 20° C as a simulant fluid for flibe at 650° C, the results of the scaling analysis require a reduced length scale at 43.9% and a reduced velocity scale at 66.3% to match the prototypical conditions in the PB-FHR. Table 4.1 shows the key scaling parameters for the 900 MWth PB-FHR [48], the 16 MWth PB-FHR test reactor [49], and the PREX 3.1 facility. For these results, \( \text{Red} \) is estimated based on the superficial flow rate for the cross sectional area in the constant area region of the core and the pebble diameter \( d \). This method is selected to give a characteristic \( \text{Red} \) for the core, but in the actual system, there would be a range of values with larger flow rates at the injection surfaces of the inner reflector and lower flow rates at the outer reflector surfaces due to the radial expansion. The shift from the axisymmetric, annular geometry of the prototypical FHR system to the quasi two-dimensional
geometry in PREX 3.1 is the largest scaling distortion. It is considered to be acceptable for the scope of work presented here because the PREX 3.1 data will still provide a valuable reference for model validation over a range of flow regimes relevant to the PB-FHR.

There are several other distortions due to the reduced area scaling in PREX 3.1. The changing density of the flibe coolant introduces different geometry scaling parameters for the core inlet and the core outlet. Also, the procurement of 1.26 cm diameter commercial HDPE spheres sets the length scaling at 42.0% and increases the density ratio to 0.96, which results in a scaling mismatch of about 10%. The resulting pebbles in PREX 3.1 are therefore more neutrally buoyant than those in the prototypical PB-FHR. This distortion is thought to be acceptable for PREX 3.1, because its primary purpose is to evaluate the impact of coupled fluid drag forces on the pebble dynamics in general rather than for one specific design. The reduction in buoyancy forces will actually allow for data collection with a wider range of drag to buoyancy force ratios to be evaluated with PREX 3.1.

It is also evident from Table 4.1 that there is a significant change in the fluid $\text{Re}_{d}$ when shifting from large core geometries for the 900 MWth PB-FHR design to small annular cores such as the FHR-16. This change is due to the linear scaling of the coolant flow rate and volume for the same core inlet and outlet temperatures and power density and the nonlinear scaling of the core cross-sectional area. PREX 3.1 is therefore limited to lower flow rates and the validation data cannot be simply extrapolated to larger drag regimes where different behavior may occur.

The other potential distortion for PREX 3.1 results is due to the uncertainty around the true friction coefficients of graphite lubricated with salt compared to HDPE lubricated with water. Preliminary scoping experiments suggest that fluoride salts may act as excellent lubricants for pebble-pebble contacts compared to helium or gas environments [48]. Additional study is needed, however, to better assess the phenomena of graphite tribology in FHR systems, which is directly relevant for the study of granular dynamics and other performance metrics, such as pebble surface wear and dust generation.
### Table 4.1: Key design scaling parameters for PREX 3.1 compared to the 900 MWth \[48\] and 16 MWth \[49\] PB-FHR core designs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PB-FHR</th>
<th>FHR-16</th>
<th>PREX 3.1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Working Fluid</strong></td>
<td></td>
<td>Flibe</td>
<td>Flibe</td>
</tr>
<tr>
<td><strong>Thermal Power</strong> [MWth]</td>
<td>900</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td><strong>Geometry</strong></td>
<td></td>
<td>Annular</td>
<td>Annular</td>
</tr>
<tr>
<td><strong>Pebble Diameter</strong> [m]</td>
<td>0.03</td>
<td>0.03</td>
<td>0.0126</td>
</tr>
<tr>
<td><strong>Number of Pebbles</strong></td>
<td>~3,000,000</td>
<td>~200,000</td>
<td>~20,000</td>
</tr>
<tr>
<td><strong>Inlet Temperature</strong> [^\circ\text{C}]</td>
<td>600</td>
<td>600</td>
<td>20</td>
</tr>
<tr>
<td><strong>Outlet Temperature</strong> [^\circ\text{C}]</td>
<td>700</td>
<td>700</td>
<td>20</td>
</tr>
<tr>
<td><strong>Fluid Density</strong> [kg/m^3]</td>
<td>1940-1990</td>
<td>1940-1990</td>
<td>998</td>
</tr>
<tr>
<td><strong>Pebble Density</strong> [kg/m^3]</td>
<td>1680-1810</td>
<td>1680-1810</td>
<td>951</td>
</tr>
<tr>
<td><strong>Pebble-Fluid Density Ratio</strong></td>
<td>0.85-0.92</td>
<td>0.85-0.92</td>
<td>0.95</td>
</tr>
<tr>
<td><strong>Buoyancy Acceleration</strong> [m/s^2]</td>
<td>0.19-0.84</td>
<td>0.19-0.84</td>
<td>0.488</td>
</tr>
<tr>
<td><strong>Active Core Cross Flow Area</strong> [m^2]</td>
<td>13.9</td>
<td>2.83</td>
<td>0.0388</td>
</tr>
<tr>
<td><strong>Re_d in Active Core</strong></td>
<td>1,200</td>
<td>105</td>
<td>&lt; 600</td>
</tr>
</tbody>
</table>
4.1.2 Experimental Setup

Figure 4.1 shows the PREX 3.1 test section in operation, with approximately 20,000 pebbles in the packed bed. The core geometry region is 1.10 m high and the quasi two-dimensional bed has a depth of 0.143 m. The width of the constant area region is 0.271 m. The complex wall geometry was generated with perforated ABS plastic blocks fabricated using three-dimensional rapid prototyping that are clamped between acrylic plates on the front and back surface of the test section. Figure 4.2 shows a view of the surface on inside reflector with an empty test section. The perforated surface used for water injection is also visible in this view. Detailed positions of the wall positions are given in Appendix D. Rubber gaskets and epoxy were used to seal the test section along the outer edges of the blocks to minimize the amount of bypass flow into the outer acrylic tank.

PREX 3.1 includes three inlet hoppers at the bottom in order to establish radial zones as pebbles circulate through the test section. Because they are used for demonstration of radial zoning, the widths of these hoppers are equal and do not reflect the actual zoning widths for an FHR core design. For reference purposes, the right boundary of the PREX 3.1 will be considered the inner reflector where coolant is injected and the left boundary will be considered the outer reflector where coolant is removed. This orientation is meant to be consistent with the annular core design of the PB-FHR even though the PREX 3.1 is a quasi two-dimensional experiment with no radial expansion.

Pebble recirculation in PREX 3.1 is required to collect step data on the pebble motion. Pebble injection is performed using a simple strategy that is novel and may have useful application in the PB-FHR design. Figure 4.3 shows a schematic diagram of the pebble injection process in PREX 3.1. Standpipes extend up from small-diameter horizontal flow lines and will have a free surface at an elevation equal to the level in the outer tank plus the pressure drop across the core. Pebbles are dropped into this standpipe and will settle based upon buoyancy with most pebbles below the free surface and some above. As a new pebble is added, the pebble at the bottom of the column is forced down into the horizontal pipe and advected into the coolant flow. The process allows for large number of pebbles to be easily injected into the divider hoppers at the bottom of the test section. Defueling was performed by manually removing pebbles from the top of the test section in small increments of 100 to 200 pebbles (<1% of the total number in the bed).
Figure 4.1: PREX 3.1 test section and manometer board operating with about 20,000 pebbles in the packed bed. Different regions of the test section are labeled.
Figure 4.2: Detailed view of PREX 3.1 inner reflective surface with no pebbles loaded in the test section. The perforated surfaces are used for water injection. Connections for coolant injection at the back of the blocks of the outer reflector are also visible.

Figure 4.3: Schematic diagram of pebble injection geometry in PREX 3.1.
PREX 3.1 is designed to accommodate a wide variety of different water flow configurations during pebble recirculation. Figure 4.4 shows the schematic of the coolant flow paths for the system. The test section has a total of 13 fluid injection lines, including three pebble injection lines, six injection lines along the bottom of the inside reflector, and four injection lines along the bottom of the outside reflector. Injection along the surface of the blocks occurs through an array of 0.63 cm holes spaced to give an effective porosity of 40% to match that of the packed bed. The flow through each injection line can be controlled using a ball valve and is instrumented with a flowmeter to measure the flow rate. Flow out of the test section can be directed through four block surfaces at the top of the outer reflector or through the top of the test section in the defueling chute.

![Schematic diagram of PREX 3.1.](image)

Figure 4.4: Schematic diagram of PREX 3.1.
4.1.3 Data Collection Procedures

For each PREX 3.1 data set, a photo record was created for both the manometer pressure levels and the pebble recirculation. Figure 4.5 shows a sample image of the manometer levels. Ten images were recorded to determine the average pressure field. Approximately 200 pebbles were removed from the bed between each pressure measurement to reduce any distortions from a pebble obstructing a manometer tap on the back surface of the test section. Pebble recirculation was completed in step increments where 100-200 pebbles were removed between sequential images. Approximately 100 time steps were recorded for each flow configuration.

![Sample data image of manometer pressure levels from PREX 3.1. The pressure tap positions are arranged so the bottom of the test section is the left-most tap and the top of the test section is the right-most tap.](image)

4.1.4 Data Processing Methods

Pebble detection and tracking between sequential images for PREX 3.1 data sets was performed using the same post-processing tools developed for the gravity-dominated systems described in Section 3.1.3. The plug flow region used for velocity field normalization was set for elevations between 55\(d\) and 65\(d\) at the lower portion of the constant area region. The lower portion was used in order to avoid the effects of channeling closer in the converging region and any significant pebble hold up due to suction at the outlets on the outer reflector surface.

The pressure field for each PREX 3.1 data set was determined directly from the manometer levels. The gage pressure of 0 Pa was set for the highest manometer tap located at the top of the defueling chute. Figure 4.6 shows the interpolated isobars for the measured pressure data for the three axial flow configurations (with \(Re_d \sim 100, 200, \) and 400 across the constant area region) and Figure 4.7 shows the interpolated isobars for the three cross flow cases (with \(Re_d \sim 100, 200, \) and 400 along the inner reflector injection surfaces). The complete set of pressure data for each PREX 3.1 fluid flow configuration along with the locations of the manometer taps are included in Appendix E. The axes in Figure 4.6, along with other figures in this chapter, are based on a Cartesian x-y plane to reflect the quasi two-dimensional geometry of the test section. Positions are also normalized by the pebble diameter \(d\).
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The pressure results for the axial flow configurations in Figure 4.6 validate the assumption that flow in packed beds will redistribute efficiently in the constant area section where isobars appear to be dominantly horizontal. The pebble motion data from these flow configurations will therefore serve as a good approximation of how different one-dimensional flow fields might impact the granular dynamics.

The results for the cross flow configurations in Figure 4.7 each show a significant deviation from the more uniform axial flow configurations. For each data set, isobars in the constant area section are oriented such that there is a negative pressure gradient running from the inner reflector where injection occurs towards the outer reflector where suction is applied on the block surfaces. These flow configurations will, therefore provide a useful basis to evaluate the effects of the coupled fluid dynamics pebbles subjected to a combination of buoyancy and drag forces.

One important observation from the isobars in the cross flow configuration is that in each case, the largest pressure gradients are located in a diagonal band that extends from the top of the injection region on the inner reflector down to the bottom of the suction region on the outer reflector. This plane represents the region of largest fluid mass flux in the test section and therefore is expected to have the largest pressure drop. The pebbles in this region will be subject to the largest drag forces, including horizontal components, and it will be important to see what impact this banding might have on the anticipated plug flow in the constant area section.

The conventions in this dissertation will refer to each of the fluid flow configurations based on the flow orientation and the approximate Reynolds number. Using this naming method, the axial flow cases are AX100, AX200, and AX400 and the cross flow cases are CR100, CR200, and CR400. The Reynolds numbers are based on estimates using the cross sectional area in the constant area region for the axial flow cases and the injection surface are along the inner reflector for the cross flow cases and should not be considered to be precise values.
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Figure 4.6: Interpolated isobars from experimental manometer pressure data (in Pa) for three axial flow configurations in PREX 3.1. Note that each image has a different pressure scale.
In order to determine the drag forces on pebbles in a packed bed based on Equation (4.4), it is necessary to determine the pressure gradient throughout the test section. The local pressure gradient is estimated using the methodology developed in [82] for unstructured grids. This method uses the slope of least squares-fitted plane for a set of nearby data points as an estimate of the local pressure gradient. The data for PREX 3.1 was processed using this algorithm and data points within a radius of about nine pebble diameters. This large distance was required due to the spacing of the manometer taps on the surface, but was found to produce reasonably smooth transitions in the pressure gradient and, by extension, pebble drag forces. Figure 4.8 shows a sample vector field of the drag forces in the constant area and converging region of PREX 3.1 for the CR400 flow configuration based on the processing algorithm. This data can be used directly by GRECO to determine the local drag forces on pebbles that are applied as a body force.
Figure 4.8: Sample vector field in the converging region representing the pebble drag forces from the experimental pressure data in PREX 3.1. This figure is for the CR400 flow configuration. The size of the arrows is proportional to the drag force.

One useful measure of the range of flow conditions covered in the PREX 3.1 data is to compare the magnitude of the drag forces to the buoyancy forces. Figure 4.9 and Figure 4.10 show this ratio for each of the axial and cross flow configurations. These results show that the data set covers the flow conditions where the drag forces range from 40% of the buoyancy force in the AX100 configuration to nine times the buoyancy force in the CR400 configuration. This is the regime of greatest interest in terms of coupling where there is parity between the two forces. The pebble motion data from PREX 3.1, therefore, will provide a strong validation test for GRECO and other analysis methods where coupled granular and fluid dynamics are needed.
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Figure 4.9: Magnitude of the pebble drag force relative to the buoyancy force for the PREX 3.1 experimental axial flow configurations.

Figure 4.10: Magnitude of the pebble drag force relative to the buoyancy force for the PREX 3.1 experimental cross flow configurations.
4.2 GRECO Model Parameters

The experimental results from the PREX 3.1 facility presented in this study can be directly compared to GRECO simulation results. Figure 4.11 shows the wall boundaries used in the GRECO simulations, which is based on the as-built geometry of the PREX 3.1 inner reflector, outer reflector, and inlet hoppers. The two-dimensional system was initially packed with a polydisperse bed with an average pebble diameter $d = 1.26$ cm and a uniform random dispersion distribution from $0.90d$ to $1.10d$. All pebbles in the system have a mass $m_p = 0.994$ g to match the mass of the HDPE spheres used in the experiment. The system is subject to a uniform upward acceleration due to buoyancy $g_{\text{eff}} = 0.488$ m/s$^2$. A total of 1,563 pebbles filled the system after the initial settling period. The small number of pebbles in the simplified two-dimensional system allows for recirculation results to be generated on time scales that are useful for the iterative design process.

Figure 4.11: GRECO simulation wall geometry for PREX 3.1 (left) and packed pebble bed (right) after recirculation with no fluid flow.
The friction coefficients in the PREX 3.1 facility of HDPE pebbles lubricated with water are difficult to measure and are the largest source of uncertainty in the GRECO simulation input parameters. A parametric study was completed for the PREX 3.1 geometry with no fluid flow to determine which friction coefficients to use as pre-predictions for the axial and radial fluid flow configurations. The simulation results presented in this chapter use an interpebble kinetic friction coefficient $\mu_p = 0.2$ and a tangential damping constant $\gamma_p = 2 \text{Ns/m}$. The pebble-wall Coulomb friction coefficients $\mu_{w1} = 0.1$ and $\mu_{w2} = 0.5$ are used for the smooth and the perforated wall surfaces, respectively. The large friction coefficients for the perforated surfaces are thought to be reasonable because pebbles moving along these walls will have additional resistance to tangential motion as they settle into the fluid injection and suction holes. GRECO hybrid static friction coefficients for the wall surfaces $\mu_{s1} = 0.01$ and $\mu_{s2} = 0.05$, 10% of the Coulomb limit, are used along with kinetic friction coefficients $\mu_{k1} = 0.09$ and $\mu_{k2} = 0.45$. Tangential damping for the wall contacts matched that for pebble-pebble friction with $\gamma_w = 2 \text{Ns/m}$. Normal forces in the GRECO simulations are handled using the material properties for HDPE-HDPE and HDPE-acrylic contacts described in Section 2.1.2 for the contact with viscoelastic damping.

Fluid drag forces coupling in the GRECO simulations is handled using the loose coupling methodology described in Section 2.3. The data processing methods for the manometer levels in PREX 3.1, described in the previous section, are used to generate a smooth pressure gradient within the test section geometry. The pressure gradient can then be used to estimate the drag force using the pebble volume from Equation (4.4). Drag forces are assumed to be constant for each Verlet cell in the GRECO simulation.

Pebble motion data for each fluid flow configuration were compiled from two complete bed recirculations performed over 1,000 macro time steps. In the two-tiered time step model in GRECO, each macro time step included the force computations for 2,000 micro time steps. A time step $\Delta t = 3.6 \times 10^{-5} \text{s}$ was used for all simulations, which matches that used for the dry systems presented in Chapter 3. All velocity data presented from the GRECO simulations is normalized by the average displacement in the constant area region at heights between 55$d$ and 65$d$.

## 4.3 Mean Pebble Velocity Fields

As in the case of the gravity-dominated systems described in Chapter 3, the local velocity field measurements at the visible wall provide the best available experimental data to compare to GRECO or other DEM simulation results. The following sections present the experimental results for PREX 3.1 with no fluid flow (buoyancy only) and for each of the axial and radial flow configurations with discussion on how these results compare to those for gravity-dominated systems. These results can be
used for direct comparison to GRECO simulation using the loose coupling method, which is described in Section 2.3.

4.3.1 Experimental Results

The local mean velocity field for each flow configuration in PREX 3.1 was evaluated using the same methodology for the gravity-dominated systems described in Chapter 3. Pebbles are tracked between sequential images and the local velocity is tallied based on the average position between the two frames and normalized by the plug flow displacement. The tallied data are compiled for cells with a side dimension of one pebble diameter.

Figure 4.12 shows the mean horizontal and vertical velocity components for PREX 3.1 with no fluid flow during recirculation. These results can be compared directly to those for PREX 3.0, discussed in Section 3.4.1. The first observation is that the general behavior of the buoyancy-dominated system closely matches that of the gravity-dominated system. Plug flow is observed in the constant area region, while large horizontal velocity components are found in the diverging and converging regions. Large vertical velocity components extend into the converging region from the defueling chute at the top of the test section and demonstrate that channeling effects are also present in the buoyancy-dominated system. The similarity between the two experiments should be expected due to the fact that gravity and buoyancy act as a uniform body force on the packed bed.
Figure 4.12: PREX 3.1 experimental horizontal (left) and vertical (right) pebble velocity fields with no fluid flow during pebble circulation. Local velocities are normalized by the average displacement in the constant area region ($55d < y < 65d$).

To provide a better understanding of the large-scale pebble flow patterns, Figure 4.13 shows the computed streamlines based on the local pebble velocity field and the magnitude of the local velocity field normalized by the average plug displacement. The results in Figure 4.13 once again show the strong similarities between the buoyancy-dominated and gravity-dominated systems. The inlet region shows significant pebble hold up on the inside reflector wall while pebbles near the outer reflector wall move faster. The PREX 3.1 results demonstrate that wall friction plays an important role in this constant-width inlet geometry because there is no radial expansion in the quasi two-dimensional test section. In the diverging region, pebbles move towards the free volume near the inner and outer reflector walls.
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After the constant area region, Figure 4.13 shows the expected channeling behavior in the converging region that is observed in gravity-dominated systems. The wall protrusion on the inside reflector at the top of the test section causes similar hold up along the right side and the largest velocities are found towards the center of the test section above the defueling chute. The smallest pebble velocities are found along the outside reflector wall and these pebbles are expected to have the longest residence times compared to the other radial zones. These effects will be discussed further in Section 4.5.

Figure 4.13: Computed streamlines for PREX 3.1 (left) and experimental pebble velocity magnitudes (right) based on the mean experimental local velocity data with no fluid flow, normalized to the pebble velocity in the plug flow region. Arrows show the relative magnitude of the local velocity for several horizontal cross sections. Velocities are normalized by the average pebble velocity in the plug flow region.
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The axial flow configurations for PREX 3.1 were selected to have near horizontal isobars so that the drag forces would act primarily in the same direction as the buoyancy forces. Figure 4.14 and Figure 4.15 show the change in the pebble horizontal and vertical velocity components relative the no flow pebble velocity data. The results are normalized by the magnitude of the local pebble velocity for the no flow, buoyancy-dominated configuration. The results are significant in that they show that there are small deviations, typically less than 10%, compared to the no flow configuration for all three of the axial flow cases. The variations between the cases for increasing drag forces also do not create any observable trends in the pebble velocity data.

The results for the axial flow configurations in PREX 3.1 demonstrate that time-averaged granular dynamics in a packed bed under uniform vertical drag forces are not dependent on the magnitude of those forces. This implies that when the friction coefficients are matched, gravity-dominated experiments will serve as excellent simulant experiments for reactor core designs with uniform, one-dimensional coolant flow. This would apply to the annular PBMR and for PB-FHR designs with simple cylindrical core configurations. It is important to note that while the granular flow pebble velocity field should not be impacted by the drag coupling, we would expect the pebble and reflector force loading to change depending on the coolant flow. The question of fluid drag on the pebble forces will be discussed further in Section 4.6.
Figure 4.14: Relative change in the experimental horizontal pebble velocity component in PREX 3.1 for the axial fluid flow configurations compared to the no fluid flow data. The differences are normalized by the magnitude of the local velocity.
Figure 4.15: Relative change in the experimental vertical pebble velocity component in PREX 3.1 for the axial fluid flow configurations compared to the no fluid flow data. The differences are normalized by the magnitude of the local velocity.

In contrast to the axial flow cases, the three cross flow configurations for PREX 3.1 were selected to have pebble drag forces with normal components to the buoyancy forces. Figure 4.16 and Figure 4.17 show the change in the pebble horizontal and vertical velocity components relative the no flow pebble velocity data. As it was presented for the axial data, the results are normalized by the magnitude of the local pebble velocity for the no flow configuration. These results show several observable trends as the magnitude of the drag force increases relative to the buoyancy force driving the pebbles up through the test section.
The first significant finding from the cross flow data concerns the pebble motion in the constant area section, where plug flow is commonly observed in gravity-dominated systems and the axial flow configurations. For the cross flow configurations in PREX 3.1, we observe in Figure 4.16 that the relative change in the horizontal velocity components are small (<10%) and show significant trend. This result shows that there is minimal radial diffusion in the constant area region even with horizontal drag forces several times larger than the buoyancy force. The lack of pebble intermixing in these cases is important for core design efforts because it implies that radial pebble zoning can be maintained in the active core region with minimal outward pebble intermixing due to radial flow configurations.

The relative change in the vertical velocity components in the plug flow region, however, show a significant impact due to the effects of the fluid drag forces. Figure 4.17 shows that as the horizontal drag forces increase, there is a dramatic increase in local pebble velocities along the inside reflector balanced by a decrease in those along the outside reflector. This result is likely due to the combined effects of the fluid drag reducing the wall forces at the injection surfaces of the inside reflector and increasing wall forces at the suction surfaces of the outside reflector. Even though the horizontal velocity components are small in this region, shearing must be occurring as pebble layers near the inside reflector move faster than those at the outside of the bed.

Figure 4.18 shows the horizontal and vertical velocity profiles in the constant area region (55d < y < 65d), which confirms that plug flow does not develop even though the horizontal velocity components are very small (< 0.02d). These results for the plug flow region are somewhat surprising because they diverge from the observed behavior of gravity and buoyancy-dominated flows, yet do not show additional pebble diffusion to the outside reflector despite the strong horizontal drag forces. One possible physical explanation may come from an insight of the kinematic model [54], which can be used as a simple approximation for gravity-dominated systems. The model assumes that horizontal pebble motion will be biased down gradients in the vertical velocity in a diffusion-like process. Under this assumption, with no drag forces, pebbles in the constant area region should be expected to move towards the inner reflector where pebbles have larger vertical velocity magnitudes. However, in the presence of horizontal drag forces towards the outer reflector, this bias would be offset. In PREX 3.1, it appears that these effects may essentially cancel each other. Future study of simple, controlled cases to study pebble diffusion in cross flow would be valuable to learn more about the physical basis for this result.
Figure 4.16: Relative change in the experimental horizontal pebble velocity component in PREX 3.1 for the cross fluid flow configurations compared to the no fluid flow data. The differences are normalized by the magnitude of the local velocity.
Figure 4.17: Relative change in the experimental vertical pebble velocity component in PREX 3.1 for the cross fluid flow configurations compared to the no fluid flow data. The differences are normalized by the magnitude of the local velocity.
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Figure 4.18: Experimental horizontal (left) and vertical (right) pebble velocity profiles in PREX 3.1 in the constant area region for the no fluid flow and cross fluid flow configurations.

The acceleration of pebbles at the inner reflector is observed in the diverging and converging region as well, but these regions also show some trends in the horizontal velocity components due to the increasing fluid drag force. Impacts in these regions should be expected due to the fact that they are where most of the observed mixing occurs for gravity-dominated flow. Figure 4.19 shows the horizontal profiles at elevations of $42d$ and $83d$. In the diverging region at $y = 42d$, we observe slightly more negative horizontal velocities with the increasing drag forces. This suggests that pebbles in this region will show a general bias to move towards the outer reflector, which will have some impact on the locations of the radial zone interfaces in the constant area region. It is important to note that these biases are on the order of 10% of the displacement in the constant area region. The impact of the drag forces on the radial zone interfaces will be further investigated in Section 4.4.

The horizontal pebble velocity profiles in the converging region at $y = 83D$, also shown in Figure 4.19, show a negative bias for the larger horizontal fluid drag forces. This implies that pebbles in this region near the suction surfaces on the outer reflector will move more slowly towards the defueling chute. This is consistent with the observed vertical acceleration of pebbles near the inside reflector relative to the no flow configuration because some pebbles must move towards the suction surface to make room for pebbles on the inner wall as the area contracts. This impact of coupled drag forces to the velocity field is expected to have an impact on the pebble residence time distributions and will be discussed in Section 4.5.
The results and discussion presented in this section make a central assumption that the observable motion of pebbles at the front wall surface in PREX 3.1 is a reasonable approximation for the motion of pebbles at deeper layers. The analysis of the pebble velocity field for gravity-dominated experiments in Chapter 3 presented a case that the motion of pebbles at the visible surface was a good representation of the bulk behavior despite the additional friction and ordered packing. This argument was based on the close quantitative match between the measured pebble recirculation rates and numerical estimates from the mean velocity data and zone interface boundaries. Similar comparisons are not possible for PREX 3.1 due to the inability to easily count pebbles injected into the inlet hoppers.

One measure to test the applicability of surface data for pebbles in the bulk is to see if there are any large discrepancies between the positions of pebbles in the second layer compared to those at the wall. Such behavior was not readily observed in the gravity-dominated systems, which supports the assumptions on the bulk versus surface behavior. During the initial testing, PREX 3.1 was loaded from the top with horizontally zoned layers of pebbles. After partial recirculation, it was readily apparent that there were significant discrepancies in the second layer of pebbles compared to those at the wall. Figure 4.20 shows clearly that a large number of light green pebbles have moved much faster behind the grey surface pebbles. This result calls into question the extrapolation of data from visible surfaces to the bulk behavior of a packed bed and merits additional future study.
From Figure 4.20, it is clear that some shearing is occurring between the first and second pebble layers. This is a common characteristic of Bagnold rheology in several classical granular flow problems such as Couette flow [29], [30] and flow down an inclined plane [32], but is not typical of the slow, dense regime where minimal shear is observed and local pebble contacts tend to be long lasting. However, early experiments by Bagnold [83] of granular Couette flow between two rotating cylinders were performed with pebbles in Newtonian fluids under near-neutral buoyancy, which are not so different from those in PREX 3.1. The best physical explanation is that, similar to Bagnold rheology, ordered packing at the wall allows for shearing to occur with less resistance than randomly packed beds. Reduced friction in PREX 3.1 due to lubrication is likely to make this distortion more important. One important point to make is that it is not clear that this distortion has a large impact on the motion of pebbles at the visible surface relative to each other compared to the pebbles in the bulk. Further study of this phenomenon is merited and could potentially provide insights on links between different granular flow regimes.

Figure 4.20: Image from PREX 3.1 initial recirculation that shows light green pebbles in the second layer that have sheared past grey pebbles at the visible wall surface.
4.3.2 Comparison to GRECO Results

GRECO results for the velocity field can be directly compared to the data collected for PREX 3.1. Figure 4.21 shows the GRECO results for the computed streamlines integrated from the average velocity field and the magnitude of the pebble velocity in the case with no fluid flow in the PREX 3.1 geometry. These results compare extremely well to the experimental data and capture the key qualitative phenomena of the granular flow in this system. Pebble hold up at both reflector surfaces is observed in the inlet region along with an acceleration of pebbles towards the outer reflector. Channeling is also observed above the defueling chute, extending up to the sharp corner at the top of the inside reflector wall. The smallest pebble velocities are observed along the outer reflector wall in the converging region.

![Figure 4.21: PREX 3.1 computed streamlines (left) and velocity magnitudes (right) from GRECO simulation with no fluid flow.](image)
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In addition to capturing the key qualitative phenomena in the no fluid flow case, the GRECO simulation results also compare well quantitatively to the mean velocity field from the experimental data. Figure 4.22 gives the error in the horizontal and vertical velocity components normalized by the magnitude of the experimental local velocity. Errors of less than 10% are generally observed throughout the geometry. Slightly larger discrepancies (up to 20%) exist for the vertical velocity component along the outside reflector and in the defueling chute. Along the outer reflector, GRECO over predicts the pebble velocity relative to the observed experimental data, while the velocity is under predicted in the defueling chute. These results may be due to shortcomings in the GRECO hybrid friction model or distortions in the motion of pebbles at the outer surface. The latter is suspected because pebbles at the outer reflector wall will be subject to much larger force loadings in the corner and therefore would be expected to move slower than other visible pebbles at the front wall of the test section. Removing pebbles from the center of the defueling chute may account for the slower motion of pebbles at the front visible surface as well.

Figure 4.22: GRECO simulation results relative error of the horizontal (left) and vertical (right) velocity components with no fluid flow. The velocity component differences are normalized by the magnitude of the experimental velocity.
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The most important test for the GRECO simulation tool is its ability to match the experimental results in PREX 3.1 with a variety of different fluid flow conditions. In this regard, the results are somewhat less accurate than the case for no fluid flow. Figure 4.23 shows the relative errors in the velocity magnitude for the three axial flow cases, where positive and negative values indicate larger and smaller GRECO velocity magnitudes, respectively, compared to the experimental results. Errors are generally within 15% of the experimental values, except along the outside reflector where much larger errors of up to 50% are observed in the constant area region and up to 35% in the converging region. These are significant errors that need to be understood in order to assess the potential use of GRECO for reactor core design purposes.

The larger errors along the outside reflector are likely due to a wide variety of factors. It was previously observed that this region had the largest errors also in the no fluid flow case, possibly due to pebble hold up in the corner relative to pebbles in the bulk. It is important to consider that this region also has the smallest pebble velocity magnitudes, which will increase the relative error. However, because the experimental results for the pebble motion in the axial fluid flow configurations showed small changes compared to the no flow case, these discrepancies are likely related to the drag forces in the GRECO model.

One other important factor to consider is the impact of the fluid coupling methodology in GRECO, which is based on using the local pressure gradient to estimate the drag forces on the pebbles. For the course pressure data from the manometer lines (tap spacing 8-10d) in PREX 3.1, significant pressure gradients were observed tangent to the reflector surfaces where coolant is removed by suction. These drag forces create body forces parallel to the surface, comparable in magnitude to the normal forces, which will move pebbles along the surface. This flow pattern may be beneficial in the prototypical reactor system because it would decrease the hold up of pebbles along the suction surfaces and decrease the variance in residence time. Further investigation of fluid flow near the wall is merited to determine how the pressure field behaves close to the suction surface to more thoroughly evaluate its impact on pebble flow.
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Figure 4.23: Relative error for GRECO simulations for PREX 3.1 with coupled drag forces for the axial flow configurations.

The GRECO pebble velocity results also show significant differences from the experimental data for the cross fluid flow configurations. Figure 4.24 shows the relative error in the pebble velocity magnitude for the CR100, CR200, and CR400 cases. Errors are, once again, typically within 15% of the experimental data, with much larger errors observed along the outer reflector surface in the constant area and converging regions. Pebble velocities along the outer reflector surface in the constant area region peak at 60% in all three cases, while those in the converging region increase from 20% in the CR100 to 50% in the CR200 configuration. The GRECO results also under predict the velocity along the inside reflector compared to the experimental results, though errors in this region are much smaller (<15%).
The combination of errors means that GRECO cannot reproduce the important experimental finding that a vertical velocity gradient exists in the constant area region where pebbles move faster along the inside reflector surface. Figure 4.25 shows the horizontal and vertical velocity profiles in the constant area region. Only a small degree of acceleration of pebbles along the inside reflector can be seen in the vertical velocity profiles, though the results with cross flow generate a more uniform, plug-like profile. The magnitudes of the horizontal velocities are small (<0.03 d), which matches the experimental finding that the cross fluid flow does not create a significant diffusion bias of pebbles in the constant area region.

An important insight into the possible source of these errors is gained from preliminary GRECO results from a previous version of the code that contained an unusual parallel coding bug. The coding error resulted in a failure to consistently update the positions of pebbles in thin horizontal interfaces between divided regions of the simulation domain. This created non-physical force distributions where the full loading of pebbles would not be transmitted through the entire bed to the reflector surfaces. In these cases, the GRECO simulation results accurately captured the acceleration of pebbles at the inner reflector and the hold up of pebble at the outer reflector that was observed in the experimental pebble velocity fields. This result suggests that the two-dimensional modeling assumption in GRECO may have limited applicability with coupled fluid flow due to the fact that the reduced degrees of freedom in the system will reduce the ability to capture the dynamics of large-scale shearing.

The origin of the errors for the cross flow configurations is difficult to determine. While the nature of force transmission in the two-dimensional bed appears to be important, it is also likely that the tangential fluid drag forces play a significant role in preventing pebbles from being held up along the outer reflector in the converging region and that pebbles in the corner may introduce distortions compared to those in the bulk. The large errors for the velocity field in the PREX 3.1 cross flow configurations suggest that additional development work is required to understand the limits of GRECO in these coupled systems.
Figure 4.24: Relative error for GRECO simulations for PREX 3.1 with coupled drag forces for the cross flow configurations.
Figure 4.25: GRECO simulation horizontal (left) and vertical (right) velocity profiles in PREX 3.1 in the constant area region for the no flow and cross flow configurations.

4.4 Radial Pebble Zoning and Inter-Mixing

The impact of coupled fluid drag forces on pebbles is of particular interest in terms of how it may impact the use of radial zoning of pebbles as a neutronics design option. Core designs with cross flow, such as the PB-FHR, must demonstrate that effects of the coolant flow field on the granular flow and on intermixing of pebbles between radial zones are well characterized and predictable. This section presents experimental results from PREX 3.1 that build an initial knowledge base on the impact of multi-dimensional porous media flow on pebble motion. These results are compared directly to GRECO simulation results in order to understand the capabilities and limitations of the code to reproduce key figures of merit from the experimental data.
4.4.1 Experimental Results

The most important figure of merit in core designs that use radial zoning is the average radial position of the zone interfaces as the pebbles circulate through the core. The location of the average zone interfaces in PREX 3.1 is inferred from the integrated streamlines through the test section from the end of the hopper divider plates due to the limitation that visible divider layers cannot be used to identify pebbles moving though the test section under different flow conditions. A second important figure of merit is the degree of pebble intermixing, or diffusion, across this zone interface. This behavior is assessed in PREX 3.1 based on the variance of pebble motion normal to the mean local velocity due to the same challenge of determining the time-history of the fluid forces on a pebble.

Figure 4.26 shows the shift in the position of the radial zone interface in PREX 3.1 for the three axial flow configurations relative to the no flow case in units of pebble diameters. These results show that small differences on the order of less than $0.5d$ for all cases in the active core region and reinforce the conclusion that one-dimensional drag forces do not significantly impact the time-averaged pebble motion relative to the buoyancy-dominated system.

Figure 4.27 shows the shift in the interface position for the three cross flow configurations. With strong horizontal body forces applied to the pebbles, we would expect to see some shift left towards the outer reflector as the pebbles circulate through the test section. This shift can be seen in Figure 4.27, however the amount of shift radial zone interface position is still on the order of less than $d$. It is also apparent from these profiles that the shift occurs primarily in the diverging region ($40d < y < 50d$) and remain fairly constant through the active core region. In the converging region, the shifts diminish as the pebbles are all forced into smaller cross-sectional areas close to the defueling chute. These results are consistent with the observations of the pebble velocity fields in Section 4.3.1, which showed small differences in the horizontal direction even in cases with significant cross flow.
Figure 4.26: Horizontal differences in radial zone interface position for PREX 3.1 axial flow configurations compared with the no flow case. Results for the grey-light green (left) and light-green-yellow (right) interfaces are normalized by $d$. 
Figure 4.27: Horizontal differences in radial zone interface position for PREX 3.1 cross flow configurations compared with the no flow case. Results for the grey-light green (left) and light green-yellow (right) interfaces are normalized by $d$. 
Figure 4.28: Standard deviation of the normal pebble velocity component normalized by the local pebble velocity magnitude in PREX 3.1 with no fluid flow.

In order to get a better understanding of the mixing phenomena for the granular flow in PREX 3.1, it is useful to evaluate the standard deviation for velocity components normal to the mean local velocity. This data provide a quantitative basis of how likely pebbles are to move off of their current streamline and is a key parameter to describe the mixing behavior in different regions of the core. Figure 4.28 shows this metric for the no flow case in PREX 3.1.

As with the velocity data discussed earlier, it is striking how similar the results in Figure 4.28 are to the gravity-dominated systems described in Chapter 3. The key qualitative findings from PREX 3.0 hold in both the diverging and converging regions. In the diverging region, we observe large amounts of pebble mixing near the outer reflector and less mixing along the inside reflector surface for $y > 40$. Slightly more mixing is observed in the constant area region of PREX 3.1, which may be the result of additional settling due to the lubrication in the wet system. Finally, in the converging region, we observe a large amount of mixing close to the inner reflector as pebbles are forced to the left above the defueling chute and very little mixing along the outer reflector surface.
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Figure 4.29 shows the standard deviation for the pebble velocity data normal to the mean local velocity in PREX 3.1 for the three cases of axial flow. The most striking observation from these results is, once again, how little change is seen for the increasing drag forces in the system. In Section 4.3.1 it was determined that the average velocity field was largely independent of the coupled drag forces. The result in Figure 4.29 reinforces the consistency in the granular dynamics for systems with one-dimensional coolant flow. The closely matched mixing behavior between the different flow configurations suggests that simple gravity-dominated experiments may be used as a basis for pebble-bed model validation and that analysis of the coupled granular and fluid dynamics is not required.

For the cross flow configurations of PREX 3.1, it is especially important to understand the mixing behavior because significant differences in the mean velocity fields were found in Section 4.3.1. Figure 4.30 shows the standard deviation for the velocity data normal to the mean local velocity for the three cross flow cases in PREX 3.1. These results demonstrate that mixing behavior in the largely consistent with the results for the no flow and axial flow configurations. Therefore, the cross flow does not lead to a significant increase in pebble diffusion towards the outer reflector as the pebbles circulate through the core. This is consistent with the previous result that the cross flow does not create a bias in the mean horizontal velocity, but with the additional conclusion that mixing behavior is also largely independent of the drag forces.

The experimental results for the position of the radial zone interfaces and pebble mixing behavior in PREX 3.1 complement the previous results for the mean velocity field. They show that many important figures of merit related to mixing phenomena are primarily independent of drag forces up to ten times the magnitude of the buoyancy force. These results imply that core geometry is the most important factor in determining the radial zone interface locations in the active core and that simplified gravity-dominated pebble-bed experiments can contribute a significant amount of useful knowledge and quantitative results on the behavior of the granular system.
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Figure 4.29: Standard deviation of the normal pebble velocity components in PREX 3.1 normalized by the local pebble velocity magnitude for axial fluid flow configurations.
Figure 4.30: Standard deviation of the normal pebble velocity components in PREX 3.1 normalized by the local pebble velocity magnitude for cross fluid flow configurations.

### 4.4.2 Comparison to GRECO Results

The position of radial zone interfaces from the experimental results based on the mean velocity streamlines can be directly compared to GRECO simulation results in each of the PREX 3.1 fluid flow configurations. Figure 4.31 and Figure 4.32 show the error for the GRECO results of both interfaces in the axial and cross fluid flow cases, respectively. In these figures, positive errors indicate that the GRECO interface is located to the right of the experimental position and vice versa. The errors in all fluid flow cases are comparable.

Figure 4.31a and Figure 4.32a show maximum errors of 1 to 2 \( d \) for the interface between the pebbles in the outer region (grey) and central region (light green) in the constant area region. These errors are introduced due to pebble motion in the
diverging region and do not increase in the constant area region where small horizontal velocity components are present. Smaller errors of less than 1 $d$ exist for the interface between the central region (light green) and inner region (yellow) can be seen in Figure 4.31b and Figure 4.32b.

The difference in errors at the two interfaces is a result of the behavior of the pebbles in the GRECO simulation at the wall in the inlet and diverging region. From the GRECO mean pebble velocity results, there is significantly more pebble hold up along the outer reflector wall in the inlet and diverging region of PREX 3.1 compared to the experimental data. Observations of the pebble motion from the GRECO simulations show that these pebbles moving slowly are rolling along the surface in a manner that accelerates pebbles in the second layer due to the kinetic friction at the point of contact. The kinetic friction between pebbles also draws pebbles towards the wall. This behavior results in the observed shift in the position of the grey-light green interface. The error is less for the light green-yellow interface because pebble hold up along the inside reflector in the inlet and diverging regions is closer to the measured velocities in the experiment.

![Figure 4.31: Horizontal errors in radial zone interface position for PREX 3.1 axial flow configurations. Results for the grey-light green (left) and light green-yellow (right) interfaces are normalized by $d$.](image)
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Figure 4.32: Horizontal errors in radial zone interface position for PREX 3.1 cross flow configurations. Results for the grey-light green (left) and light green-yellow (right) interfaces are normalized by $d$.

As it was for the experimental results in the preceding section, the variance in the normal pebble velocity component compared to the local mean velocity vector is a useful quantification of the likelihood that pebbles will move off of their current streamline path. Figure 4.33 shows the standard deviation of the normal velocity components in PREX 3.1 in the no fluid flow, AX400, and CR400 configurations. These results are normalized by the magnitude of the local velocity. In contrast to the experimental results (Figure 4.29 and Figure 4.30), large variances can be seen in the converging region, including along the outer reflector, as pebbles must move past one another in the two-dimensional GRECO geometry. These results match those from the gravity-dominated systems in Chapter 3 and show one of the key limits of the GRECO modeling assumptions due to the limitation that it cannot capture how pebbles move past one another in the prototypical three-dimensional system.
Figure 4.33: GRECO results for the standard deviation of the normal velocity components in PREX 3.1 normalized by the local velocity magnitude for no flow (left), AX400 (center), and CR400 (right) configurations.

4.5 Recirculation Rates and Residence Time Distributions

The statistical distribution of residence times is an important figure of merit for pebble bed reactors because it is one of the primary determinants, along with the neutron flux distribution, of fuel burnup. The previous sections of this chapter show that one-dimensional coolant flow has a small impact on mean pebble vertical velocities and therefore average residence times should also be mostly independent of the drag forces in these cases. In contrast, the axial flow configurations for PREX 3.1 showed significant changes in the vertical velocity profiles, especially for pebbles located along the inner reflector wall.
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The following discussion develops an improved physical understanding of how fluid drag forces impact pebble residence time distributions for both axial and cross flow configurations. This is achieved by using the statistics on the pebble velocity data for PREX 3.1 to evaluate the overall pebble recirculation rates, the residence time distributions of pebbles in the test section, the residence time distributions for each radial zone, and the variance of the tangential velocity data. Combined, these results provide a better understanding of the links between local pebble dynamics and important results for the system as a whole.

Finally, this section compares the experimental results from PREX 3.1 with GRECO simulation results under the different coupled flow configurations. The ability to validate GRECO and to evaluate its shortcomings will make it a more useful tool to study granular dynamics in the process of designing reactor cores.

4.5.1 Results Based on Experimental Velocity Field

The PREX 3.1 test section is located in a large tank of water and therefore has limited access to precisely control and document pebble injection into the hoppers at the bottom of the system. This makes it impractical to precisely track the number of pebbles circulated in each radial zone and to perform tests with a small number of tracked pebbles, which was possible in the gravity-dominated systems described in Chapter 3. The results presented in this section, therefore, are based on the statistical data collected for the local pebble velocity. The average values and statistical distributions can be used to develop a number of important insights on the impact of coupled fluid drag on the pebble recirculation.

Table 4.2 shows the overall recirculation rates of each pebble color in PREX 3.1, given as a percentage of all recirculated pebbles. These results are derived by integrating the vertical velocity profile at \( y = 24d \) over the width of each radial zone to get the flux of each pebble type. This method was used in Section 3.6.2 to demonstrate that the surface velocity data in PREX 3.0 represents a reasonable representation of the overall bulk behavior and the derived numerical results matched the experimental data within 2% for the inlet region. It is clear for the no flow case in PREX 3.1 that there is more balance between the center (light green) and outer (grey) zones due to the fact that PREX 3.1 is a quasi two-dimensional geometry that has no radial expansion. The recirculation rates for the inner (yellow) pebbles are found to be significantly less than the other zones. The mean velocity fields and visual observations suggest that this is due primarily to hold up along the inner reflector surfaces in the inlet and converging regions.

The results for the axial fluid flow configurations in Table 4.2 once again show that the uniform flow field has a small impact on the pebble dynamics. These flow configurations show no clear pattern due to increasing drag forces, which is also observed in the previous sections related to the pebble velocity field and mixing.
behavior. The small variations for the axial flow cases are likely due to errors from integrating the velocity profile over the small width of the inlet hopper region. These differences may also be the result of drag forces in the inlet region where fluid was injected into the bed and horizontal isobars and uniform axial flow may not yet be established.

<table>
<thead>
<tr>
<th></th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No Flow</strong></td>
<td>18.6 %</td>
<td>40.5 %</td>
<td>40.9 %</td>
</tr>
<tr>
<td><strong>AX100</strong></td>
<td>19.5 %</td>
<td>40.8 %</td>
<td>39.6 %</td>
</tr>
<tr>
<td>(+ 0.9 %)</td>
<td>(+ 0.4 %)</td>
<td>(- 1.3 %)</td>
<td></td>
</tr>
<tr>
<td><strong>AX200</strong></td>
<td>18.8 %</td>
<td>43.1 %</td>
<td>38.1 %</td>
</tr>
<tr>
<td>(+ 0.2 %)</td>
<td>(+ 2.6 %)</td>
<td>(- 2.8 %)</td>
<td></td>
</tr>
<tr>
<td><strong>AX400</strong></td>
<td>17.8 %</td>
<td>40.9 %</td>
<td>41.4 %</td>
</tr>
<tr>
<td>(- 0.8 %)</td>
<td>(+ 0.4 %)</td>
<td>(+ 0.4 %)</td>
<td></td>
</tr>
<tr>
<td><strong>CR100</strong></td>
<td>19.9 %</td>
<td>41.8 %</td>
<td>38.3 %</td>
</tr>
<tr>
<td>(+ 1.3 %)</td>
<td>(+ 1.4 %)</td>
<td>(- 2.7 %)</td>
<td></td>
</tr>
<tr>
<td><strong>CR200</strong></td>
<td>20.6 %</td>
<td>43.3 %</td>
<td>36.1 %</td>
</tr>
<tr>
<td>(+2.0 %)</td>
<td>(+ 2.8 %)</td>
<td>(- 4.8 %)</td>
<td></td>
</tr>
<tr>
<td><strong>CR400</strong></td>
<td>20.9 %</td>
<td>43.7 %</td>
<td>35.4 %</td>
</tr>
<tr>
<td>(+ 2.3 %)</td>
<td>(+ 3.2 %)</td>
<td>(- 5.5 %)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Pebble recirculation rates in PREX 3.1 for no flow, axial flow, and cross flow cases. Rates are based on the integration of the velocity profiles in the inlet region at $y = 24d$. The difference from the no fluid flow configuration is given in parentheses. Numerical results have an accuracy of about ±2% based on PREX 3.0 experimental results discussed in Chapter 3.

As expected from the mean pebble velocity results, the overall pebble recirculation rates for the cross flow configurations in PREX 3.1 in Table 4.2 show a more significant impact from the coupled drag forces. As the horizontal drag forces increase, we observe an increase in the recirculation rates for the yellow and light green pebbles and a decrease in that of the grey pebbles. The yellow pebbles have the greatest relative increase in recirculation rates, which is consistent with the observations in Section 4.3.1 that pebbles located near the inner reflector have larger vertical velocities as the drag forces reduce the hold up due to wall friction. There is
also an increase in the recirculation rate of light green pebbles as these pebbles also have larger vertical velocity components, though the relative change is less.

In balance with the increase in the other two zones, the grey pebble recirculation rates decrease significantly with the increasing magnitude of the cross flow drag forces. This decrease is likely due, in part, to additional pebble hold up at the suction faces of the outer reflector. It is important to note that while permanent pebble hold up at the suction faces is one proposed phenomena of concern for reactor designers and regulators, no pebbles at the outer reflector surface in PREX 3.1 were observed to be in a completely static state and all pebbles displayed some motion along the wall towards the defueling region. From the pressure field data shown earlier in this chapter, it is apparent that there is some pressure gradient tangential to the wall face, which will help to prevent permanent pebble hold up due to suction. The detailed behavior of pebble dynamics along surfaces with suction is beyond the scope of this project and would be worthwhile to investigate in future studies.

Figure 4.34: Computed isochrones for PREX 3.1 with no fluid flow based on the mean experimental local pebble velocity data. The isochrones are spaced by a constant plug displacement of 5d.
Isochrones are useful measure of pebble residence time distributions within the core as they show the spatial spread of pebbles that are inserted at the same time. For the gravity-dominated systems in Chapter 3 it was possible to visualize the isochrones in the system by loading thin layers of pebbles at regular intervals in PREX 2. For PREX 3.1, the isochrones shown in Figure 4.34 for the no flow configuration are based on the integration of pebble motion from the inlet region at $y = 25d$ based on the mean velocity field and are spaced with a constant displacement of $5d$ in the constant area region ($55d < y < 65d$). The results show that there is significant hold up of pebbles along the inside reflector in the inlet region, followed by a leveling of the isochrones in the diverging region. Plug flow is observed in the absence of fluid flow as the isochrones maintain their shape through the constant area region. Finally, a large amount of channeling is observable in the converging region as pebbles accelerate towards the defueling chute. These results closely match the general large-scale flow patterns observed in the gravity-dominated systems.

Based on the small numerical differences for the average velocity field in PREX 3.1 for each of the axial flow configurations, we should expect to see only small changes in the isochrones for these cases. Figure 4.35 shows the isochrones for each of the axial flow configurations and confirms that they remain largely unaffected by the changing drag forces on the pebbles. These results also show that the isochrones remain very consistent between the cases even in the regions of non-uniform cross-sectional area where some horizontal pressure gradients may occur at small length scales. The additional flow does not appear to reduce the amount of pebble hold up at the walls, which is an important phenomenon to characterize and is highly dependent on the reactor core geometric configuration.

Figure 4.36 shows the isochrones in PREX 3.1 for the three cross flow configurations. As expected from the changes in the mean velocity field, these results show a significant change as the magnitude of the horizontal drag forces increase. From the CR100 to the CR400 case, we observe a large acceleration of pebbles along the inside reflector and, to a lesser extent in the center region of the active core, relative to the pebbles located at the outer reflector wall. These results clearly show that plug flow does not occur with these flow conditions even though pebbles in the constant area region show no horizontal migration towards the outside reflector. Shearing must therefore be occurring as layers of pebbles move past each outer near the inner reflector which also leads to local packing rearrangement.
Figure 4.35: Computed isochrones for PREX 3.1 axial fluid flow configurations based on the mean experimental local pebble velocity data. The isochrones are spaced by a constant plug displacement of $5d$. 
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Figure 4.36: Computed isochrones for PREX 3.1 cross fluid flow configurations based on the mean experimental local pebble velocity data. The isochrones are spaced by a constant plug displacement of $5d$.

For complex core geometries, the standard deviation of pebble velocity data tangential to the local mean velocity field provides a useful measure of the impact stochastic uncertainty at the pebble scale on the overall residence time distributions. These pebble motion results inform how much variation should be expected in different regions of the core in the time that it takes for pebbles to move along their current averaged streamline. Figure 4.37 shows the variance of the tangential velocity data normalized by the magnitude of the local mean velocity in PREX 3.1 with no fluid flow. These results, once again, show the consistency in the behavior of the buoyancy and gravity-dominated systems when compared to the PREX 3.0 results in Chapter 3.
In the inlet region, there are very small stochastic variation in the pebble motion data and we would expect there to be small differences in the residence time along each of the streamlines as pebble approach the diverging region. Variations in pebble residence time through this region should therefore be dominated by the path length of the streamline or the normal stochastic motion of pebbles normal to the mean velocity.

Figure 4.37: Standard deviation of the tangential velocity data normalized by the local velocity magnitude in PREX 3.1 with no fluid flow.

The trends in the diverging region in Figure 4.37 are also consistent with the gravity-dominated system shown more variation for pebbles located near the inner reflector compared to those near the outer reflector. Visual observation during data collection suggest that the larger variances along the inner reflector could be related to the sharp corner in the wall geometry that is more difficult for pebbles to move past than the smooth surfaces in PREX 3.0. In this case, more free volume above the corner may be available at times for pebbles to move longer distances in some time steps.
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The constant area region in PREX 3.1 showed plug flow behavior, but had standard deviations on the order of 20% of the mean plug velocity. This is a significant increase in the tangential stochastic variation of <5% observed in PREX 3.0. One possible explanation may be the differential motion of pebbles at the transparent wall surface compared to pebbles in the bulk, previously discussed in Section 4.3.1. As pebbles in the second layer move past those at the wall, there will be changes in the local packing configurations that may restrict pebble motion along the wall. It is also important to note that due to the fact that velocities in the constant area region are low, small variations in the tangential motion can lead to large relative standard deviations.

Finally, Figure 4.37 shows that the largest tangential variances occur in the converging region, especially along the outer reflector wall. With the small normal variances discussed in Section 4.4.1, this result suggests that the stochastic variation in pebble motion is based on the phenomena of pebbles stalling along their streamlines as other pebbles move past them towards the defueling chute. These variations are also the primary explanation of the larger variations in the residence times of the grey pebbles near the outer reflector.

Figure 4.38 and Figure 4.39 show the standard deviation for the tangential velocity data in each of the axial and radial flow configurations, respectively. These results match the same general trends observed in the buoyancy-dominated case, but there are also a few important trends that can be observed. In all cases, the inlet region shows small variations while the largest standard deviations occur along the outer reflector surfaces in the converging region. The matched behavior for the axial flow cases should be expected, as this chapter presents a strong argument that the impact of fluid drag coupling is small for one-dimensional flow. However, it is a significant result that the cross flow cases also show these trends where there are noticeable changes in the vertical velocity across the width of the test section. This suggests that the variation in tangential pebble motion is primarily geometry dependent, even when the coupled drag forces impact the velocity field.

One additional trend that can be seen for both the axial and cross flow cases is the general decrease in the tangential variation in the constant area region at larger drag forces relative to the no flow configuration. The appearance of a larger relative decrease in the variance towards the inner reflector for the cross flow configurations in Figure 4.39 is due to the vertical velocity profile gradient while the magnitude of the standard deviation remains relatively constant. The physical explanation for this trend could be that the combination of drag forces and agitation due to the porous media flow creates a more compact bed and therefore it is more difficult for pebbles in the bulk to move past those observed at the surface. Additional future study of the distortions for pebble motion at transparent wall surfaces relative to the bulk would be extremely valuable to test this hypothesis.
Figure 4.38: Standard deviation of the tangential pebble velocity components in PREX 3.1 normalized by the local pebble velocity magnitude for axial flow configurations.
In order to evaluate the residence time distributions for each of the radial zones in PREX 3.1, a Monte Carlo method was used to tally the stochastic nature of pebble motion through the test section. This method was used in the previous analysis of gravity-dominated systems and is described in Section 3.6.2. The results shown here are tallied from 1,000 pebble paths in each radial zone. Initial pebble positions are assigned based on a velocity weighted cumulative probability distribution for each hopper width at a height $y = 25d$. Pebble steps are based on random sampling of the experimental velocity distributions for cells of dimension $2d$ until pebbles reach a height $y = 105d$. A vertical displacement of $0.05d$ in the constant area region was used as the time step between path positions.
Figure 4.40 shows the cumulative probability distribution results for the Monte Carlo simulation with no flow. The results show similar behavior compared to the gravity-dominated systems studied in Chapter 3. The light green pebbles in Zone 2 show both the shortest average residence time and the smallest variation. This is consistent with the fact that these pebbles follow relatively short streamlines through the central region of the test section and experience the largest amount of channeling in the converging region, accompanied by no direct wall contact between the inlet hoppers and the defueling chute. The yellow pebbles in Zone 2 show slightly longer residence times as they experience some hold up in the inlet and converging regions. The longest residence times and variance are observed in the grey pebbles in Zone 3. These pebbles experience a significant amount of hold up along the outer reflector wall in the converging region even though they reach the constant area region in about the same average time as the yellow pebbles. These results show generally well-behaved distributions that can be directly used in neutronic analysis of pebble burnup in different flux regions in the core.

The residence time distributions for the axial flow configurations show, as expected, very similar behavior to the no flow case. Figure 4.41 shows the cumulative probability distribution for the AX400 flow configuration with the largest drag forces. These results follow the same general trends as those with no flow and support the strong case that coupled analysis for one-dimensional coolant fluid flow is not required.

The most significant impact of fluid drag forces can be seen in the residence time distributions for the three cross flow configurations, shown in Figure 4.42. These results show a dramatic change in the residence time of the different zones as the horizontal drag forces increase relative to the buoyancy forces. There is a clear shift to shorter residence times for the yellow pebbles in Zone 1 at the higher flow cases so that they are the quickest to move through the core in the AX400 data set. In contrast, there is a modest positive shift in the residence time distributions for the light green pebbles and a dramatic shift for the grey pebbles. The grey pebbles are circulating much more slowly through the core in the higher flow conditions as a result of hold up along the suction faces on the outer reflector wall. These results align with the changes in the vertical velocity profiles for the cross flow cases observed across the constant area region in Section 4.3.1.

The results of the Monte Carlo sampling suggest that coupled drag forces will have a significant impact on pebble residence time distributions in cases of cross flow. Interestingly, because neutron fluences and pebble powers will be higher near the center of the core, one effect of cross flow may be to cause pebbles to emerge with more uniform burnup, because pebbles moving through low power regions will have longer residence times than pebbles moving through high power regions. The no flow and axial flow configurations appear to maintain the same local packing
constraints observed in gravity-dominated systems where plug flow is established. These results are likely a result of the reduction in wall friction effects along the injection faces of the inner reflector under cross flow that allows for pebbles to move past their neighbors. Significantly, this shearing occurs in a bed that remains fully packed with no observed fluidization of stable free surfaces forming near the injection face.

![Cumulative residence time probability distributions in PREX 3.1 for no fluid flow cases. Results from Monte Carlo method using experimental velocity data.](Image)

Figure 4.40: Cumulative residence time probability distributions in PREX 3.1 for no fluid flow cases. Results from Monte Carlo method using experimental velocity data.

![Cumulative residence time probability distributions in PREX 3.1 for AX400 axial flow case. Results from Monte Carlo method using experimental velocity data.](Image)

Figure 4.41: Cumulative residence time probability distributions in PREX 3.1 for AX400 axial flow case. Results from Monte Carlo method using experimental velocity data.
Figure 4.42: Cumulative residence time probability distributions in PREX 3.1 for cross flow cases. Results from Monte Carlo method using experimental velocity data.
4.5.2 Comparison to GRECO Results

The GRECO simulation results for overall pebble recirculation rates and Monte Carlo residence time distributions can be compared directly to the experimental data from PREX 3.1. Table 4.3 gives the recirculation fraction of each pebble type from the GRECO runs for the no fluid flow, axial flow, and cross flow configuration. The differences from the GRECO results and those based on the integration of the mean experimental velocity field in the inlet region are included for each fluid flow configuration in parentheses. The errors show a general trend for all of the cases. Relatively small differences (\(\sim +3\%\)) are seen for Zone 2 (light green). GRECO significantly over predicts the recirculation rate of Zone 1 (yellow) by about 5-7\% and under predicts the recirculation rate of Zone 3 (grey) by about 8-10\%. In contrast to the gravity-dominated systems in Chapter 3 where similar discrepancies were found, PREX 3.1 is a quasi-two dimensional system. Therefore radial expansions cannot be the reason behind the errors in PREX 3.1

The best explanation for the differences in the recirculation rates is that they are due to the errors in the radial zone interface positions and mixing from the GRECO simulations. The shift of the grey-light green interface by about 2 \(d\) to the left accounts for both the increase in the recirculation rate for Zone 2 and the decrease in the recirculation rate for Zone 3. The interface position between Zone 1 and Zone 2 cannot account for the increased recirculation rate of yellow pebbles because the errors were quite small (< 1 \(d\)). Instead, the observed increased recirculation rate is likely the result of increased mixing between the zones in the GRECO simulations, resulting in more Zone 1 pebbles moving through the test section. Direct statistics on pebble mixing is not available for PREX 3.1, but this explanation is consistent with the observed increase mixing at interfaces from the gravity-dominated experiments discussed in Section 3.5.
Table 4.3: GRECO simulation pebble recirculation rates in PREX 3.1 for no flow, axial flow, and cross flow cases. The values in parentheses are the difference from the numerical results based on the experimental velocity data in Table 4.2.

GRECO results for PREX 3.1 were also processed to generate the variance of the tangential velocity component relative to the average local velocity vector that can be compared to the experimental data. As with the results for the normal component variance, discussed in Section 4.4.2, these statistics are useful to see how well the stochastic variability in pebble dynamics is matched between the two-dimensional GRECO simulation and the three-dimensional packing in the experiment. Figure 4.43 shows the standard deviation from the GRECO simulation with no fluid flow case normalized by the magnitude of the local velocity. Compared the experimental results (Figure 4.37, above), the GRECO statistics show good agreement in the converging region with variances of about 30%, up to 45% for the slowest moving pebbles along the outer reflector. Smaller variations are observed from the GRECO results in the constant area region away from the reflector walls. Larger variation in pebble motion occurs compared to the experimental results in the inlet and diverging regions, especially along the outer reflector. The latter discrepancy is due, in part, to the smaller pebble velocities along the outer reflector in the GRECO simulation.
Figure 4.43: GRECO results for the standard deviation of the tangential velocity data normalized by the local velocity magnitude in PREX 3.1 with no fluid flow.

The most significant finding from the experimental results of the tangential variation was that the fluid drag coupling had a relatively small impact on the standard deviation in all of the flow configurations. Figure 4.44 and Figure 4.45 show the tangential standard deviation from the GRECO velocity data normalized by the magnitude of the local velocity for the axial and cross fluid flow cases. The same trends can be observed in both data sets. Small changes are seen in the variances for the inlet and diverging regions, while there is a slight increase in the standard deviation for the constant area region. The latter trend is the opposite of that from the experimental data. However, the magnitude of the change in the standard deviations are small in the constant area region.

The most dramatic changes in Figure 4.44 and Figure 4.45 occur in the converging regions where there is a large increase in the variability of pebble motion from the low to high flow cases in both the axial and cross fluid flow configurations. Combined with the large variances for the normal component, discussed in Section 4.4.1, it is clear that there is a very large amount of stochastic variability in pebble
motion for the converging region in the GRECO simulation results. This is due to the limited degrees of freedom in the two-dimensional system as pebbles must move around each other as the container area reduces. The increased in variability with the fluid drag forces is most likely tied to the larger accelerations that pebbles experience when they move into free volume under the increased body forces. The additional pressure of pebble loading in the converging region will be addressed further in Section 4.6.

Figure 4.44: GRECO results for the standard deviation of the tangential velocity components in PREX 3.1 normalized by the local velocity magnitude for axial flow configurations.
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Figure 4.45: GRECO results for the standard deviation of the tangential velocity components in PREX 3.1 normalized by the local velocity magnitude for axial flow configurations.

The statistics on the pebble velocity data from GRECO simulation results were used to generate pebble residence time distributions using the Monte Carlo method described in Section 3.6.2. The Monte Carlo simulation was performed using the same methodology as the experimental data in the previous section. Figure 4.46 shows the residence time distributions for PREX 3.1 in the case with no fluid flow. The GRECO simulation results match those from the experiment well in this case, which is consistent with the small errors in the local velocity data. From the GRECO results, Zone 3 pebbles along the outer reflector have the longest average residence time, followed by this in Zone 1 along the inner reflector. The pebbles in Zone 2 move through the core with the shortest mean residence time and the smallest
variance. These are the same trends observed from the Monte Carlo runs using the experimental velocity data.

The most important experimental finding using the Monte Carlo method to estimate pebble residence time distributions in PREX 3.1 was the increase in residence time for the pebbles in Zone 3 for the cross fluid flow configurations. This trend was not found in the GRECO-derived Monte Carlo results because the simulation velocity field did not match the increase in pebble vertical velocities along the inner reflector. Figure 4.47 shows the residence time distributions using the GRECO velocity data from the CR400 flow configuration. This result has similar residence times in Zone 3 compared to the no flow configuration, which is consistent with the discrepancy in the velocity field results. The residence time distributions for Zones 1 and 2 show some convergence for the case with the strongest horizontal fluid drag forces, but not the large shift in Zone 1 residence times seen in the results from the experimental velocity data.

The residence time distributions generated from the GRECO velocity data show that the predictive capability of the Monte Carlo results depends on the quality of the velocity statistics used for input. The errors in the GRECO residence time distribution results for PREX 3.1 are consistent with the errors for the local average pebble velocity field. It appears, however, that the distortions in the velocity component statistics are second order compared to the errors in the mean velocity field. This is based on the relatively good level of agreement between the GRECO and experimental residence time distributions for the no fluid flow configuration. This conclusion implies that the Monte Carlo method remains a promising strategy to quickly estimate pebble residence time distributions for reactor design purpose. Additional effort should be focused on developing confidence in the predictive capabilities of models to capture the mean pebble velocity field, which will also improve the accuracy of the residence time statistics.
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Figure 4.46: Cumulative residence time probability distributions in PREX 3.1 for no fluid flow cases. Results from Monte Carlo method using GRECO velocity data.

Figure 4.47: Cumulative residence time probability distributions in PREX 3.1 for CR400 flow case. Results from Monte Carlo method using GRECO velocity data.
4.6 Pebble Loading Forces

GRECO was also used to evaluate the statistics on the pebble force loadings for each of the PREX 3.1 fluid flow configurations. These results will be impacted by the two-dimensional modeling assumption because the constrained geometry will transmit forces between pebbles in very different packing configurations. Investigations by Landry et al. [77] on static pebble beds using two and three dimensional DEM simulations show that for the same container geometry, the two dimensional system has larger average wall pressures by a factor of 2 to 3. This result suggests that GRECO wall pressure data will be conservative compared to the three-dimensional DEM results.

Figure 4.48 shows the impact of the axial fluid flow configurations on the pebble normal force loading. These are based on the GRECO normal force magnitudes for pebble-pebble and pebble-wall contacts with viscoelastic damping described in Section 2.1.2. The results are normalized by the buoyancy body force \(m_{p} g^{eff}\). The cases of axial fluid flow show consistent force distributions for the three cases, but with different magnitudes. The pebble loading in the inlet and diverging regions are small, while there is an increase in pebble loading through the constant area and converging regions. The maximum loadings are approximately 300 \(m_{p} g^{eff}\), 450 \(m_{p} g^{eff}\) and 750 \(m_{p} g^{eff}\) for the AX100, AX200, and AX400 cases, respectively. The complex fluid flow field prevents any direct conclusions about the correlation between pebble forces and uniform drag forces, but Figure 4.48 shows that the effective body forces due to fluid drag forces can induce large changes in the magnitude of the contact forces.

The results for the pebble normal force loadings in the PREX 3.1 cross fluid flow configurations show the same general trends as the axial fluid flow cases. Figure 4.49 shows the mean normal forces for pebbles in the CR100, CR200, and CR400 cases with peak loadings of about 300 \(m_{p} g^{eff}\), 500 \(m_{p} g^{eff}\), and 1100 \(m_{p} g^{eff}\), respectively. It is worthwhile to note that while the maximum fluid drag forces occur in a diagonal band in the center of the test section where there is the largest fluid flux, the peak pebble loadings still occur in converging region where the forces are concentrated on the reflector surfaces. The larger force magnitudes are consistent with the larger fluid drag forces acting on the pebbles in these flow configurations.
Figure 4.48: GRECO results for the average pebble normal force loading for the axial flow configurations. The forces are normalized by the buoyancy force \(m_p g^{eff}\).
Figure 4.49: GRECO results for the average pebble normal force loading for the cross flow configurations. The forces are normalized by the buoyancy force ($m_p g_{\text{eff}}$).

It is important to note that while the average normal contract forces are large compared to the buoyancy force, PREX 3.1 is scaled with an effective buoyancy acceleration that is 20 times smaller than the acceleration under gravity. Compared to the forces for the gravity-dominated systems, the forces on the pebbles in the buoyant systems are very small in their actual magnitudes. Figure 4.50 shows the pebble normal force loading for PREX 3.1 with no fluid flow compared to the gravity-dominated PREX 3.0 simulation, described in Chapter 3. Although the wall geometry in these two systems is slightly different, both cases show maximum pebble forces on the order of 250 times greater than the effective gravity body force. This result supports the assertion that buoyant pebbles in the PB-FHR will be subject to greatly reduced force loading than pebbles in high-temperature gas systems loaded under gravity. Adding an additional reduction in the force magnitude due to the two
dimensional modeling assumption in GRECO suggests that the PB-FHR could be designed with very low pebble and reflector force loadings, which would reduce the amount of wear and erosion for the graphite structures.

Figure 4.50: GRECO results for the average pebble normal force loading in PREX 3.1 with no fluid flow (left) compared to the gravity-dominated PREX 3.0 system, which is described in Chapter 3 (right). The forces are normalized in both cases by the effective gravity body force \( m_p g^{\text{eff}} \).

4.7 Conclusions

This chapter covers experimental and GRECO simulation results for PREX 3.1, a scaled granular system based on the core design of a 16 MWth PB-FHR test reactor. In this experiment, the advection of a fluid through the bed creates drag forces on the pebbles and the coupled pebble and fluid dynamics must be considered. The results from PREX 3.1 are the first known to the author to track the motion of pebbles in slow dense granular flow in the presence of a multi-dimensional fluid flow field. The results presented in this chapter help to build confidence that the PB-FHR core design will perform as intended with a diverging core region, radial pebble zoning, and complex fluid-pebble force interactions. The experimental results for granular flow from PREX 3.1 were directly compared to GRECO simulation results in order to determine the applicability of the code and modeling assumptions for such complex systems.
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The mean pebble velocity field was analyzed for pebbles at the visible surface of PREX 3.1 with several fluid flow configurations and a reference case with no fluid flow. Three fluid flow configurations with near-uniform upward flow were studied with drag forces ranging from $0.5 \ m_p g^{eff}$ up to $3 \ m_p g^{eff}$. In addition, three cross fluid flow configurations were studied with drag forces ranging from $0.5 \ m_p g^{eff}$ up to $10 \ m_p g^{eff}$. These results cover the range of interest for the PB-FHR core where the fluid drag forces are on a comparable scale to the buoyancy forces. In all cases, the mean pebble velocity field showed smooth time-averaged behavior and the pebble bed remained densely packed. The ability to maintain dense pebble packing is vital for a core to stay within its design basis and therefore these results address one key viability issue for the annular PB-FHR core.

For the axial fluid flow configurations in PREX 3.1, the results for mean velocity field, radial zone interface position, pebble mixing, and residence time distributions showed minimal difference from the case with no fluid flow. This result is significant because it suggests that the behavior of dense granular flow with uniform body forces is mostly independent of the magnitude of those body forces. Therefore, reactor core designs with negligible fluid drag forces or one-dimensional coolant flow aligned with or against the gravity forces can be studied using conventional gravity-dominated scaled experiments. In order to accurately capture the pebble dynamics in the prototypical system, care must be taken to match the friction coefficients. This is especially important for the friction for pebble-wall contacts. The potential to run scaled dry experiments for these cases is a significant finding because these tests can be completed relatively quickly and at reduced cost early in the design process.

The PREX 3.1 results for the cross fluid flow configurations presented in this chapter show some interesting and surprising trends. The mean pebble velocity field showed that pebbles at inner radial positions had larger vertical velocities with increasing cooling injection rates along the inner reflector. This resulted in a decrease in the residence time distribution for these pebbles. In contrast, pebbles at outer radial positions in PREX 3.1 had smaller vertical velocities and longer residence times as the coolant flow rate increased. The shift in residence times for pebbles in different zones could be used by core designers as an additional degree of freedom to optimize fuel burn up as pebbles recirculated through the core.

Significantly, the changes in the vertical velocity profile observed for the cross fluid flow cases were not accompanied by an outward diffusion bias in the pebble motion compared to the case with no fluid flow. Radial pebble zone interface positions showed a shift on the order of one pebble diameter that develops in the diverging region, which showed the highest level of pebble mixing. The position of the radial zone interface remained constant at different elevations in the constant area region, even in the cases with the largest horizontal drag forces. The consistent
observed behavior of radial pebble zoning with coupled fluid and pebble dynamics in PREX 3.1 supports the viability of radial zoning in the annular PB-FHR core.

The comparison of GRECO simulation results to the PREX 3.1 experimental data presents a somewhat mixed picture on the accuracy of the code for coupled systems. The GRECO results for the axial fluid flow cases showed reasonable agreement with errors up to 20% some regions of the test section geometry. The cross flow cases, however, showed much larger errors of up to 50% along the outside reflector where the experimental velocities were much smaller than the GRECO results. The relative errors in this region are very large, in part, because these pebbles have the smallest pebble velocities. Regardless of the source of the distortion, the large errors suggest that GRECO results in systems with coupled fluid drag forces cannot be used with high confidence at this point and future development work on coupled pebble and fluid dynamics with multidimensional fluid flow fields is required.
Chapter 5

Conclusions

The central objective of this dissertation is to improve the fundamental understanding of granular dynamics in pebble bed reactor cores. This study achieves this goal through a combination of experimental and computational analysis. The primary case study presented here is the annular core of the PB-FHR, which includes a novel complex reflector geometry, radial pebble zoning, and multidimensional coolant flow. The PB-FHR core is a unique case study that is very different from previously studied classical problems in the granular flow literature. These design elements introduce important challenges for the design and licensing of this class of reactors. The results of this study address these basic viability questions and show that the granular flow in such complex pebble bed reactor cores can be quantified through the use of scaled experiments and simulations.

The goals of this dissertation were to (1) develop a new discrete element method (DEM) code GRECO that can be used to estimate pebble recirculation behavior in the core design process, (2) complete new experimental studies of granular flow in gravity-dominated systems with complex reflector geometries, (3) complete new experimental studies of coupled fluid and pebble dynamics in a scaled facilities, and (4) use the collected experimental data to validate the DEM code for its intended use. All of these goals have been achieved. The GRECO simulation tool is a simplified DEM code that uses a two-dimensional geometry assumption and a new friction model that can capture key static phenomena of interest at the reflector surfaces. The Pebble Recirculation Experiment (PREX) facilities were used to generate a large amount of data on the pebble velocity field, radial zone interfaces, and residence time distributions for core geometries with diverging regions and coupled fluid flow. The comparison of GRECO simulation results and those from the visible surfaces of the PREX experiments generally show quantitative agreement in the local velocity field of 10-15%. These errors are likely acceptable for early phases of the core design process before geometry-specific scaled experiments and large scale three-dimensional simulations can be completed.
The following sections of this concluding chapter include discussions of the key findings from this dissertation and their implications for the design and analysis of pebble bed reactor cores. Section 5.1 reviews the key experimental findings from PREX 2, 3.0, and 3.1 presented in this study and Section 5.2 covers the validation of GRECO based on the results of the PREX experiments. The discussion of the GRECO results are intended to inform future users of the code on its useful applications as well as important distortions due to its simplified two-dimensional geometry that limit its predictive capabilities. Finally, Section 5.3 describes some recommendations for future study, including gaps in experimental data and future improvements for GRECO and three-dimensional DEM simulation codes.

5.1 Key Experimental Findings

This dissertation presents both qualitative and quantitative results from three scaled granular flow experiments that contribute significantly to our general understanding of fuel pebble recirculation in pebble bed reactor cores. PREX 2 and 3.0 are conventional gravity-dominated systems that include diverging regions and radial pebble zoning. These facilities are angular wedges that capture some of the radial geometry of the PB-FHR core. PREX 3.1 is a quasi two-dimensional scaled facility that was used to produce the first known results for granular flow in the presence of coupled multidimensional fluid drag forces. The results from these facilities provide an important knowledge base that improves the viability of innovative pebble bed core designs.

The results from PREX 2 and 3.0 demonstrate that dense granular flow in diverging geometries show smooth time-averaged behavior and are a viable option for reactor core design. In both experimental facilities the diverging regions remained densely packed and the average pebble motion showed radial acceleration towards areas of free volume in the expanding geometry. For the PB-FHR, the reflectors in diverging core geometries provide additional shielding for structures at the bottom of the core and reduce the total primary coolant inventory, which can reduce the capital costs of the reactor.

Radial zones are maintained in the densely packed bed for both gravity-dominated PREX facilities before pebble circulate to the active fore region. The preservation of radial zoning from the inlet hoppers to the active core gives additional degrees of freedom for neutronics design. Pebbles at various burnup levels can be recirculated through the core in different radial zones, which can be used to optimize the pebble discharge burnup levels and spatial power distributions.

The amount of stochastic variation for the pebble motion in the diverging region is important for core design efforts because it establishes the degree of mixing that occurs at the interfaces for the radial zone in the active core region where plug flow is expected in systems without strong fluid drag coupling. The gravity-dominated
Chapter 5. Conclusions

PREX experiments demonstrate that the largest variances normal to the average velocity direction are observed in the diverging region. Therefore, pebbles in the diverging region show the greatest probabilities to move between different streamlines as they circulate through the core. Even with this greater level of stochastic variation, the degree of mixing for the radial zone interfaces was found to be consistent and quantifiable. Radial zone interfaces widths were found to be about four pebble diameters for the 95th percentile – i.e. there is less than a 5% probability of finding pebbles that have migrated more than two pebble diameters from the average interface position. The interface width for the 99th percentile is about six pebble diameters. The task is left for core neutronics analysts to determine the impact of this level of mixing at the radial zone interfaces.

The gravity-dominated PREX experiments also provide useful findings on the residence time distributions for the entire pebble bed and for distinct radial zones. The longest residence times and largest variances for annular core geometries will be expected for pebbles that are in contact with the outer reflector as they circulate through the system. These pebbles have the longest path length and the smallest velocities as they are significantly impacted by wall friction in the converging region. From a design perspective, this finding suggests that the use of inert graphite pebbles in the outer radial pebble region could be of great benefit to simplify the analysis of pebble residence times due to the fact that the stochastic uncertainty for fuel pebble residence times will be reduced. The inert graphite pebble layer would provide valuable neutron shielding for the outer reflector and could be easily replaced when they are subject to large amounts of irradiation damage.

The results presented in this dissertation from the PREX 3.1 facility provide many important insights into the impact of coupled fluid drag forces on granular flow and build on the knowledge base developed for complex container geometries in the gravity-dominated systems. PREX 3.1 was used to track pebble motion to generate data in configurations with no fluid flow, with vertical axial flow, and with cross flow that produced significant horizontal fluid drag forces on the pebbles. These cases covered the range of flow rates where the drag forces range from a small fraction up to about ten times larger than buoyancy forces. Significantly, the results from the PREX 3.1 case with no fluid flow matched all of the important general flow characteristics from the PREX 3.0 gravity-dominated system.

For the PREX 3.1 configurations with axial fluid flow, the most significant finding of this study is that these cases show very small changes from the no fluid flow results. This finding applies for the mean pebble velocity field, radial zone interface average position, and pebble residence time distributions. Slightly less stochastic variation was found with the increasing fluid drag forces, which may be a result of the drag forces developing a slightly more compact bed. The small changes in pebble flow for these axial flow configurations supports the important conclusion
that in cases of one-dimensional coolant flow or negligible drag forces, scaled “dry”
experiments can be used to assess pebble motion in specific core designs early in the
development process. These experiments will need to match the friction coefficients,
especially for pebble-wall contacts, of the prototypical system to improve their
predictive capabilities. This testing capability would allow for geometry-specific
pebble granular flow data to be used early in the design process at greatly reduced
cost.

Perhaps the most surprising experimental results of this dissertation are those for
the cross fluid flow configurations of PREX 3.1, which included both horizontal and
vertical fluid drag forces on the pebbles as they circulated through the test section. In
these cases, the injection of fluid along the surface of the inside reflector and removal
along the surface of the outside reflector did not generate a significant horizontal
diffusion bias for pebbles moving through the core. Some additional outward
motion was observed in the diverging region where most of the pebble mixing occurs,
but radial zones were maintained and near-zero horizontal pebble velocities were seen
in the constant area region. These results demonstrate the basic viability of radial
zoning in reactor core configurations with multi-dimensional fluid flow fields with
drag forces up to ten times larger than buoyancy forces. Larger reactors with higher
drag forces would require additional study in the future to confirm similar behavior.

While there were small differences in the horizontal pebble motion, the cross
fluid flow configurations of PREX 3.1 showed a dramatic impact on the vertical
velocity profiles of the granular flow. Fluid injection along the inside reflector face
was observed to greatly reduce the hold up along this wall surface due to friction.
Significant shearing was observed as pebbles along the inside reflector surface moved
past pebbles at outer positions. As noted above, this behavior was not accompanied
by a large change in the horizontal motion of the pebbles, as the radial zone
interfaces remained roughly constant in position. Instead, this behavior was found to
have a large impact on the residence time distributions for each of the radial zones.
As the fluid injection rate increase, the residence times of pebbles close to the inner
reflector decreased while those near the outer reflector increased. This basic behavior
could be used in core neutronics design to reduce the differences in pebble burnup
levels as the pass through high power regions near the center of the core.

Overall, the results from the coupled pebble and fluid dynamics in PREX 3.1
achieved the objective of demonstrating the viability of pebble recirculation in
complex annular core geometries with coupled fluid drag forces. In addition, the
detailed data on the motion of pebbles at the visible surface provide an important
initial basis to quantify the impact of fluid drag forces on pebble motion that has not
been studied in past experiments. The results also support the value of scaled
experiments using simulant fluids at early stages in the reactor design process, which
can provide important insights into key phenomena at greatly reduced cost.

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5.2 Validation of GRECO for Reactor Core Design

GRECO is a simplified two-dimensional DEM simulation tool that was successfully developed to support this dissertation. GRECO is intended to be useful in the design stages of reactor design where large-scale models of the complete packed bed are too computationally intensive. A new pebble-wall friction model was developed for GRECO based on a zero tangential displacement constraint that is physically analogous to surface roughness or rolling friction. The advantage of this friction model is that it can capture the phenomena of pebbles that are stagnant along a reflector surface with coolant suction and a non-zero fluid velocity normal to the face. GRECO was parallelized in order to improve its speed on multicore desktop computers. Useful preliminary results for systems up to about 10,000 pebbles can be generated on an eight-core desktop computer in less than a day, while longer studies of pebble residence time with multiple bed recirculations can be completed in about one week.

GRECO simulation results were compared directly to those of pebbles at the visible surfaces of the PREX facilities. The most important figures of merit that can be used to validate GRECO are the local pebble velocity fields, radial zone interface positions, and residence time distributions. The interface positions and residence time distributions are influenced by the stochastic nature of pebble motion that can be extracted from DEM simulation results with little difficulty. A Monte Carlo algorithm using the statistics of local pebble motion was developed to study residence times using both experimental and GRECO velocity data.

For the gravity-dominated systems, GRECO produced excellent qualitative and quantitative results compared to the experimental data. Local velocity errors in PREX 2 and 3.0 were found to be typically within 10-15% of the experimental values. The largest errors were found close to the defueling chute, which is one anticipated distortion of the two-dimensional GRECO model assumption. Conservation of pebble mass requires larger velocities in the narrow defueling chute for the angular wedge compared to a two-dimensional geometry. This distortion is not significant from an overall neutronics design perspective because it is a low power region. Larger relative errors were also observed along the outer reflector surface in the converging region due to the very small pebble velocity magnitudes in this region. Normalized by the pebble diameter, the errors for the GRECO velocity field were within 0.5 pebble diameters everywhere in the geometry except for the defueling chute.

One of the important distortions from the GRECO simulation results was the different stochastic behavior of pebbles in the constrained two-dimensional system. The GRECO velocity results did not reproduce some of the important experimental findings for variance in pebble motion normal and tangential to the average local velocity direction. These errors impacted the GRECO results for the average radial
zone interface positions. For PREX 2 and 3.0, GRECO estimates for the radial zone interface position were found to be within two pebble diameters of the observed positions. The experimental results suggest that conserving area from the inlet hoppers to the active core region is a more accurate method to estimate the position of the radial zone interfaces. Further, the additional stochastic variation in the GRECO velocity data produced less distinct pebble zone interfaces than were observed in the PREX facilities. Therefore, it is recommended that GRECO predictions for mixing at the interfaces can be a conservative upper bound when incorporated into neutronics analysis.

The discrepancies in the stochastic pebble motion data were found to be of second order importance for the residence times produced by the Monte Carlo simulation. The pebble residence time distributions based on the GRECO pebble velocity statistics showed excellent agreement with those generated from the experimental velocity data and therefore can be integrated into the neutronics design effort to evaluate its impact on fuel burnup levels. The uncertainties introduced by the GRECO model assumptions are believed to be less than those associated with the friction coefficients in the prototypical reactor environment.

While the GRECO results showed excellent agreement for the gravity-dominated systems, this study identified some shortcomings in the PREX 3.1 system with coupled fluid drag forces. A parametric study was completed to determine which wall friction coefficients should be used for the smooth and perforated surfaces on the inner and outer reflectors. With these tuned values, GRECO was able to match the pebble velocity in the no fluid flow case to within 10% of the observed experimental values.

The surface friction coefficients from the parametric study were then used to predict the pebble velocity results for the axial and cross fluid flow configurations. The GRECO results for the axial fluid flow cases showed reasonable agreement with errors up to 20% some regions of the test section geometry. The cross flow cases, however, showed much larger errors of up to 50% along the outside reflector where the experimental velocities were much smaller than the GRECO results. The relative errors in this region are very large, in part, because these pebbles have the smallest pebble velocities. Regardless of the source of the distortion, the large errors suggest that GRECO results in systems with coupled fluid drag forces cannot be used with high confidence at this point and future development work on coupled pebble and fluid dynamics with multidimensional fluid flow fields is required.

In summary, the validation basis developed for GRECO in this dissertation presents a somewhat mixed picture. On one side, GRECO produces excellent results compared to systems that have gravity-dominated flow and predominantly one-dimensional fluid flow. On the other side, GRECO shows some large deficiencies in the cross flow cases for PREX 3.1. The validation space for preliminary design
efforts using GRECO therefore covers a wide variety of pebble bed reactor core designs, but omits the annular core design of the PB-FHR with radial coolant flow. However, the experimental results of this dissertation provide a number of important insights into granular flow in these complex coupled systems that can be applied to future iterations of the PB-FHR core design and tested in scaled experimental facilities while additional development work continues to find better analysis methods.

5.3 Recommendations for Future Work

While this study has achieved its primary objective to improve our general understanding of granular dynamics in pebble bed reactor cores, there is additional future work that will be needed to aid the design and licensing efforts of this promising future technology. The results presented in this dissertation suggest several areas that merit attention in both experimental and computational analysis of granular flow. In addition, the full implications of the conclusions presented here will depend on an improved understanding of the consequences of granular flow phenomena from the perspective of core neutronics design.

One of the major challenges for the study of granular flow, including the experiments in this dissertation, is the limited ability to observe pebble motion in the bulk away from visible wall surfaces. The two major distortions from observing pebbles at the surface are the increase in ordered packing and the change in friction forces for the smooth surface compared to the dense randomly packed bed. The comparison of the overall pebble recirculation fractions based on direct mass measurement and integration of the surface velocity data from the gravity-dominated experiments in Chapter 3 suggest that the surface motion is a good approximation of the bulk behavior. However, observations from the surface of PREX 3.1 in Chapter 4 show that there is significant shearing between the first and second layers of pebbles near the visible surface and that this distortion may introduce large uncertainties around the validity of the collected pebble velocity data.

The most successful technique to study the bulk behavior of granular materials has been the use of matched index of refraction fluids [37], [81]. These studies allow for small sets of pebbles to be tracked, but cannot provide information for the entire packed bed that can be compared directly to high fidelity DEM simulations. These results also do not provide the critical pebble rotation information that is needed to validate the empirical friction models used in all DEM simulations. More recent studies have used fluids with matched index of refraction to study the porosity variation and packing behavior of granular materials [84]-[86], which do not provide much insight into the large-scale dynamics of these systems.

Preliminary work has been completed at U.C. Berkeley to fill this experimental gap with the construction of the X-Ray Pebble Recirculation Experiment (X-PREX), shown in Figure 5.1. This facility will use digital x-ray tomography to image a packed
Chapter 5. Conclusions

bed of plastic pebbles instrumented with a thin metal wire through the center. Imaging from multiple angles will produce data on the translational and rotational motion of all the pebbles in a packed bed. These experiments will provide data that will be directly comparable to the results of three-dimensional DEM simulations.

Figure 5.2 shows photographs and x-ray images from two steps in the gravity drainage of a quasi two-dimensional silo with 60° hopper angle from the X-PREX facility. The layer of white lines in the x-ray image shows the instrumented (yellow) pebbles that were initially set as a horizontal band at the top of the test section. These preliminary results show that the pebbles behind the visible surface are moving much faster down the inclined surfaces of the hopper compared to those at the wall. This confirms the need for additional experimental data that can accurately capture the behavior of pebbles recirculating in the bulk to validate analysis methods.

Figure 5.1: The X-Ray Pebble Recirculation Experiment (X-PREX) facility at U.C. Berkeley that will use digital x-ray tomography to track the translational and rotational motion of all pebbles in a densely packed bed.
The experimental program for the X-PREX facility includes pebble motion in a quasi two-dimensional silo with different hopper angles for converging and diverging geometries, a gravity dominated cylindrical test section, and a scaled cylindrical test section with coupled fluid flow. Separate studies such as pebble motion around vertical tubes (e.g. a control rod drive tube) and pebble displacement from control elements inserted directly into the packed bed are also under consideration for the future and would provide useful results for core design efforts.

The results of the GRECO analysis in this dissertation also suggest that future work is needed to improve the ability to simulate granular dynamics in core designs with multi-dimensional coolant flow configurations. The conservatively high forces and limited degrees of freedom in the two-dimensional geometry introduce large uncertainties in the predictive capability of GRECO for the design of these systems. Future parametric studies with GRECO should be completed to determine if different simulation parameters from the gravity or buoyancy-dominated cases might improve the accuracy for the coupled flow configurations.
Chapter 5. Conclusions

An additional opportunity for development of DEM simulation methods would be to take advantage of the annular core configuration of the PB-FHR to simulate granular dynamics in an angular wedge with periodic boundary conditions. This geometry would greatly reduce the total number of pebbles in the system, which would decrease the total computation time, and be able to capture the three-dimensional force distribution in the bed. This methodology combined with the validation data from the X-PREX facility could produce a powerful new analysis capability for future design and licensing efforts.

The final, and perhaps most important, area for future study based on the results of this dissertation will be to determine the consequences of granular flow phenomena on reactor performance and safety characteristics. This effort requires a comprehensive study of the impact of a broad range of granular phenomena on the core neutronics performance and is expected to be a required part of any future effort to license a pebble bed reactor design. The most important questions raised in this study surround implications of stochastic uncertainties of the average position and mixing characteristics of radial pebble zone interfaces and pebble residence times. Other issues related to porosity variations in the bed will also need to be studied and have been identified by the U.S. Nuclear Regulatory Commission as an area of interest for pebble bed cores. The results of these neutronics studies, combined with the improved understanding of granular dynamics in this dissertation, should serve to build confidence in the design process of pebble bed reactor cores that will improve their viability from both commercial development and regulatory perspectives.
References


References


References


[37] D. Bedenig, W. Rausch, and G. Schmidt, “Parameter studies concerning the flow behavior of a pebble bed with reference to the fuel element movement in


References


References


References


References


Appendix A

Drag Force on a Spherical Pebble

This appendix presents a derivation for the net fluid drag force on a spherical pebble in a linear pressure field with a constant pressure gradient. The assumption of a linear pressure gradient is based on the smooth pressure fields that are produced from porous media analysis and this method does not capture the effects of pore-scale fluid flow structures. The approximation for fluid drag forces formulated here is appropriate for static pebble beds or systems where the ratio of pebble to fluid velocity scales is small.

The net drag force on a sphere $F_{\text{drag}}$ can be determined by integrating the scalar pressure values over the inward surface normal, formulated as

$$ F_{\text{drag}} = -\int_{\partial \Omega} P(r,\theta,\phi) \hat{n} dS_R \quad (A.1) $$

where $P(r,\theta,\phi)$ is the position-dependent fluid pressure and $\hat{n}$ is the unit normal vector over the surface $dS_R$. The surface normal vector for a sphere is

$$ \hat{n} = \begin{bmatrix} \sin \theta \cos \phi \\ \sin \theta \sin \phi \\ \cos \theta \end{bmatrix} \quad (A.2) $$

and the area integral in spherical coordinates at constant radius $R$ is

$$ dS_R = R^2 \sin \theta d\theta d\phi \quad (A.3) $$

In this analysis the pressure field is assumed to be linear with a constant pressure gradient. The $x$-component of the pressure field with $P = 0$ at $r = 0$ can be expressed in the spherical coordinate bases by

$$ P(r,\theta,\phi) = \frac{\partial P}{\partial x} R \sin \theta \cos \phi \quad (A.4) $$

Substituting Equations (A.2) – (A.4) into Equation (A.1) and taking values at the pebble surface where $r = R$, gives the following set of integrals
Appendix B. PREX 2 Geometry

\[
\mathbf{F}_{\text{Drag}} = \begin{bmatrix}
\int_0^{2\pi} \int_0^\pi \left( -\frac{\partial P}{\partial x} R \sin \theta \cos \varphi \right) \left( \sin \theta \cos \varphi \right) R^2 \sin \theta \, d\theta 
& \int_0^{2\pi} \int_0^\pi \left( -\frac{\partial P}{\partial x} R \sin \theta \cos \varphi \right) \left( \sin \theta \sin \varphi \right) R^2 \sin \theta \, d\theta \\
\int_0^{2\pi} \int_0^\pi \left( -\frac{\partial P}{\partial x} R \sin \theta \cos \varphi \right) \left( \cos \theta \right) R^2 \sin \theta \, d\theta
\end{bmatrix}
\quad (A.5)
\]

The terms in Equation (A.5) can be evaluated analytically and reduce to find that

\[
\mathbf{F}_{\text{Drag}} = \begin{bmatrix}
-\frac{\partial P}{\partial x} R^3 \frac{4}{3} \\
0 \\
0
\end{bmatrix}
= \begin{bmatrix}
-\frac{\partial P}{\partial x} V_p \\
0 \\
0
\end{bmatrix}
\quad (A.6)
\]

where \( V_p \) is the pebble volume. The absence of \( y \) and \( z \) drag force components is consistent with the symmetry of the problem given a pressure drop only in the \( x \) direction.

The same process can be repeated to generate similar results for the drag forces due to linear pressure fields in the \( y \) and \( z \) directions. By linear combination, these results can be combined in the general formulation of the drag force where

\[
\mathbf{F}_{\text{Drag}} = \begin{bmatrix}
-\frac{\partial P}{\partial x} R^3 \frac{4}{3} \\
-\frac{\partial P}{\partial y} R^3 \frac{4}{3} \\
-\frac{\partial P}{\partial z} R^3 \frac{4}{3}
\end{bmatrix}
= -\frac{\partial P}{\partial x} V_p
\quad (A.7)
\]

The formulation in Equation (A.7) for the net drag force is particularly useful for coupling pebble and fluid dynamics because the fluid pressure field can be determined directly from experimental manometer levels or estimated using established porous media flow correlations.
Appendix B

PREX 2 Geometry

This appendix gives the as-built reflector geometry for PREX 2.0 used in the GRECO models for this dissertation. Table B.1 gives the coordinates for the inner and outer reflector surfaces and Table B.2 gives the coordinates of the inlet hopper divider plate. The coordinates used for the GRECO wall boundaries approximate the curved surfaces in PREX 2.0 as a series of short linear segments. Due to the fact that PREX 2.0 is an axisymmetric wedge, the positions are given in cylindrical \( r-z \) coordinates. The inlet hopper divider plates are indexed from the inner reflector to the outer reflector.
### Appendix B. PREX 2 Geometry

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Table B.1: GRECO input geometry coordinates (in m) for the inner and outer reflector surfaces in PREX 2.
### Appendix B. PREX 2 Geometry

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Table B.2: GRECO input geometry coordinates (in m) for the inlet hopper divider plates in PREX 3.0. The plates are indexed from the inner reflector to the outer reflector.
Appendix C

PREX 3.0 Geometry

This appendix gives the as-built reflector geometry for PREX 3.0 used in the GRECO models for this dissertation. Table C.1 gives the coordinates for the inner and outer reflector surfaces and Table C.2 gives the coordinates of the inlet hopper divider plate. The coordinates used for the GRECO wall boundaries approximate the curved surfaces in PREX 3.0 as a series of short linear segments. Due to the fact that PREX 3.0 is an axisymmetric wedge, the positions are given in cylindrical $r$-$z$ coordinates. The inlet hopper divider plates are indexed from the inner reflector to the outer reflector.
### Appendix C. PREX 3.0 Geometry

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Table C.1: GRECO input geometry coordinates (in m) for the inner and outer reflector surfaces in PREX 3.0.
### Appendix C. PREX 3.0 Geometry

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Table C.2: GRECO input geometry coordinates (in m) for the inlet hopper divider plates in PREX 3.0. The plates are indexed from the inner reflector to the outer reflector.
Appendix D

PREX 3.1 Geometry

This appendix gives the as-built reflector geometry for PREX 3.1 used in the GRECO models for this dissertation. Table D.1 gives the coordinates for the inner and outer reflector surfaces and Table D.2 gives the coordinates of the inlet hopper divider plate. Due to the fact that PREX 3.1 is a quasi two-dimensional geometry, the positions are given in Cartesian x-y coordinates. For reference purposes, the inner reflector is located on the right side of the test section and the outer reflector is located on the left side of the test section. The inlet hopper divider plates are indexed from the inner reflector to the outer reflector (i.e. right to left). These conventions are used to match the fluid flow orientation of the PB-FHR core.
### Appendix D. PREX 3.1 Geometry

#### Table D.1: GRECO input geometry coordinates (in m) for the inner and outer reflector surfaces in PREX 3.1.

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#### Table D.2: GRECO input geometry coordinates (in m) for the inlet hopper divider plates in PREX 3.1. The plates are indexed from the inner reflector to the outer reflector.

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Appendix E

PREX 3.1 Pressure Field Data

This appendix gives the pressure data collected from 44 manometer taps located at the rear surface of PREX 3.1. Figure E.1 shows the position of the manometer taps in relation to the reflector wall surfaces. The average spacing of the manometer taps is on the order of $8d$. Table E.1 gives the coordinates of the manometer tap positions. Table E.2 and Table E.3 include the pressure measurements (in Pa) derived from the elevation reading in the manometer lines. The gage pressure is set for manometer $ID = 44$, which is located at the top of the defueling chute and was the lowest recorded pressure for all fluid flow configurations.
Figure E.1: Positions of 44 manometer taps on the rear surface of PREX 3.
### Appendix E. PREX 3.1 Pressure Field Data

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Table E.1: Position of manometer taps on the rear surface of PREX 3.1.
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### Appendix E. PREX 3.1 Pressure Field Data

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Table E.2: PREX 3.1 manometer pressure data (in Pa) for axial flow cases AX100, AX200, and AX400. The gauge pressure is set by Manometer ID 44, which has the highest elevation at the top of the defueling chute.
### Appendix E. PREX 3.1 Pressure Field Data

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Table E.2 (continued): PREX 3.1 manometer pressure data (in Pa) for axial flow cases AX100, AX200, and AX400. The gauge pressure is set by Manometer ID 44, which has the highest elevation at the top of the defueling chute.
### Appendix E. PREX 3.1 Pressure Field Data

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Table E.3: PREX 3.1 manometer pressure data (in Pa) for cross fluid flow cases CR100, CR200, and CR400. The gauge pressure is set by Manometer ID 44, which has the highest elevation at the top of the defueling chute.
### Appendix E. PREX 3.1 Pressure Field Data

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Table E.3 (continued): PREX 3.1 manometer pressure data (in Pa) for cross fluid flow cases CR100, CR200, and CR400. The gauge pressure is set by Manometer ID 44, which has the highest elevation at the top of the defueling chute.