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HEAT STORAGE IN UNSATURATED SOILS

Initial Theoretical Analysis of Storage Design and Operational Methods

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ABSTRACT

Unsaturated soil beneath a greenhouse serves as a seasonal storage medium for low temperature heat obtained from solar collectors. The storage configuration consists of an array of vertical helical storage ducts. The computer code PT, developed at Lawrence Berkeley Laboratory, calculates the axisymmetric temperature distribution for a single duct system. Presently heat transfer in the soil is considered to be purely by conduction, but the effect of unsaturated flow will be included in future work. The results of these calculations will guide the construction of an optimal storage system currently being planned.
INTRODUCTION

Unsaturated soils are considered to be a potentially effective storage medium for low-temperature heat. While several publications have discussed general soil heat storage characteristics (Childs and Malstaff, 1982; Milly, 1982; Nir et al., 1981) and others have given preliminary experimental results (Sepaskay and Boersma, 1979; Nir and Amiel, 1981) the storage configurations which are technologically sound and economically viable for different climates and types of soil are still to be determined.

This investigation examines the use of unsaturated soil heat storage in a semi-arid climate. Heat is supplied as low temperature warm water (60-65°C) obtained from solar collectors and is transferred to the soil (initially 24°C) by pumping the water through vertical helical ducts. The heat is used for winter warming of a greenhouse which overlies the storage medium. At the first stage in the calculation heat transfer in the soil is considered to be purely by conduction with temperature- and saturation-independent soil thermal properties. Future calculations will include the effect of unsaturated flow in the storage medium on soil thermal properties and the effect of the addition of phase change material (PCM) in the storage medium.

The present paper presents analysis of a variety of scenarios involving the variation of supply and demand of energy, surface temperature, length and spacing of the storage ducts, and fluid flow rate through the ducts. The results of these calculations are intended to aid in the design of an optimal storage system currently being planned.

CONFIGURATION OF THE HEAT STORAGE SYSTEM

Geometry

The heat storage system consists of a square array of vertical helical storage ducts placed in unsaturated soil initially at 24°C. The top of the helix is 3 m below the ground surface and its length is 5-7 m. The helix has a diameter of 1 m and the spacing between adjacent ducts is 6.8-8 m. Between 0.5 and 1 m below the ground surface there is a shallow charge zone consisting of horizontal ducts. Figure 1 shows a schematic diagram of the storage system.
Energy Supply and Demand

During deep charge (summer) water warmed by the solar collectors (60-65°C) is pumped into the bottom of the vertical helix and cools as it flows to the top, depositing heat in the surrounding soil. During deep discharge (winter) cool water (20°C) is pumped into the top of the helix and warms as it flows to the bottom, extracting heat from the soil. Additionally during winter warm water is pumped through the horizontal ducts, to charge the shallow heat storage zone. Heat is transferred by diffusion to the ground surface, then into the greenhouse air. Due to seasonal climatic changes the energy supply and demand varies throughout the year; this is reflected in the variation of the duration of pumping each day.

Ground Surface Temperature

The ground surface temperature has an annual sinusoidal variation with a mean value of 24°C and an amplitude of ±4°C. The maximum temperature occurs July first, the minimum December 30. In addition, unusually warm or cold winters are considered in which short-term (5-10 days) changes of 5°C are added to or subtracted from the sinusoidal pattern. During exceptionally warm winter periods, deep charge occurs instead of deep discharge-shallow charge.

METHODOLOGY

The computer program PT (Bodvarsson, 1982), developed at Lawrence Berkeley Laboratory, was used to calculate the temperature distributions and heat flows for the proposed heat storage system.

Capabilities of PT

PT uses the integrated-finite-difference method to calculate heat and mass transfer in a water-saturated porous or fractured medium. It can be used for one-, two-, or three-dimensional complex geometry problems involving heterogeneous materials. Fluid density is temperature- and pressure-dependent and fluid viscosity is temperature-dependent. The vertical deformation of the rock matrix may be calculated using a one-dimensional consolidation theory. Rock thermal conductivity and intrinsic permeability may be temperature-dependent and anisotropic. The following physical effects may be included: (1) heat convection and conduction in the aquifer/aquitard system, (2) regional groundwater flow, (3) multiple heat and/or mass sources and sinks, (4) hydrologic or thermal barriers, (5) constant pressure or temperature boundaries, and (6) gravitational effects. PT was developed from the code CCC (Lippmann, et al., 1977) which has been used for many years for a variety of energy storage, geothermal and waste isolation problems. PT employs a much more efficient solution technique than CCC to solve the coupled mass and energy equations. Both PT and and CCC have been validated against a large number of analytical solutions and have been used to match the results of several field experiments (Bodvarsson, 1982; Buscheck et al. 1983).
Features Used for This Problem

For the first stage of this calculation no mass transfer is considered in the unsaturated soil, so heat transfer there is purely by conduction using uniform temperature- and saturation-independent thermal properties for a medium consisting of 60% soil, 20% water, and 20% air. In the duct heat transfer is dominated by convection, but conduction is also calculated.

PT is used to calculate the axisymmetric temperature distribution in the region around a single duct. The helix is approximated by a cylindrical conduit. For a duct in the interior of the array by symmetry an insulated boundary is assumed to be at a constant radial distance from the axis of the helix. The contribution of ducts on the edge of the array is studied by considering a duct surrounded by a radially infinite storage medium.

Energy Supply and Demand Calculation

For the calculation, the seasonally variable supply and demand of energy is averaged to a series of constant segments ranging from five days to one month in length. To determine the duration of pumping each day, the supply or demand of energy for each duct is equated to the energy deposited or extracted for each duct during N hours:

\[
E = C_w (T_{in} - T_{out}) Q N
\]

where

- \( E \) is the supply or demand of energy per duct (MJ/day).
- \( C_w \) is the specific heat of water (MJ/kg°C).
- \( T_{in} \) is the duct inlet temperature, 60 - 65°C during deep charge, 20°C during deep discharge.
- \( T_{out} \) is the duct outlet temperature (°C).
- \( Q \) is the fluid flowrate through the duct, positive during deep charge, negative during deep discharge (kg/hr).
- \( N \) is the duration of pumping each day (hr/day).

Thus \( N \) is given by

\[
N = \frac{E}{C_w (T_{in} - T_{out}) Q}
\]

\( E, C_w, T_{in}, \) and \( Q \) are given constants, while \( T_{out} \) is a variable calculated by PT. To calculate \( N \) for the first day of operation \( T_{out} \) is assumed to be 24°C. For subsequent days the final value of \( T_{out} \) for a given day is used to calculate \( N \) for the next day. Clearly as \( T_{out} \) approaches \( T_{in} \) \( N \) gets unrealistically large (＞24 hrs/day). This indicates that heat conduction through the soil cannot keep up with energy supply or demand, or that the storage medium is fully charged or fully depleted.
RESULTS

A variety of scenarios have been calculated by PT including variation in duct length and spacing, inlet temperature, and fluid flowrate through the duct, and different sequences of warm, average, or cool winters alternating with average summers. These results will be detailed in the poster session. One sequence is described below to illustrate the results being studied.

The sequence consists of 1) a pre-charge winter in which deep charge at a low rate occurs; 2) a summer in which further deep charge at a higher rate occurs; 3) a warm winter in which deep discharge-shallow charge alternates with deep charge. The duct length is 7 m, duct spacing is 6.8 m, inlet temperature is 60°C, and fluid flowrate through the duct is 193 kg/hr. The energy supply and demand is shown in Figure 2, along with the ground surface temperature. Figure 2 also shows some of the results calculated by PT: the number of hours per day of pumping, the outlet temperature, and the heat flux through the ground surface. Note that when the duct flowrate reverses, the outlet temperature is measured at a new location resulting in a discontinuous curve. Figure 3 shows a series of contour plots of the calculated temperature distribution in the storage medium during the sequence. Note that during deep charge fluid flows up the duct, while during deep discharge fluid flows down it.

![Figure 2. Boundary conditions and calculated results.](image1)

![Figure 3. Calculated temperature distributions.](image2)
CONCLUSION

Through the use of a numerical model, the thermal performance of an unsaturated soil heat storage system has been evaluated for a range of geometrical configurations and a variety of climatic conditions. The results of this study will aid the design of a storage system currently being planned. This paper represents the first phase of a coupled field and theoretical study of the unsaturated soil heat storage concept. Future plans involve calculating the coupled fluid flow in the unsaturated soil and the incorporation of phase change material in the storage system.

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REFERENCES


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