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STEADY FLOW MODEL USER'S GUIDE

Christine Doughty, Goran Hellstrom, Chin Fu Tsang, and Johan Claesson

*Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

+Department of Mathematical Physics
Lund Institute of Technology
Lund, Sweden

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Introduction

Sophisticated numerical models that solve the coupled mass and energy transport equations for nonisothermal fluid flow in a porous medium have been successfully used to match analytical results (Tsang et al., 1977) as well as field data (Tsang, Buscheck and Doughty, 1981; Papadopulos and Larson, 1978) for aquifer thermal energy storage (ATES) systems. Generally these models are expensive and time-consuming to use. Typically an ATES study is concerned primarily with energy balances and heat flows. Often the fluid flow field is simple and reaches steady-state rapidly. As an alternative for this sort of ATES problem the Steady Flow Model (SFM), a simplified but fast numerical model, has been developed (Hellstrom and Claesson, 1978; Doughty et al., 1982). Rather than solving the mass transport equation to obtain a fluid flow field that varies with time, a steady purely radial flow field is prescribed in the aquifer, and incorporated into the heat transport equation which is then solved numerically. Gravity is not considered, thus buoyancy flow (natural convection) is neglected. This is a reasonable assumption for ATES systems with low-permeability or vertically stratified aquifers, small temperature difference between injected and native waters, or short cycle duration.

While the radial flow assumption limits the range of ATES systems that can be studied using the SFM, it greatly simplifies use of this code. The preparation of input is quite simple compared to that for a sophisticated coupled mass and energy model, and the cost of running the SFM is far cheaper as well. Furthermore, the simple flow field allows use of a special calculational mesh that eliminates the numerical dispersion usually associated with the numerical solution of convection problems.

An application of the SFM is described in Doughty et al. (1982). The present report defines the problem considered, briefly outlines the algorithm used to solve it, then describes the input and output for the SFM.
Problem Description

The ATES system considered (Figure 1) consists of a single vertical injection/production well that fully penetrates a laterally infinite, horizontal aquifer of uniform thickness, \( H \). Results are also applicable for a multiple-well system where well spacing is large enough so that the thermal behavior of individual wells is not significantly affected by neighboring wells. The requirement for non-interference is discussed in Tsang et al. (1978). Under the single-well idealization, there is radial symmetry with respect to the well. Furthermore, the aquifer is assumed to be homogeneous with bulk thermal conductivity \( \lambda_a \), and bulk heat capacity per unit volume (solid plus fluid) \( C_a \). It is bounded above and below by impermeable confining layers which may be of arbitrary thickness. The caprock and bedrock may be heterogeneous with spatially variable bulk thermal conductivity \( \lambda_c \) and heat capacity per unit volume \( C_c \). The heat capacity per unit volume of water is \( C_w \). All material properties are assumed to be independent of time and temperature. Initially the entire system may be at uniform temperature, have a linear vertical temperature gradient, or have an arbitrary temperature distribution. Above the caprock the boundary temperature \( T_{z1} \) may be constant or vary sinusoidally. Below the bedrock the temperature \( T_{z2} \) is constant. Either cap or bedrock or both may be very thick so that the boundary temperature is never felt. Either or both may also be absent entirely, leaving boundary temperature directly adjacent to the aquifer.

The SFM considers an ATES cycle composed of injection, storage, production, and rest periods of duration \( t_i \), \( t_s \), \( t_p \), and \( t_r \), respectively. The injection and production periods must be of equal duration \( (t_i = t_p) \), but the storage and rest periods may be of different duration, or absent. The temperature of
Figure 1. Schematic drawing of the ATES System modeled by the Steady Flow Model. For a symmetric problem only the top half of the system need be modeled, with the dashed line representing an insulated boundary.
the injected water is constant, \( T_i \). The same constant flow rate, \( Q \), is used during injection and production periods, so the injected and produced volumes are equal. In the aquifer fluid flow is purely radial.

At the end of the injection period, the volume of injected water is \( V_w = Q t_i \). It is convenient to define another volume, the thermal volume \( V = (C_w/C_a) V_w \). The thermal volume is the cylindrical volume in the aquifer (solid plus fluid) which would have, at constant temperature \( T_i \), a thermal energy equal to the total heat energy of the injected fluid. The thermal volume may be written as \( V = \pi R^2 H \), thus defining \( R \), the thermal radius:

\[
R = \sqrt{\frac{V}{\pi H}} = \sqrt{\frac{C_w Q t_i}{C_a \pi H}} \quad (1)
\]

An essential result of the SFM calculation is the temperature, \( T_p \), of the water extracted from the aquifer during the production period. The time-average of \( T_p \) is proportional to the energy recovery factor, \( \epsilon \), which is defined as the ratio of the produced to injected energy when equal volumes of water have been injected into and produced from the aquifer. The energy content of the water is defined relative to a reference temperature, \( T_0 \). The recovery factor is given by:

\[
\epsilon = \frac{\int_{t_i}^{t_i + t_s + t_p} (C_w T_p - C_w T_0) Q \, dt}{\int_{0}^{t_i} (C_w T_i - C_w T_0) Q \, dt} \quad (2)
\]

This expression can be written more simply as:

\[
\epsilon = \frac{T_p - T_0}{T_i - T_0} \quad (3)
\]

where \( T_p \) denotes the average temperature of the water extracted during the production period.
Numerical Formulation

In general, when numerically solving problems involving convection, a mesh-dependent numerical dispersion is introduced, which causes thermal front smearing. In many cases the numerical dispersion completely overshadows the physical dispersion caused by conduction. The SFM avoids this effect by solving the energy equation explicitly, using a calculational mesh specifically designed for the problem being solved.

The mesh is constructed so that all the cells of a horizontal row have equal volume. Due to cylindrical symmetry, the radial dimension of the cells decreases as their radial distance to the axis of the system increases, as shown in Figure 2. There are \( M_r \) cells between \( r = 0 \) and \( r = R \), the thermal radius defined in (1). The radial dimension of an arbitrary cell, say the \( m \)th cell is \( R_{m+1} - R_m \), where \( R_m = \sqrt{(m-1)/M_r} R \). The volume of the \( m \)th cell, which is proportional to \( R_{m+1}^2 - R_m^2 \), is independent of \( m \), thus all cells in a given row have equal volume. During the injection period, whenever time \( t \) is equal to \( t_i/M_r \), \( 2t_i/M_r \), \( 3t_i/M_r \), \( \ldots \), \( t_i \), the temperature distribution in the aquifer is translated horizontally one cell away from the well \( (r = 0) \) and the injection temperature, \( T_i \), is assigned to the first cell in each row. This translation every timestep, \( t_i/M_r \), simulates a constant volumetric fluid flow rate at the well:

\[
Q = \frac{C_{a m} R^2 H}{C_{w i}}
\]

and a horizontal Darcy velocity:

\[
v(r) = \frac{Q}{2\pi H r}
\]

in the aquifer at radius \( r \). When \( t = t_i \), the temperature field has been translated \( M_r \) times and the thermal front coincides with the thermal radius, \( R \), if the vertical heat losses are not too large.
Figure 2. Scale drawing of a typical SFM mesh. The cell numbering scheme is illustrated by labeling selected (column, row) pairs.
Heat transfer by convection is accounted for by translation of the aquifer temperature field every time step \( \Delta t/M_r \). Heat conduction is described by the ordinary heat equation:

\[
C \frac{\delta T}{\delta t} = \nabla \cdot (\lambda \nabla T) = - \nabla \cdot \mathbf{q}
\]

where \( \mathbf{q} \) is heat flow per unit area. The integral form of equation 6 is solved numerically for each mesh cell during every timestep \( \Delta t \). For cell \((m,n)\), i.e., the cell in the \(m\)th column, and \(n\)th row:

\[
\int \nabla \cdot \mathbf{q} \, dV = \int \nabla \cdot \mathbf{q} \, dV = \int \mathbf{q} \cdot \hat{n} \, dA
\]

where the right-hand side describes the heat transfer to all neighboring cells. Using the explicit-finite-difference approximation equation 7 becomes:

\[
C_{m,n} \frac{T_{m,n}(t + \Delta t) - T_{m,n}(t)}{\Delta t} = q_r^{m,n} 2\pi R_m (z_{n+1} - z_n) - q_r^{m+1,n} 2\pi R_{m+1} (z_{n+1} - z_n)
\]

\[
+ q_z^{m,n} \pi (R_{m+1}^2 - R_m^2) - q_z^{m+1,n} \pi (R_{m+1}^2 - R_m^2)
\]

where:

\[
q_r^{m,n} = \frac{T_{m-1,n} - T_{m,n}}{R_m - R_{m-1}} + \frac{T_{m+1,n} - T_{m,n}}{R_m - R_{m+1}}
\]

and

\[
q_z^{m,n} = \frac{T_{m,n-1} - T_{m,n}}{z_n - z_{n-1}} + \frac{T_{m,n+1} - T_{m,n}}{z_{n+1} - z_n}
\]
In the above equations, $C_{m,n}$, $T_{m,n}$, $\lambda_{m,n}$ and $q_{m,n}$ represent the average value of $C$, $T$, $\lambda$, and $q$, respectively, over the $(m,n)$th cell which has volume $V_{m,n}$. The time step $\Delta t$ is chosen so as to ensure numerical stability of the solution.

During the storage and rest periods no translation of the temperature field occurs and heat transfer is purely by conduction. During the production period, convection is treated as during the injection period. The length of the production period, $t_p$, is given as input ($t_p = t_i$). Every time interval $t_p/M_r$ the temperature distribution is shifted one cell toward the well, and the temperatures from the first cell in each row are averaged volumetrically to give the production temperature. Note that during each period the flow field is steady, either radially inward or outward, or zero; all transients are ignored.

Figure 3 shows the temperature distributions at various times during the first cycle as generated by the SFM with and without conduction to illustrate the superposition of conduction and convection. The SFM may be used for two types of problems: those with a horizontal plane of symmetry through the middle of the aquifer and those without. For "symmetric" problems, only the top half of the aquifer and upper confining layer need be modeled. The plane of symmetry is treated as an insulated boundary, so vertical heat flow at the lower edge of the bottom row of elements is zero. For asymmetric problems, for example those with a temperature gradient with depth, a seasonally variable surface boundary temperature, or cap and bed rocks with different properties, the vertical heat flow at the lower edge of the bottom row of elements is calculated using a constant boundary temperature, $T_{z2}$.

A typical mesh consists of about 1000 cells, with values of $M_r$ ranging from 10 to 40. The computer time required for a typical annual cycle is about 15 seconds on a CDC 7600 computer. A listing of the code is given in Appendix 3.
TEMPERATURE FIELDS
SIMULATED BY STEADY FLOW MODEL

$t = 30$ days
During injection

With no conduction

With conduction
and convection

$t = 90$ days
End of injection

$t = 180$ days
End of storage

$t = 270$ days
End of production

$\epsilon = 1$

$\epsilon < 1$

Figure 3. Dimensionless temperature distributions at various times during an injection-storage-production cycle, with and without conduction.
INPUT

All input is read in LIST DIRECTED READ statements (free format). Multiple variables read in a single READ statement may be on the same line separated by commas, or on successive lines. Each READ statement is numbered below. A sample input deck is shown in Appendix 1.

1. NRUN       Number of runs
   NUT - flag = 0  do not print initial T, ë, C distributions
             = 1  do print initial T, ë, C distributions
   NPR - flag = 0  printout is 132 columns wide
             = 1  printout is 80 columns wide

Mesh definition - items 2-6 -- see Figure 2

2. M       First dimension of mesh (number of columns)
   N       Second dimension of mesh (number of rows)

3. NN11    First aquifer row
   NN2    Last aquifer row

Note: for "symmetric" problems NN2=N

4. RLIM (m)  Thermal radius (R, defined in equation 1)
   MRLIM  Number of mesh columns between r=0 and RLIM
           (in text called Mr)

Vertical mesh spacing - items 5-6 -- see Figure 4

5. ZTOP    Z-coordinate of top of mesh (m)
   NANT  Total number of groups of equal-thickness rows

6. (NA(I),A(I),I = 1,NANT)
   NA(I) = Number of rows in Ith group
   A(I) = Thickness of each row in Ith group of rows (m)

   NANT
   Note: \[ \sum_{I=1}^{NANT} NA(I) = N \]
-11-

<table>
<thead>
<tr>
<th>Vertical Mesh Spacing (not to scale)</th>
<th>Input</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of mesh</td>
<td>I</td>
<td>NA(I)</td>
</tr>
<tr>
<td>100 m</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Caprock</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Bottom of mesh, insulated boundary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>because NN2=N</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Sample vertical mesh spacing for a "symmetric" problem with NANT = 8.
Initial Conditions and Material Properties - items 7-9

7. VALUE Default initial temperature $T$ (°C), assigned to all cells except those described in item 9.

8. ITYP - flag for additional assignment of $T$ values
   
   $\begin{align*}
   = 1 & \text{ all cells have } T \text{ equal to VALUE, no additional assignments} \\
   = 11 & \text{ all cells have } T \text{ equal to VALUE, except for certain cells, described in item 9.} \\
   = 13 & \text{ all cells have } T \text{ equal to VALUE, except for certain blocks of cells, described in item 9.}
   \end{align*}$

   If ITYP = 1 skip item 9

   If ITYP = 11
   9.1 NUMEX Number of cells with different value of $T$
   9.2 $(I(K), J(K), VALUE(K), K=1, NUMEX)$
      
      $I(K)$ - column of $K$th cell
      $J(K)$ - row of $K$th cell
      VALUE($K$) - value of $T$ for $K$th cell

   If ITYP = 13
   9.1 IBLOCK Number of blocks of cells with different value of $T$
   9.2 $(IMIN(K), IMAX(K), JMIN(K), JMAX(K), VALUE(K), K=1, IBLOCK)$
      
      IMIN($K$), IMAX($K$), JMIN($K$), JMAX($K$) - definition of $K$th block, $I$ identifies columns, $J$ identifies rows.
      VALUE($K$) - value of $T$ for $K$th block

Repeat items 7 through 9, substituting thermal conductivity RLAM (W/mK) (in text called $\lambda$) for initial temperature $T$.

Repeat items 7 through 9, substituting volumetric heat capacity $C$ (J/m$^3$K) for initial temperature $T$. Note that all aquifer cells must have $C$ equal to CO value read in item 12.
Linear initial temperature variation - items 10-11

10. ILIN - flag = 0  No linear initial temperature variation
   = 1  Linear initial temperature variation defined in 11
        (overrides T values read in INDATA; used as radial
         outer boundary condition)

11. Read if ILIN=1 only
    TSURF (°C)  Temperature at top of linear variation
    TDEPTH (°C) Temperature at bottom of linear variation
    DEPTH (m)  Depth over which variation occurs

12. CA (J/m^3 K)  Aquifer volumetric heat capacity (in text called C_a)
    RAACAW (J/m^3 K)  Water volumetric heat capacity (in text called C_w)
    TBOUND (°C)  Temperature of water at lower boundary of mesh (In
                 text called T_z2). If ILIN = 0, TBOUND is radial
                 outer boundary condition also.
    TREF (°C)  Reference temperature used in energy calculations
                (called T_0 in text)

13. Upper boundary temperature
    T1 (°C)  Average value
    T2 (°C)  Amplitude of sinusoidal variation
    TIME1(s)  Phase
    TAU (s)  Period of variation (default 31536000 s = 365 days)

Note:  \( T_Z1 = T1 + T2 \sin \left( \frac{2\pi}{T1} (t - TIME1)/TAU \right) \)
For constant upper boundary temperature, set T2 = 0

14. NQM  Number of periods to simulate
    IPER  Number of periods per cycle
15. **PERIOD (s)**
   Length of period \( t_i = t_p = \text{PERIOD}, t_s = L \cdot \text{PERIOD}, t_r = K \cdot \text{PERIOD} \), where \( L \) and \( K \) are integers or zero.

16. **(VT(I),I=1,IPER)**
   Flag \( VT(I) \) describes \( I \)th period as:
   
   \[
   \begin{align*}
   &1. \quad \text{injection} \\
   &0. \quad \text{rest or storage} \\
   &-1. \quad \text{production}
   \end{align*}
   \]

17. **(TIN(I),I=1,IPER)**
   Injection temperature \((^\circ C)\), used for \( VT(I)=1. \), otherwise ignored (in text called \( T_i \)).

18. **TA (s)**
   Time interval between small printouts

**TB (s)**
   Time interval between big printouts

**TIMEM (s)**
   Maximum simulation time, overrides NQM if \( \text{NQM} \cdot \text{PERIOD} > \text{TIMEM} \)

19. **TIME (s)**
   Starting time

   Items 2 through 19 are repeated \( \text{NRUN} \) times.

---

**OUTPUT**

Two output files are written by the SFM, STEADY.OUT and STEADY.BIN.

An example of STEADY.OUT is shown in Appendix 2. It contains the following items:

1. **Input data**

   1.1 **NCHECK** = 1  indicates that the mesh has been generated.

   2  indicates that mass flow rates have been calculated.

   3  indicates that midpoint coordinates of each mesh cell have been calculated.

   1.2 Input parameters are listed. If \( \text{NUT}=1 \), initial temperature, thermal conductivity, and heat capacity distributions are printed.
2. Output data

2.1. Timestep information -- identifies the mesh cell which controls the conduction timestep.

2.2. At the start of each period the number of the period, NQ, the conduction timestep, DT, the number of conduction timesteps per convection timestep, ISTAB, and the fluid flow rate, FLOW, are given. For storage and rest periods, with no convection, ISTAB is not used.

2.3. At each small-printout interval the inlet or outlet temperature, and energy input and output so far are given.

2.4. At each big-printout interval the temperature field is printed as well.

2.5. At the end of each cycle an energy balance is printed, including the energy stored (energy in + energy out), and the recovery ratio (ε) for that cycle.

STEADY.BIN is a binary file containing temperature fields suitable for input to a plotting program. The following information is included, written in free format:

1. M, N, (RM(I), I = 1, M), (ZM(I), I = 1, N)
   The number of columns and rows in the mesh, and the radial and depth coordinates at which temperature is calculated.

   At each big-printout interval:

2. TIME, ((T(II, JJ), II = 1, M), JJ = 1, N)
   The current time and temperature field.
Nomenclature

A  surface area of the \((m,n)\)th mesh cell \(\left( \text{m}^2 \right)\)

C  volumetric heat capacity \(\left( \frac{\text{J}}{\text{m}^3 \text{K}} \right)\)

\[ C_a = \phi C_w + (1-\phi)C_r \]  aquifer volumetric heat capacity \(\left( \frac{\text{J}}{\text{m}^3 \text{K}} \right)\)

H  aquifer thickness (m)

\( M_r \)  number of mesh cells in each row between \( r = 0 \) and \( R \)

q  heat flow rate per unit area \(\left( \frac{W}{\text{m}^2} \right)\)

Q  volumetric fluid flow rate \(\left( \frac{\text{m}^3}{\text{s}} \right)\)

r  radial coordinate (m)

R  thermal radius (m)

\[ R_m = \sqrt{\frac{m-1}{M}} R \]  distance to the inner edge of the \( m \)th column of mesh cells (m)

t  time (s)

\[ t_c = t_i + t_s + t_p + t_r \]  length of one cycle, where \( t_i, t_s, t_p, \) and \( t_r \) are length of injection, storage, production, and rest periods, respectively (s)

\( \Delta t \)  timestep for conduction (s)

T  temperature (K)

\( T_0 \)  reference temperature (K)

\( T_i \)  injection temperature (K)

\( T_p \)  production temperature (K)

\( \bar{T}_p \)  production temperature averaged over production period (K)

\( T_{z1} \)  upper boundary temperature (K)

\( T_{z2} \)  lower boundary temperature (K)

\[ v = \frac{Q}{2\pi H R} \]  steady radial darcy velocity \(\left( \frac{\text{m}}{\text{s}} \right)\)
Nomenclature

\[ V = \pi R^2 H = (C_w/C_a) V_w \] thermal volume (m^3)

\[ V_{m,n} \] volume of the (m,n)th mesh cell (m^3)

\[ V_w = Q_t i = Q_t p \] volume of water injected and produced (m^3)

\[ z \] vertical coordinate (m)

\[ z_n \] vertical distance from the top of the caprock to the top of the nth row of mesh cells (m)

\[ \varepsilon \] recovery factor, ratio of produced to injected energy, with energies measured relative to \( T_0 \).

\[ \lambda \] thermal conductivity (m K^-1)

\[ \phi \] porosity

Subscripts

\( w \) water

\( r \) rock

\( a \) aquifer

\( c \) confining layer

\( m,n \) refers to the cell in the mth column and nth row of the mesh (also used as a superscript)
Acknowledgement

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References


Appendix 1
Sample Problem Input

<table>
<thead>
<tr>
<th>READ Statement</th>
<th>Data Entry</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1,1,0</td>
<td>NRUN, NUT, NPR</td>
</tr>
<tr>
<td>2.</td>
<td>34,15</td>
<td>M,N</td>
</tr>
<tr>
<td>3.</td>
<td>10,15</td>
<td>NN11,NN2 (N=NN2 for a &quot;symmetric&quot; problem)</td>
</tr>
<tr>
<td>4.</td>
<td>10., 12</td>
<td>RLIM, MRLIM</td>
</tr>
<tr>
<td>5.</td>
<td>0.,8</td>
<td>ZTOP, NANT</td>
</tr>
<tr>
<td>6.</td>
<td>1, 100., 1,50., 1,20.</td>
<td>(N(I), A(I), I=1, NANT)</td>
</tr>
<tr>
<td>6.</td>
<td>1,10., 1,5., 2,2., 4,1., 4,2.</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>20.</td>
<td>T initial conditions: all 20°C</td>
</tr>
<tr>
<td>8.</td>
<td>1</td>
<td>RLAM initial conditions: all 2. W/mK except one block (the aquifer) with 2.5 W/mK</td>
</tr>
<tr>
<td>7.</td>
<td>2.</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>13</td>
<td>C initial conditions: all 2.6 x 10^6 J/m^3 K except one block (the aquifer) with 2.4 x 10^6 J/m^3K (aquifer C equals CO read in 12 below)</td>
</tr>
<tr>
<td>9.1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9.2</td>
<td>1, 34, 10, 15, 2.5</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>2.6E+06</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>9.1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9.1</td>
<td>1, 34, 10, 15, 2.4E+06</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>0</td>
<td>ILIN (Since ILIN = 0, there is no item 11)</td>
</tr>
<tr>
<td>12.</td>
<td>2.4E+06,4.1E+06,20., 20.</td>
<td>CO, RAACAW, TBOUND, TREF</td>
</tr>
<tr>
<td>13.</td>
<td>20.,0.,0., 31536000.</td>
<td>T1, T2, TIME1, TAU</td>
</tr>
<tr>
<td>14.</td>
<td>12, 4</td>
<td>NQM, IPER</td>
</tr>
</tbody>
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### Appendix 1
Sample Problem Input

<table>
<thead>
<tr>
<th>READ Statement</th>
<th>Data Entry</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.</td>
<td>7884000.</td>
<td>PERIOD (1/4 year)</td>
</tr>
<tr>
<td>16.</td>
<td>1.,0.,-1.,0.</td>
<td>(VT(I), I=1,IPER) (Injection, storage, production, and rest periods are of equal length.)</td>
</tr>
<tr>
<td>17.</td>
<td>100.,0.,0.,0.</td>
<td>(TIN(I),I=1, IPER)</td>
</tr>
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<td>TA,TB,TIMEM (TIMEM slightly greater than desired to allow for round-off errors)</td>
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STEADY FLOW MODEL

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NCHECK = 1
NCHECK = 2
NCHECK = 3

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INPUT PARAMETERS
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MESH DEFINITION
N= 34 N= 15
MN1= 10 MN2= 15
MLIM = 10.0 MLIM = 12 AQUIFER THICKNESS = 10.0

ILIN = 0
HEAT CAPACITY OF AQUIFER = 0.240E+07
HEAT CAPACITY OF WATER = 0.410E+07
TEMPERATURE AT BOUNDARY = 20.000
ENERGY BALANCE WITH T-BEF = 20.0
ATMOSPHERE TEMPERATURE FUNCTION
AVERAGE = 20.0 AMPLITUDE = 0.0
PHASE-TIME = 0.0 SEC. PERIOD = 315360000.0 SEC.
NUMBER OF PERIODS = 12 PERIODS PER CYCLE = 4
TIME FOR ONE PERIOD = 78840000.0 SEC.

PERIOD 1 2 3 4
TEMP 100.0 0.0 0.0 0.0
FLOW 0.233E-03 0.000E+00 0.233E-03 0.000E+00

PRINTOUT INTERVALS TA = 1296000.0 TB = 78840000.0
START TIME = 0.0 END TIME = 63080000.0

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INITIAL CONDITIONS AND MATERIAL PROPERTIES
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CAP is multiplied by 1.6. The RADIUS values are listed for different DEPTHS.
OUTPUT

TIMESTEP-INFORMATION

ICELL=... 34   JCELL=... 10   DISTAB=... 9576.009
CIN(I,J)=... 0.1592E-07
GFZ(I,J)  GFZ(I,J+1)   GFR(I,J)  GFR(I+1,J)
0.582E+02  0.654E+02  0.104E+04  0.212E+04
R(I)       R(I+1)
0.166E+02  0.168E+02
Z(J)       Z(J+1)
0.191E+03  0.192E+03

MAIN LOOP

NQ=  1   DT=  9521.74   ISTAB=  69   FLOW=0.233E-03 M/S

TIME= 1304479.4 SEC.   15 DAYS 2.4 HOURS
ENERGY IN=... 0.5027E+11   ENERGY OUT=... 0.0000E+00
TEMP. IN=... 100.0   TEMP. OUT=... 0.0

TIME= 2599437.3 SEC.   30 DAYS 2.1 HOURS
ENERGY IN=... 0.1508E+12   ENERGY OUT=... 0.0000E+00
TEMP. IN=... 100.0   TEMP. OUT=... 0.0

TIME= 3894395.3 SEC.   45 DAYS 1.8 HOURS
ENERGY IN=... 0.2513E+12   ENERGY OUT=... 0.0000E+00
TEMP. IN=... 100.0   TEMP. OUT=... 0.0

TIME= 5189327.0 SEC.   60 DAYS 1.5 HOURS
ENERGY IN=... 0.3519E+12   ENERGY OUT=... 0.0000E+00
TEMP. IN=... 100.0   TEMP. OUT=... 0.0

TIME= 6484251.0 SEC.   75 DAYS 1.2 HOURS
ENERGY IN=... 0.4524E+12   ENERGY OUT=... 0.0000E+00
TEMP. IN=... 100.0   TEMP. OUT=... 0.0

TIME= 7779175.0 SEC.   90 DAYS 0.9 HOURS
ENERGY IN=... 0.5529E+12   ENERGY OUT=... 0.0000E+00
TEMP. IN=... 100.0   TEMP. OUT=... 0.0

NQ=  2   DT=  9567.96   ISTAD=  1   FLOW=0.000E+00 M/S
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## Temperature and Time

**TEMPERATURE** | **TIME**
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23652158.0 SEC.

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### TEMPERATURE

- Time: 1943503.0 SEC.
- Energy In: ±0.4032E+12
- Energy Out: ±0.1548E+12

### TEMPERATURE

- Time: 2073626.0 SEC.
- Energy In: ±0.6032E+12
- Energy Out: ±0.1661E+12

### TEMPERATURE

- Time: 2203701.0 SEC.
- Energy In: ±0.6032E+12
- Energy Out: ±0.1919E+12

### TEMPERATURE

- Time: 23332010.0 SEC.
- Energy In: ±0.6032E+12
- Energy Out: ±0.267E+12

### TEMPERATURE

- Time: 23652158.0 SEC.
- Energy In: ±0.6032E+12
- Energy Out: ±0.2811E+12

**TEMPERATURE** | **TIME**
---|---
23652158.0 SEC.

**TEMP**

- Energy In: ±0.6032E+12
- Energy Out: ±0.1661E+12

**TEMP**

- Energy In: ±0.6032E+12
- Energy Out: ±0.1919E+12

**TEMP**

- Energy In: ±0.6032E+12
- Energy Out: ±0.267E+12

**TEMP**

- Energy In: ±0.6032E+12
- Energy Out: ±0.2811E+12
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**TIME= 31536190.0 SEC. 0 DAYS 0.1 HOURS**
**ENERGY IN= 0.0000E+00 ENERGY OUT= 0.0000E+00**
**TEMP. IN= 0.0 TEMP. OUT= 0.0**

**TIME= 32402642.0 SEC. 10 DAYS 0.7 HOURS**
**ENERGY IN= 0.5027E+11 ENERGY OUT= 0.0000E+00**
**TEMP. IN= 100.0 TEMP. OUT= 0.0**

**TIME= 33697652.0 SEC. 25 DAYS 0.5 HOURS**
**ENERGY IN= 0.1509E+12 ENERGY OUT= 0.0000E+00**
**TEMP. IN= 100.0 TEMP. OUT= 0.0**

**TIME= 34993742.0 SEC. 40 DAYS 0.1 HOURS**
**ENERGY IN= 0.2513E+12 ENERGY OUT= 0.0000E+00**
**TEMP. IN= 100.0 TEMP. OUT= 0.0**

**TIME= 36296612.0 SEC. 55 DAYS 2.4 HOURS**
**ENERGY IN= 0.3519E+12 ENERGY OUT= 0.0000E+00**
**TEMP. IN= 100.0 TEMP. OUT= 0.0**

**TIME= 37591332.0 SEC. 70 DAYS 2.0 HOURS**
**ENERGY IN= 0.4524E+12 ENERGY OUT= 0.0000E+00**
**TEMP. IN= 100.0 TEMP. OUT= 0.0**

**TIME= 38886052.0 SEC. 85 DAYS 1.7 HOURS**
**ENERGY IN= 0.5529E+12 ENERGY OUT= 0.0000E+00**
**TEMP. IN= 100.0 TEMP. OUT= 0.0**

**TIME= 38886052.0 SEC. 55 DAYS 1.7 HOURS**
**ENERGY IN= 0.5529E+12 ENERGY OUT= 0.0000E+00**
**TEMP. IN= 100.0 TEMP. OUT= 0.0**

**TIME= 39181772.0 SEC. 100 DAYS 3.2 HOURS**
**ENERGY IN= 0.6534E+12 ENERGY OUT= 0.0000E+00**
**TEMP. IN= 100.0 TEMP. OUT= 0.0**
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**TEMP:**
- 91 DAYS 8.4 HOURS
- 100 DAYS 2.4 HOURS
- 115 DAYS 1.2 HOURS
- 130 DAYS 2.6 HOURS
- 145 DAYS 1.4 HOURS
- 160 DAYS 0.3 HOURS
### Temperature vs. Time

**Time:** 47312724.0 Sec.

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**Depth vs. Radius**

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**Energy In:** 0.6032E+12 **Energy Out:** 0.0000E+00

**Temp. In:** 0.0 **Temp. Out:** 0.0
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<tr>
<th>TIME</th>
<th>ENERGY IN</th>
<th>ENERGY OUT</th>
<th>TEMP. IN</th>
<th>TEMP. OUT</th>
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**TEMPERATURE**

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<tbody>
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**DEPTH**

- 1.4
- 3.5
- 4.5
- 5.4
- 6.1
- 6.0
- 7.4
- 7.9
- 8.4
- 8.9
- 9.4
- 9.8
- 10.2
- 10.6
- 11.0
- 11.4
- 11.7

**RADIUS**

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</table>

**NU = 6 DT = 9567.96 ISTAB = 1 FLOW = 0.0000E+00 M/S**
TIME = 5519532.0 SEC.  273 DAYS 20.0 HOURS
ENERGY IN=...0.6032E+12  ENERGY OUT=...-3073E+12
TEMP. IN=...  0.0  TEMP. OUT=...  0.0

TIME = 55731140.0 SEC.  280 DAYS 0.9 HOURS
ENERGY IN=...0.6032E+12  ENERGY OUT=...-3073E+12
TEMP. IN=...  0.0  TEMP. OUT=...  0.0

TIME = 57032188.0 SEC.  295 DAYS 2.3 HOURS
ENERGY IN=...0.6032E+12  ENERGY OUT=...-3073E+12
TEMP. IN=...  0.0  TEMP. OUT=...  0.0

TIME = 58324068.0 SEC.  310 DAYS 1.1 HOURS
ENERGY IN=...0.6032E+12  ENERGY OUT=...-3073E+12
TEMP. IN=...  0.0  TEMP. OUT=...  0.0

TIME = 59625116.0 SEC.  325 DAYS 2.6 HOURS
ENERGY IN=...0.6032E+12  ENERGY OUT=...-3073E+12
TEMP. IN=...  0.0  TEMP. OUT=...  0.0

TIME = 60916996.0 SEC.  340 DAYS 1.4 HOURS
ENERGY IN=...0.6032E+12  ENERGY OUT=...-3073E+12
TEMP. IN=...  0.0  TEMP. OUT=...  0.0

TIME = 62208676.0 SEC.  355 DAYS 0.2 HOURS
ENERGY IN=...0.6032E+12  ENERGY OUT=...-3073E+12
TEMP. IN=...  0.0  TEMP. OUT=...  0.0

**************************************************************************
ENERGY BALANCE  CYCLE=...  2
ENERGY (IN)=...0.603E+12  ENERGY (OUT)=...-0.307E+12
ENERGY STORED=...0.296E+12  RECOVERY RATIO=...0.510
REFERENCE TEMPERATURE.=...  20.0
**************************************************************************

NQ=  9  DT=  9521.74  ISTAB=  69  FLOW=0.233E-03 M/S
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<td><strong>RADIUS</strong></td>
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**TIME** = 63079316.0 SEC. **Q DAYS** 0 **2.0 HOURS**

**ENERGY IN** = 0.00000*00 **ENERGY OUT** = 0.00000*00

**TEMP. IN** = 100.0 **TEMP. OUT** = 0.0
Appendix 3
SFM Source Code

0001 PROGRAM CARC ! (INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT)
0002 INCLUDE 'STEADY1.INC/LIST'
0003 COMMON /CMN1/ T(100, 25), ELAM(100, 25), C(100, 25),
0004 1 FR(100, 25), FZ(100, 25), GFR(100, 25),
0005 2 GFG(100, 25), R(100), Z(100), A(100), CIN(100, 25)
0006 COMMON /CMN2/ BM(100), ZM(100)
0007 COMMON /CMN51/ M, N, N1, N1
0008 COMMON /CMN4/ TNEW(100, 25)
0009 COMMON /CMN5/ TIMEQ(100), Q(100), TIN(100)
0010 DIMENSION VT(65), TBZ(25)
0011 PI=3.1415926535
0012
0013 C* * * * * * * INPUT * * * * * * *
0014 READ(5, *) NRUN, NUT, NPR
0015 NRUNC=0
0016 2000 CONTINUE
0017 NRUNC=NRUNC+1
0018 READ(5, *) M, N
0019 M1=M+1
0020 N1=N+1
0021 READ(5, *) NN, NN2
0022 READ(5, *) R1M, R1LIM
0023 CALL INDIR(Z, L)
0024 IF(L.NE.N1) STOP 1
0025 CALL INDATA(M, N, T)
0026 CALL INDATA(M, N, R1)
0027 CALL INDATA(M, N, C)
0028 READ(5, *) ILIN
0029 IF(ILIN.EQ.1) READ(5, *) TSURF, TDEPTH, DEPTH
0030 READ(5, *) CO, RAAC, TBOUND, TREF
0031 READ(5, *) T1, T2, TIME1, TAU
0032 READ(5, *) NQM, IPER
0033 READ(5, *) PERIOD
0034 READ(5, *) (VT(I), I=1, IPER)
0035 READ(5, *) (TIN(I), I=1, IPER)
0036 READ(5, *) TA, TE, TIME
0037 READ(5, *) TIME
0038
0039 C* * * * * * * PREPARATION OF INPUT * * * * * * *
0040 WRITE(6, 2001)
0041 2001  FORMAT(1H1, 20(1H=), /, ' STEADY FLOW MODEL', /, 1X, 20(1H=))
0042 NN1=M-1
0043 R1M=FLOAT(R1M)
0044 R1=R1M/SQRT(R1M)
0045 R(1)=0.
0046 DO 10 I=2, N1
0047 FI=FLOAT(I-1)
0048 R(I)=SQRT(FI)*R1
0049 10 CONTINUE
0050 2002 FORMAT(2X, 'NCHECK=1', I3)
0051 NTA=0
0052 NTB=0
0053 TIMEQ(I)=PERIOD
0054 DO 30 I=2, NQM
0055 TIMEQ(I)=TIMEQ(I-1)+PERIOD
0056 30 CONTINUE
0057 NCHECK=1

-35-
WRITE (6,2002) NCHECK
HEIGHT=Z(N1)-Z(NN11)
DO 40 I=1,NQII
IP=MOD ((I-1),IPER)+1
Q(I)=VT(IP)*PI*RLIM*RLIM*HEIGHT*CO/(PERIOD*RAACAW)
TIN(I)=TIN(IP)
40 CONTINUE
NCHECK=2
WRITE (6,2002) NCHECK
TIME=TIME+TIME
TIM1=0
ENE=0.
ENEUT=0.
IF (TAU.EQ.0.) TAU=31536000.
C*'*'.'.'* CALCULATION OF TEMPERATURE COORDINATES '**'*'*'*
DO 80 I=1,M
RM(I)=(R(I)+R(I+1))/2.
80 CONTINUE
DO 90 J=1,N
ZN(J)=(Z(J)+Z(J+1))/2.
90 CONTINUE
NCHECK=3
WRITE (6,2002) NCHECK
C*'*'.'.'* START-TEMP LINEAR WITH DEPTH '**'*'*'*
DO 105 J=1,N
TBZ(J)=TBOUND
IF (ILIN.EQ.0) GO TO 120
DO 110 J=1,N
TPOINT=TSURF+(TDEPTH-TSURF)*ZN(J)/DEPTH
110 T(I,J)=TPOINT
TBZ(J)=TPOINT
120 CONTINUE
C*'*'.'.'* PRINT OF INPUT '**'*'*'*
WRITE (6,125)
125 FORMAT (///,1X,'20(1H-),/'), 'INPUT PARAMETERS',/,'1X,20(1H-)
WRITE (6,130) M,N
130 FORMAT (/'4X,'MESH DEFINITION',/,'4X,'M=...',I3,' N=...',I3)
WRITE (6,140) NN11,NN2
140 FORMAT (/'4X,'NN11=...',I3,' NN2=...',I3)
WRITE (6,141) RLIM,MRLIM,HEIGHT
141 FORMAT (/'4X,'RLIM=',F6.1,' MRLIM=',I3,' AQUIFER THICKNESS=',F6.1)
WRITE (6,150) ILIN
150 FORMAT (///,1X,'20(1H-),/'), 'INPUT PARAMETERS',/,'1X,20(1H-)
WRITE (6,160) TSURF,TDEPTH
160 FORMAT (/'2X,'LINEAR STARTING TEMPERATURES',/,'2X,'TSURFACE=',F6.1,' TDEPTH=',F6.1,' DEPTH=',E9.3)
WRITE (6,170) CO,RAACAW,TBOUND,TREF
170 FORMAT (/'2X,'HEAT CAPACITY OF AQUIFER=',E9.3/, '2X,'HEAT CAPACITY OF WATER=',E9.3/, '2X,'TEMPERATURE AT BOUNDARY=',E8.3/)
*2X,'ENERGY BALANCE WITH T-REF=' F6.1)
WRITE(6,190) T1,T2,TIME1,TAU
190 FORMAT(2X,'ATMOSPHERE TEMPERATURE FUNCTION',/)
*4X,'AVERAGE=' F6.1, ' AMPLITUDE=' F6.1,
*4X,'PHASE-TIME=' F12.1, ' SEC. PERIOD=' F12.1, ' SEC.')
WRITE(6,210) NQM,IPER
210 FORMAT(2X,'NUMBER OF PERIODS=',I3,
** PERIODS PER CYCLE=',I3)
WRITE(6,220) PERIOD
220 FORMAT(2X,'TIME FOR ONE PERIOD',F10.1, ' SEC.')
WRITE(6,230) (TIN(I),I=1,IPER)
230 FORMAT(2X,'TEMP.',12(I10))
WRITE(6,250) (Q(I),I=1,IPER)
250 FORMAT(2X,'FLOW ',12(I1X,E9.3))
WRITE(6,260)TA,TB,TIME,TIMEM
260 FORMAT(2X,PRINTOUT INTERVALS TA=',F12.1,' TB=',F12.1,/'
* START TIME=',F12.1,' END TIME=',F14.1)
IF(NUT.EQ.0) GO TO 145
142 FORMAT(/,'INITIAL CONDITIONS AND MATERIAL PROPERTI
XES',/,'1X,44(1H-),/,' OUTPUT',/,'1X,18(1H-)
C**'**'**'CALCULATION OF GF **'**'**'
C**'**'**' HEATCONDUCTANCES **'**'**'
DO 270 I=1,M
GPZ(I,1)=2./((Z(2)-Z(1))/RLAM(I,1))
270 CONTINUE
DO 290 J=2,N
DO 280 I=1,M
GPZ(I,J)=2./((Z(J)-Z(J-1))/RLAM(I,J-1)+(Z(J+1)-Z(J))/RLAM(I,J))
280 CONTINUE
290 CONTINUE
DO 310 J=1,N
DO 300 I=1,M
GPZ(I,J)=2./((Z(J)-Z(J-1))/RLAM(I,J-1)+(Z(J+1)-Z(J))/RLAM(I,J))
300 CONTINUE
310 CONTINUE
C**'**'**' GF=HEATCONDUCTANCE*AREA **'**'**'
DO 340 J=1,W1
DO 330 I=1,M
GPZ(I,J)=GPZ(I,J)*PI*(R(I+1)-R(I))*R(I)
330 CONTINUE
340 CONTINUE
0172  DO 360 I=1,N1
0173  DO 350 J=1,N
0174  GFR(I,J)=GFR(I,J)*2.*PI*R(I)*(Z(J+1)-Z(J))
0175  350 CONTINUE
0176  360 CONTINUE
0177
0178  C**CALCULATION OF CIN**
0179  DO 380 I=1,N
0180  DO 370 J=1,N
0181  CIN(I,J)=1./(C(I,J)*PI*(R(I+1)**2-R(I)**2)*(Z(J+1)-
0182  *Z(J)))
0183  370 CONTINUE
0184  380 CONTINUE
0185
0186  C**WEIGHTS FOR CALCULATION OF TEMP.OUT**
0187  DO 390 J=NN11,NN2
0188  A(J)=(Z(J+1)-Z(J))/HEIGHT
0189  390 CONTINUE
0190
0191  C**TIMESTEP**
0192  CALL DTIME(M,N,DTSTAB)
0193  ISTACO=0
0194  NQ=0
0195  IYC=0
0196  IT=0
0197  ITMAX=0
0198
0199  C**START OF MAIN LOOP**
0200  OPEN (UNIT=1,NAME='STEADY.BIN',TYPE='NEW',
0201  1 FORM='UNFORMATTED',ACCESS='SEQUENTIAL')
0202  WRITE(1)N,N,(RM(I),I=1,M),(ZM(I),I=1,N)
0203  WRITE(6,405)
0204  405 FORMAT(//,1X,13(IH-),/,1X,'MAIN LOOP',/,1X,13(IH-))
0205  1000 CONTINUE
0206  IF(IT.LT.ITMAX) GO TO 420
0207  IT=0
0208  IYC=IYC+1
0209  NQ=NQ+1
0210
0211  C**CHECK OF WATERFLOW**
0212  AQP=ABS(Q(NQ))
0213
0214  C**CALCULATION OF TIMESTEP**
0215  IF(AQP.GE.(1.E-10)) GO TO 410
0216  ITMAX=IFIX(PERIOD/DTSTAB)+1
0217  DT=PERIOD/ITMAX
0218  ISTAB=1
0219  GO TO 419
0220  410 CONTINUE
0221  ISTAB=IFIX(PERIOD/(MRLIM*DTSTAB))+1
0222  DT=PERIOD/(MRLIM*ISTAB)
0223  ITMAX=MRLIM*ISTAB
0224  419 WRITE(6,415)NQ,DT,ISTAB,Q(NQ)
0225  415 FORMAT(//,1X,62(1H-),/,2X,'NQ=',I4,' DT=',E10.2,' ISTAB=',I4, 
0226  'FLOW=',E9.3,' M/S',/,1X,62(1H-),/)
0227  420 CONTINUE
0228  ISTACO=ISTACO+1
IT = IT + 1

C*** AIR TEMP. ***
TZ = T1 + T2 * SIN(2 * PI * (TIME - TIME1) / TAU)

C*** CALCULATION OF HEATFLOWS ***
DO 430 I = 1, M
FZ(I, 1) = GFZ(I, 1) * (T4 - T(I, 1))
FZ(I, N1) = 0.
IF(N, NE, N2) FZ(I, N1) = GFZ(I, N1) * (T(I, N) - TBOUND)
430 CONTINUE
DO 450 I = 1, M
DO 440 J = 2, N
FZ(I, J) = GFZ(I, J) * (T(I, J-1) - T(I, J))
440 CONTINUE
450 CONTINUE
DO 460 J = 1, N
FR(I, J) = 0.
FR(M1, J) = GFR(M1, J) * (T(M, J) - TBZ(J))
460 CONTINUE
DO 470 I = 2, M
DO 480 J = 1, N
FH(I, J) = GFR(I, J) * (T(I-1, J) - T(I, J))
470 CONTINUE
480 CONTINUE
C*** CALCULATION OF NEW TEMPERATURES ***
DO 500 I = 1, M
DO 490 J = 1, N
T(I, J) = T(I, J) + CIN(I, J) * (FZ(I, J) - FZ(I, J+1) + FR(I, J)
* - FR(I+1, J)) * DT
490 CONTINUE
500 CONTINUE
C*** CONVECTIVE TRANSPORT ***
C*** CALC. OF TEMP. OUT. ***
IF(ISTAB .NE. ISTACO) GO TO 670
TOUT = 0.
IF(AQP .LT. (1.E-10)) GO TO 670
DO 520 I = 1, M
DO 510 J = 1, N
THEW(I, J) = T(I, J)
510 CONTINUE
520 CONTINUE
IF(Q(NQ) .LT. 0.) GO TO 570
DO 550 J = NN11, NN2
DO 540 I = 2, M
T(I, J) = TNEW(I-1, J)
540 CONTINUE
550 CONTINUE
DO 560 J = NN11, NN2
TNEW(I, J) = TIN(NQ)
560 CONTINUE
GO TO 620
570 CONTINUE
DO 580 J = NN11, NN2
TOUT = TOUT + A(J) * T(I, J)
580 CONTINUE
DO 600 J=NN11,NN2
DO 590 I=1,MN1
  T(I,J) = TNEW(I+1,J)
590 CONTINUE
DO 600 J=NN11,NN2
  T(M,J) = (TNEW(M,J) + TBOUND) / 2.
610 CONTINUE
620 CONTINUE

C* START OF ENERGY BALANCE PART **
C* CALCULATION OF ANNUAL BALANCE **
IF (Q(NQ).LT.0.) GO TO 630
  WEX = ABS(Q(NQ)) * RAACAW * (TIN(NQ) - TREF)
  ENEXIN = ENEXIN + WEX * DT * ISTAB
GO TO 640
630 IF (Q(NQ).LT.0.) GO TO 640
  WEX = ABS(Q(NQ)) * RAACAW * (TREF - TOUT)
  ENEXUT = ENEXUT + WEX * DT * ISTAB
640 CONTINUE
670 CONTINUE

C* END OF EXTRAPOLATION **
TIME = TIME + DT

C* CHECK IF ANNUAL CYCLE COMPLETED
IF (IT .NE. ITMAX) GO TO 690
ITIM2 = IYC/IPER
IF (ITIM1 .EQ. ITIM2) GO TO 690

C* PRINT OUT OF ANNUAL ENERGY BALANCE
ESTORE = ENEXIN + ENEXUT
ERATIO = -ENEXUT/ENEXIN
WRITE (6, 680) ITIM2, ENEXIN, ENEXUT, ESTORE, ERATIO,
* TREF
680 FORiAT (IH ,
** ++++++++++++++++++ ++++++++++++++++++ ++++++++++++++++++ ++++++++++++++++++
** , '2X , ' ENERGY BALANCE ',
** CYCLE=... ', 'I3 , /2X , ' ENERGY (IN)=... ', 'E10.3 ,
** ENERGY (OUT)=... ', 'E10.3 , /2X , ' ENERGY STORED=... ',
** E10.3 , ' RECOVERY RATIO=... ', 'F5.3 , /2X ,
** REFERENCE TEMPERATURE=... ', 'F6.1 , /2X ,
** ++++++++++++++++++ ++++++++++++++++++ ++++++++++++++++++ ++++++++++++++++++
) ITIM1 = ITIM2
690 CONTINUE

C* CHECK OF PRINT **
NTAN = IPIX (TIME/TA)
NTBN = IPIX (TIME/TB)
IF (NTBN .NE. NTB) GO TO 740
IF (NTAN .NE. NTA) GO TO 830
IF (TIME .GE. TIMEM) GO TO 740
GO TO 860

C* PRINT OF TEMP. **

0343 740 CONTINUE
0344      IBIG=1
0345 830 CONTINUE
0346      CALL UTTEMP(IBIG,NPH,NQ,TIME,ENEXIN,ENEXUT,TOUT)
0347      IBIG=0
0348
0349      C***** CHECK FOR MAXTIME
0350      C***** SET TIME AND PRINT COUNTERS
0351 860 CONTINUE
0352      IF(TIME.GE.TIMEM) GO TO 900
0353      NTA=NTAN
0354      NTB=NTBN
0355      IF(ISTACO.EQ.ISTAB) GO TO 880
0356      GO TO 420
0357 880 CONTINUE
0358      ISTACO=0
0359      GO TO 1000
0360 900 CONTINUE
0361      IF(NRUNC.NE.NRUN) GO TO 2000
0362      STOP
0363      END
SUBROUTINE INDIR(B,L)
DIMENSION NA(100),A(100),B(100)
READ(5,*),ZTOP,NANT
READ(5,*),(NA(I),A(I),I=1,NANT)
B(1) = ZTOP
L=1
DO 10 J=1,NANT
NE=NA(J)
DO 5 I=1,NE
L=L+1
B(L) = B(L-1) + A(J)
5 CONTINUE
10 CONTINUE
RETURN
END

SUBROUTINE INDATA(MM,NN,A)
DIMENSION A(100,25),B(51)
READ(5,*),VALUE
DO 10 I=1,MM
DO 5 J=1,NN
A(I,J) = VALUE
5 CONTINUE
10 CONTINUE
READ(5,*),ITYP
IF(MOD(ITYP,11).NE.0) GO TO 80
READ(5,*),NUSEX
DO 70 NOM=1,NUSEX
A(I,J) = VALUE
70 CONTINUE
80 CONTINUE
RETURN
END

C***** ALL CELLS = VALUE ********
DO 10 I=1,MM
DO 5 J=1,NN
A(I,J) = VALUE
5 CONTINUE
10 CONTINUE
RETURN
END

C***** 11 IN ITYP, SPECIFIC-CELL = VALUE ********
IF(MOD(ITYP,11).NE.0) GO TO 80
READ(5,*),NUMEX
DO 70 NUM=1,NUMEX
READ(5,*),I,J,VALUE
A(I,J) = VALUE
70 CONTINUE
80 CONTINUE
RETURN
END

C***** 13 IN ITYP, BLOCK-CELLS = VALUE ********
IF(MOD(ITYP,13).NE.0) GO TO 120
READ(5,*),IBLOCK
DO 110 IBL=1,IBLOCK
READ(5,*),MIN,MAX,JMIN,JMAX,VALUE
DO 90 I=MIN,MAX
DO 80 J=JMIN,JMAX
A(I,J) = VALUE
80 CONTINUE
90 CONTINUE
110 CONTINUE
120 CONTINUE
RETURN
END
SUBROUTINE DTIME(MM,NN,DT)
INCLUDE 'STEADY1.INC/LIST'
COMMON /CMN1/ T(100,25),RLAM(100,25),C(100,25),
FR(100,25),FZ(100,25),GFR(100,25),
2 GFZ(100,25),F(100),Z(100),A(100),CIN(100,25)
COMMON /CMN2/ MM(100),NZ(100)
COMMON /CMN5/ M,N,M1,N1
COMMON /CMN4/ TNEW(100,25)
COMMON /CMN5/ TIMEQ(100),Q(100),TIN(100)

F=0.
DO 20 I=1,MM
DC 10 J=1,NN
FTRY=CIN(I,J)* (GFZ(I,J) +GFZ(I,J+1) +GFR(I,J) +GFR(I+1,J))
IF(FTRY.LT.F) GO TO 10
F=FTRY
ICE.LL=I
JCELL=J
10 CONTINUE
20 CONTINUE
DT=1./(2.*F)
C**TIMESTEP-INFORMATION**
WRITE(6,100) ICEL,JCEL,DT
100 FORMAT(1X,1X,20(1H-),/,
*I= ICCELL=--','J=JCELL='I3='DTSTAB='F14.3)
WRITE(6,101)CIN(ICEL,JCELL),GFZ(ICEL,JCELL),GFZ(ICEL,JCELL+1),
GFR(ICEL,JCELL),GFR(ICEL+1,JCELL),R(ICEL),
R(ICEL+1),Z(ICEL),Z(JCELL),Z(JCELL+1)
101 FORMAT(1X,'CIN(I,J)='E10.3,'GFZ(I,J) GFZ(I,J+1)'
*,'GFR(I,J) GFR(I+1,J)'4(E10.3,1X)'
*,'R(I) R(I+1)'
*,'Z(J) Z(J+1)2(E10.3,2X)
RETURN
END
SUBROUTINE UTDATA(IFORM, ITEXT, MM, NN, AB, NPR)

DIMENSION AB(100,25), TEXT(5), B(100)

INCLUDE 'STEADY1.INC/LIST'

COMMON /CMN1/ T(100,25), RLM(100,25), C(100,25),
           PH(100,25), PZ(100,25), GFR(100,25),
           GFZ(100,25), R(100), Z(100), A(100), CIN(100,25)

COMMON /CMN2/ RM(100), ZM(100)

COMMON /CMN3/ H, M, N1, N1

COMMON /CMN4/ TNEW(100,25)

COMMON /CMN5/ TIMEQ(100), Q(100), TIN(100)

DATA TEXT/*HTEMP, 4HRALAM, 3RCAP, 4HISOR, 4HISOZ/

WRITE (6,5) TEXT(ITEXT)

5 FORMAT (1HO, 2X, A4, /, '=====*)

IF (ITEXT.EQ.3) WRITE (6,6)

IF (ITEXT.EQ.3) WRITE (6,6)

FORMAT (2X, 'MULTIPLY BY 1.66*)

IMIN=1

IRUN=MM

ICOL=17

IF (NPR.EQ.1) ICOL=11

CONTINUE

IMAX=MIN0 (IRUN, ICOL) + IMIN - 1

IF (NPR.EQ.1) GO TO 35

DO 20 J=1, NN

WRITE (6, 30) (RM(I), 1=IMIN, IMAX)

20 CONTINUE

30 FORMAT (1X, 111 (1H-))

IF (NPR.EQ.1) WRITE (6, 31)

31 FORMAT (1X, 76 (1H-))

IF (IFORM.EQ.1) GO TO 35

DO 30 J=1, NN

WRITE (6, 15) ZM(J), (AB(I,J), 1=IMIN, IMAX)

30 CONTINUE

DO 40 J=1, NN

35 GO TO 40

40 IF (IRUN.LE.0) GO TO 25

IMIN=IMAX+1

GO TO 3

43 CONTINUE

RETURN

END
SUBROUTINE UTTEMP(IBIG,NPR,NQ,TIME,EXIN,EXUT,TOUT)

INCLUDE 'STEADY1.INC'

COMMON /CMN1/ T(100,25),RLAM(100,25),C(100,25),
           F(100,25),F2(100,25),GF(100,25),
           GFZ(100,25),R(100),Z(100),A(100),CIN(100,25)

COMMON /CMN2/ RM(100),ZM(100)

COMMON /CMN5/ M,N,M1,N1

COMMON /CMN4/ TNEW(100,25)

COMMON /CMN5/ TIMEQ(100),Q(100),TIN(100)

IF(IBIG.EQ.0)GO TO 830

WRITE(6,750)TIME

CALL UTDATA(0,1,M,N,T,NPR)

WRITE(1,TIME,((T(IJ,IJ),IJ=1,M),JJ=1,N))

WRITE(6,760)

WRITE(6,750)TIME

750 FORMAT(/' TEMPERATURE @ TIME=',F15.1,' SEC.')

760 FORMAT((IX)

WRITE(1,TIME,(T(IJ,IJ),IJ=1,M),JJ=1,N))

WRITE(6,760)

760 FORMAT((IX)

WRITE(6,750)TIME

CONTINUE

830 FORMAT(/' ENERGY IN=',E10.4,'

840 FORMAT(2X,'TIME=',F12.1,' SEC. @',F14,' DAYS',F5.1,' HOURS',

840 FORMAT(2X,'TEMP. IN=',F5.1,6X,' TEMP. OUT=',F5.1,/)

RETURN

END
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