IMPLEMENTATION AND VERIFICATION OF THE FULLY COUPLED T-H-M CODE, T2STR, FOR MULTIPHASE FLOW IN POROUS MEDIA

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ABSTRACT
We present the formulation details of the research code T2STR, capable of simulating a fully coupled thermo-hydro-mechanical (THM) analysis of porous media under multiphase conditions. The IFDM based computer code TOUGH2 is modified using features from FEM based computer code Geocrack3D to include the mechanical effects. The dual mesh technique is natural for combining both discretization methods and is used in our implementation.

T2STR is implemented to carry out a fully coupled, one way coupled (only deformation as function of hydro-thermal effects), and original TOUGH2 simulations. T2STR also allows the user to study the variation in porosity, permeability and capillary pressure as function of mean effective stress in both the one-way and fully coupled approaches. The coupled sets of equations in T2STR have been combined using the dual mesh concept.

Numerical examples are presented to show the accuracy and capability of the enhanced T2STR code.

The code modifications to TOUGH2 and the additional code required to run the fully coupled simulations will be publicly available and will be posted on the web.

BACKGROUND
TOUGH2 is a program for calculation of multiphase, multi-component, non-isothermal flow in porous media (Pruess et al., 1999). Some of the strengths of the code include:

- Use of the integral finite difference approach, which can accommodate general geometry (with the constraint that the mesh be Voronoï).
- Implementation of several equation-of-state modules to represent different fluid mixtures.
- Continual development to add new capability such as multiple volatile organic compounds (TMVOC) and chemical reactions (TOUGHREACT).

One physical phenomenon that is not included in TOUGH2 is deformation and stress. For some problems, stress coupling can be important (Swenson et al., 2004). As a logical extension of TOUGH2 to add stress coupling, the development of the code T2STR was undertaken (Gosavi et al., 2005).

FORMULATION
The equations of conservation of mass and energy are solved in TOUGH2 code using the Integrated Finite Difference Method (IFDM) (Narasimhan and Witherspoon, 1976). The aspect of deformable porous media is added through additional terms in flow equations and through the addition of equation of conservation of momentum for the solid phase (Gosavi et al., 2005). The momentum equation is discretized using the finite element method (FEM).

The modifications in the fluid mass and energy equations have been implemented using the original TOUGH2 implementation (Pruess et al., 1999).

The Newton-Raphson formulation for the finite element equations can be obtained by defining the residual as follows

\[ \mathbf{R} = g - f (\Delta u, \Delta p, \Delta T) \]  

where \( g \) represents forces independent of unknown variables, i.e., pressure, temperature, and displacements, and \( f \) represents the internal forces and the hydrostatic forces.

Single Phase Formulation
TOUGH2 uses phase pressure and temperature as primary variables for single phase. The pressure in momentum equation is pressure on the solid which, for single phase conditions, is equal to the fluid phase pressure. Then, using the first order approximation of
a three variable Taylor series for \( f \) to obtain the solution at iteration \( i \), it can be written as

\[
\left( \frac{\partial f}{\partial \Delta u} \right)^{(i-1)} \delta \Delta u^{(i)} + \left( \frac{\partial f}{\partial \Delta p} \right)^{(i-1)} \delta \Delta p^{(i)} + \left( \frac{\partial f}{\partial \Delta T} \right)^{(i-1)} \delta \Delta T^{(i)} = g - \varepsilon^{(i-1)} f(\Delta u, \Delta p, \Delta T)^{(i-1)}
\]

\[ (2) \]

Using the modified effective stress law, we can write the residual as

\[
R = \left\{ \int_V N^{(i)} b \, dV + \int_S N^{(i)} t \, dS - \int_V B^T D_B \, dV \right\} \Delta u_s
\]

\[ (3) \]

\[
\left( \int_V B^T DB \, dV \right) \Delta u_s - \left( B^T \alpha m N \Delta p \, dV \right)
\]

\[
- \left( \frac{3K \alpha_f}{V} \right) \frac{B^T \alpha m N \Delta T \, dV}{V}
\]

\[
- \left( \int_V B^T \alpha m N p_s \, dV \right) + \left( B^T \sigma_\alpha \, dV \right)
\]

Then the Newton-Raphson formulation for single phase becomes

\[
\begin{aligned}
&1^\text{st} \text{iter.} \\
&\left( K_s \right)^{(i-1)} \delta \Delta u^{(i)} + \left( Q_p^{(i-1)} \right)^{(i-1)} \delta \Delta p^{(i)} + \left( Q_T^{(i-1)} \right)^{(i-1)} \delta \Delta T^{(i)} = \\
&\left( Q_p^{(i-1)} \right)^{(i-1)} \delta \Delta \Delta p^{(i)} + \left( Q_T^{(i-1)} \right)^{(i-1)} \delta \Delta \Delta T^{(i)}
\end{aligned}
\]

\[ (4) \]

The phase coefficient matrices for temperature-pressure and for temperature-saturation, respectively, are given as

\[
\begin{bmatrix}
\frac{\partial T}{\partial p_g} \\
\vdots \\
\frac{\partial T}{\partial p_{\text{numNodes}}}
\end{bmatrix}
\]

\[ C_{p_s}^T \]

\[ (5) \]

\[
\begin{bmatrix}
\frac{\partial T}{\partial S_g} \\
\vdots \\
\frac{\partial T}{\partial S_{\text{numNodes}}}
\end{bmatrix}
\]

\[ C_{s_s}^T \]

\[ (6) \]

### Two Phase Formulation

The primary variables in TOUGH2 for two phase conditions are gas phase pressure and gas phase saturation. The momentum equations need to be reformulated to express using those variables.

**Solid Phase Pressure**

The solid phase pressure can be written as

\[
p_s = p_g + p_{s_s} = \sum_{\psi} p_{\psi} S_{\psi}
\]

\[ (5) \]

Using capillary pressure, the change in solid phase pressure, in vector form can be written as

\[
\Delta p = \Delta p_s + C_{s_s}^{p} \Delta S_s
\]

\[ (6) \]

where \( C_{s_s}^{p} \) is the diagonal (square) matrix of size equal to the number of nodes, given as

\[
\begin{bmatrix}
l-S_g \frac{\partial p_g}{\partial S_g} - p_g \\
\vdots \\
0 - (1-S_g) \frac{\partial p_g}{\partial S_g} - p_g
\end{bmatrix}
\]

\[ (7) \]

and denominated as phase coefficient matrix for pressure-saturation.

**Temperature**

The temperature for two phase problem is expressed as function of gas phase pressure and saturation in two phase problems in TOUGH2, i.e.

\[
T = T \left( p_g, S_g \right)
\]

\[ (8) \]

The change in temperature, in vector form, is

\[
\Delta T = C_{p_s}^T \Delta p_g + C_{s_s}^T \Delta S_g
\]

\[ (9) \]

### Implementation

Then, after rearranging, the residual from equation (3) can be written as equation (12).

\[
R = \left\{ \int_V N^T b \, dV + \int_S N^T t \, dS - \int_V B^T D_B \, dV \right\} \Delta u_s
\]

\[ (12) \]

\[
\begin{aligned}
&\left( \int_V B^T DB \, dV \right) \Delta u_s \\
&- \left( \int_V B^T \left( 3 K \alpha_f \right) m \, N \Delta p_s \, dV \right) \\
&- \left( \int_V B^T \left( 3 K \alpha_f \right) m \, N \Delta S_s \, dV \right) \\
&+ \left( B^T \sigma_\alpha \, dV \right)
\end{aligned}
\]

The final two-phase Newton-Raphson formulation becomes
Generalized Fully Coupled Formulation

Since the phase coefficient matrices are constant with respect to the element properties, using the notations in single phase formulation, these can be rewritten as

\[ Q_{p_e} = -Q_T C_{p}^{T} - Q_p \]  

and

\[ Q_{s_e} = -Q_T C_{s}^{T} - Q_p C_{s}^{g} \]  

In single phase, the independent variables are pressure and temperature and hence the phase coefficient matrices \( C_{p}^{T} \) and \( C_{s}^{g} \) (or \( C_{s}^{T} \)), will be zero. Also, the coefficient matrix \( C_{p}^{T} \) will be the phase coefficient matrix between the temperatures and hence evaluate to unity. Hence, it can be easily seen, that the two phase formulation will automatically fall to single phase formulation if the variables switch to single phase variables.

The generalized formulation, applicable for single phase or two phase conditions, then can be written as

\[
\begin{align*}
\text{subject to} & \quad \left( K_e \right)^{(i-1)} \Delta u^{(i)} + \left( Q_{p_e} \right)^{(i-1)} \Delta p_e^{(i)} \\
& + \left( Q_{s_e} \right)^{(i-1)} \Delta S_e^{(i)} \\
& - \left( \int \nabla b \right) dV + \int b \nabla t dS - \int \left( \int B^{T} D B_{e} dV \right) \Delta u_e \\
& + \left( \int \nabla b \right) dV + \int b \nabla t dS - \int \left( \int B^{T} D B_{e} dV \right) \Delta u_e \\
& - \left( \int B^{T} \alpha m N p_0 dV \right) + \int B^{T} \sigma_{0} dV \\
\end{align*}
\]  

\[ \text{(13)} \]

\[
\begin{align*}
\text{subject to} & \quad \left( K_e \right)^{(i-1)} \Delta u^{(i)} + \left( Q_{p_e} \right)^{(i-1)} \Delta p_e^{(i)} \\
& + \left( Q_{s_e} \right)^{(i-1)} \Delta S_e^{(i)} \\
& - \left( \int \nabla b \right) dV + \int b \nabla t dS - \int \left( \int B^{T} D B_{e} dV \right) \Delta u_e \\
& + \left( \int \nabla b \right) dV + \int b \nabla t dS - \int \left( \int B^{T} D B_{e} dV \right) \Delta u_e \\
& - \left( \int B^{T} \alpha m N p_0 dV \right) + \int B^{T} \sigma_{0} dV \\
\end{align*}
\]  

\[ \text{(16)} \]

where \( V_1 \) and \( V_2 \) represent the primary variables corresponding to the phase condition. Again, \( Q_{V_1} \) and \( Q_{V_2} \) will be implemented as shown in equations (14) and (15), and would evaluate to the correct matrices depending on the phase of the element.

VERIFICATION PROBLEMS

The T2STR code is tested using various benchmark problems and verified for its accuracy using analytical solutions or published results.

2D Consolidation problem on a smooth impervious boundary

A two dimensional plain strain consolidation problem studied by Gibson et al.(1970) is used for verification purpose. Gibson et al.(1970) provided the exact analytical solution to the problem. The solution is expressed using the dimensionless parameters and obtained using two displacement functions.

Mathematical Model

We consider a Finite strip loaded over the center as shown in Figure 1. Due to symmetry only half of the reservoir is modeled. A constant stress \(-\sigma_0\) is applied suddenly on the surface \( z = 0 \) over the length \( b \) (2b for the entire model) of a fluid saturated sample of height \( h \). The consolidation test is assumed to satisfy the plain strain condition.

The plain strain problem is solved by Gibson et al. (1970) by neglecting gravity, without any source, under isothermal and single phase conditions, with invariant porosity and assuming incompressible solid and incompressible fluid.

\[
\begin{align*}
\frac{k}{\mu} \nabla^2 p &= \frac{\partial \varepsilon}{\partial t} \\
\end{align*}
\]  

\[ \text{(17)} \]

The fluid flow equation, then reduces to

\[
\begin{align*}
\frac{k}{\mu} \nabla^2 p &= \frac{\partial \varepsilon}{\partial t} \\
\end{align*}
\]  

\[ \text{(17)} \]

The static equilibrium equation, in absence of body forces and considering the plain strain conditions, can be written as follows

\[
\frac{\partial \sigma_{i j}}{\partial x_j} = 0 \quad i, j = (y, z) \\
\]  

\[ \text{(18)} \]

where, the stresses are given as follows

\[
\sigma = D \Delta \varepsilon - m \left( p + p_0 \right) \\
\]  

\[ \text{(19)} \]
under isothermal conditions and without any initial stresses, assuming incompressible solid.

**Analytic Solution**

The solution is obtained using two displacement functions $E$ and $\Psi$, each being function of two space variables and time and satisfying the following equations (Gibson et al., 1970)

$$c \nabla^4 E = \nabla^2 (\partial E / \partial t), \quad \nabla^2 \Psi = 0 \quad (20)$$

where $c$, the coefficient of consolidation is given as

$$c = \frac{2Gk\eta}{\gamma_w} \quad (21)$$

The time evolution of the surface displacement for different $h/b$ ratios and for different values of Poisson’s ratio is given in the original paper.

**Simulation details and results**

To simulate the plain strain problem, a domain of size 2m x 150m x 10m is created with the grid of size 2 x 125 x 23 in TOUGH2. The load is applied over 10m. Gravity effects were neglected to be consistent with the assumption in the solution obtained by Gibson et al. (1970). The analytical solution developed is based on the assumption of zero atmospheric pressure. To have an effective atmospheric pressure to be zero, the correct initial stress was used. Also, TOUGH2 includes the fluid compressibility by default. An option was introduced in the Record “T2STR” where the fluid can be simulated as incompressible with user-defined value of fluid compressibility.

The simulation parameters for Poisson’s ratio of zero and $h/b = 1$ are listed in Table 1.

**Table 1. Simulation Parameters. (2D Gibson, Set 1)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Density</td>
<td>2600 kg/m$^3$</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.1</td>
</tr>
<tr>
<td>Permeability (x, y, z)</td>
<td>1e-14 m$^2$</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>1.8e9 Pa</td>
</tr>
<tr>
<td>Biot-Willis Factor</td>
<td>1.0</td>
</tr>
<tr>
<td>Gravity</td>
<td>0 m/s$^2$</td>
</tr>
<tr>
<td>Initial Stress (+y &amp; z s/c)</td>
<td>-1.00e6 Pa</td>
</tr>
</tbody>
</table>

The simulation is carried out for non-zero Poisson’s ratio and with compressible solid grains. The simulation parameters are listed in Table 2.

**Table 2. Simulation Parameters. (2D Gibson, Set 2)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Density</td>
<td>2600 kg/m$^3$</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.10</td>
</tr>
<tr>
<td>Permeability (x, y, z)</td>
<td>1e-14 m$^2$</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.2</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>1.8e9 Pa</td>
</tr>
<tr>
<td>Biot-Willis Factor</td>
<td>0.778</td>
</tr>
<tr>
<td>Gravity</td>
<td>0 m/s$^2$</td>
</tr>
<tr>
<td>Initial Stress (+y &amp; z s/c)</td>
<td>-1 e6Pa</td>
</tr>
</tbody>
</table>
The corner node displacements and the dimensionless displacements compare very well as seen in the figures. The negligible difference in the initial time can be attributed to coarser mesh. Thus, the fully coupled T2STR code and the analytically obtained results are found to be in excellent agreement.

One dimensional Thermo-elastic Consolidation (THM) problem

A problem based on the paper of Aboustit et al. (1982), used by Lewis and Schrefler (1998), is used to verify the complete THM formulation.

Aboustit et al. (1982, 1985) have given the coupled finite element formulation of quasi-static, linear thermoelastic consolidation assuming infinitesimal strain. Lewis and Schrefler (1998) have solved the same problem studying the isothermal consolidation, thermo-elastic deformation, and non-isothermal consolidation as well. Gatmiri and DeLage (1997) have also studied the problem using a new concept of thermal void ratio state surface. An analysis, similar to that of Lewis and Schrefler (1998), is carried out using T2STR. There is some inconsistency in the problem data sets and the parameters in the papers. Since the T2STR consolidation (Hydro-mechanical) code has already been verified, the hydro-mechanical model was used to set the common ground for comparison of the complete thermo-hydro-mechanical problem.

The problem consists of a column subjected to surface load $F_0$ and a constant surface temperature $T_s$ differing by $\Delta T$ from the reservoir initial temperature of $T_0$. The fluid and solid are considered incompressible and the thermal expansion of fluid is neglected. In the heat transfer problem the convective heat transfer is also neglected by Lewis & Schrefler (1998).

Mathematical Model

Considering the above assumptions, the equation of conversation of mass reduces to

$$\phi \frac{\partial (S_\nu \rho_\nu \varepsilon)}{\partial t} + \nabla \cdot q_\nu + S_\nu \rho_\nu \frac{\partial \varepsilon}{\partial t} = 0 \quad (22)$$

where the terms due to solid and fluid compressibility are neglected and no external source is present. In the case of non-isothermal analysis, the conservation of energy equation is given as

$$\frac{\partial (\phi \sum S_\nu \rho_\nu \varepsilon \varepsilon + (1 - \phi) \rho_s \varepsilon)}{\partial t} = -\nabla \cdot (\sum q_\nu \varepsilon h_\nu) - \nabla \cdot J^H$$

(23)

where

$$J^H = \sum J^H_c + J^H_s$$

$$= \left( \sum \lambda_\nu + \lambda_s \right) \Delta T \quad (24)$$

The $\lambda$'s represent the thermal conductivities of the solid and fluids. Neglecting the convective heat transfer term and considering heat transfer only in one dimension, the energy equation becomes

$$\frac{\partial (\phi \sum S_\nu \rho_\nu \varepsilon \varepsilon + (1 - \phi) \rho_s \varepsilon)}{\partial t} = -\left( \sum \lambda_\nu + \lambda_s \right) \frac{\partial T}{\partial z} \quad (25)$$
where, the thermal conductivities have been assumed constant with respect to time.

In the implementation using T2STR, to match the average heat capacity and avoid its variation with temperature and pressure, the fluid internal energy term is zeroed and equivalent constant value is added to obtain the correct average heat capacity.

**Simulation and Results**

The simulation parameters are listed in Table 3.

### Table 3. Simulation Parameters (THM Single Phase Problem).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>2m x 2m x 7m</td>
</tr>
<tr>
<td>Mesh</td>
<td>3 x 3 x 49</td>
</tr>
<tr>
<td>Young’s Modulus, $E$</td>
<td>5.886e7 Pa</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu$</td>
<td>0.4</td>
</tr>
<tr>
<td>Permeability, $k$</td>
<td>7.3e-13 $m^2$</td>
</tr>
<tr>
<td>Avg. Thermal Conductivity, $\lambda$</td>
<td>836.8 W/mC</td>
</tr>
<tr>
<td>Avg. heat capacity, $(\rho c)_u$</td>
<td>40 kCal/ m³C</td>
</tr>
<tr>
<td>Specific Heat (derived), $c$</td>
<td>104.67 J/kg C</td>
</tr>
<tr>
<td>Thermal Expansion Co., $\alpha_T$</td>
<td>0.3e-6 1/C</td>
</tr>
<tr>
<td>Biot-Willis Coefficient, $\alpha$</td>
<td>1.0</td>
</tr>
<tr>
<td>Density of rock, $\rho_S$</td>
<td>2200 kg /m³</td>
</tr>
<tr>
<td>Density of water, $\rho_w$</td>
<td>1000 kg/m³</td>
</tr>
<tr>
<td>External Load, $F_0$</td>
<td>1e4 Pa</td>
</tr>
<tr>
<td>Initial reservoir pressure, $p_0$</td>
<td>1e5 Pa</td>
</tr>
<tr>
<td>Initial reservoir temperature, $T_0$</td>
<td>5 C</td>
</tr>
<tr>
<td>Applied surface temperature, $T_S$</td>
<td>55 C</td>
</tr>
</tbody>
</table>

The results compare very well with the plots given by Lewis et al. (1998) and are shown in Figure 6. The slight variations in the plots can be attributed to inconsistencies in parameter values, assumptions regarding constant parameters (values not available) and differences in the implementation. The effect of a coupled formulation and its importance is also evident from the plot. This verifies the accuracy of the coupled thermo-hydro-mechanical T2STR code.

**Two Phase Thermo-elastic Consolidation Problem**

The same 1D thermo-elastic consolidation problem was solved with two phase condition. Lewis and Schrefler (1998) have done it for lower temperature and taking into account the air as a third phase.

**Simulation and Results**

The parameters required for the simulation was mostly similar to the single-phase consolidation problem. The initial conditions were changed to demonstrate the implementation for a two phase problem. The parameters used were as listed in Table 4. There is no analytical solution available for this problem and hence the results are shown and are discussed with the physical understanding of the problem.

The variation in pressure, temperature and saturation is seen in Figure 7, Figure 8, and Figure 9 at time 10, 1e4 and 1e7 seconds respectively. The displacement plots under different simulation runs are also shown in Figure 10.

As is evident, since there is small amount of gas, initially the load is taken by the solid and hence we see the downward displacement corresponding to the load. This displacement can be easily calculated using the simple elasticity calculations and is verified. In the case of a single phase isothermal problem, the load would shift to the liquid and the pressure would increase. But since there is highly compressible gas existing in the reservoir, we should not expect significant rise in pressure. However, this problem includes heating at the top of the reservoir. This causes vaporization and increased pressure in the heated cells. Due to the relatively low
permeability of the reservoir, the drainage is not rapid.

Table 4. Simulation Parameters (Two Phase).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>2m x 2m x 7m</td>
</tr>
<tr>
<td>Mesh</td>
<td>3 x 3 x 49</td>
</tr>
<tr>
<td>Young’s Modulus, $E$</td>
<td>$5.886e7$ Pa</td>
</tr>
<tr>
<td>Poisson’s ratio, $ν$</td>
<td>0.4</td>
</tr>
<tr>
<td>Permeability, $k$</td>
<td>$7.3e-13$ m²</td>
</tr>
<tr>
<td>Avg. Thermal Conductivity, $λ$</td>
<td>836.8 W/m°C</td>
</tr>
<tr>
<td>Specific Heat (derived), $c$</td>
<td>100 J/kg°C</td>
</tr>
<tr>
<td>Thermal Expansion Co., $α_T$</td>
<td>0.31e-6 1/C</td>
</tr>
<tr>
<td>Biot-Willis Coefficient, $α$</td>
<td>1.0</td>
</tr>
<tr>
<td>Density of rock, $ρ_s$</td>
<td>2200 kg/m³</td>
</tr>
<tr>
<td>Density of water, $ρ_w$</td>
<td>1000 kg/m³</td>
</tr>
<tr>
<td>External Load, $F_0$</td>
<td>1e4 Pa</td>
</tr>
<tr>
<td>Initial reservoir pressure, $p_0$</td>
<td>1e5 Pa</td>
</tr>
<tr>
<td>Initial gas saturation, $S_g$</td>
<td>0.08</td>
</tr>
<tr>
<td>Applied surface temperature, $T_s$</td>
<td>150 C</td>
</tr>
<tr>
<td>Initial reservoir temperature, $T_0$</td>
<td>99.6 C</td>
</tr>
</tbody>
</table>

In the displacement plots, Figure 10, the simulations other than the complete THM is carried out using one way coupling. This helps to see the individual effects of pressure and temperature on the column.

The “Hydro-Mech” legend plot indicates the one way coupling simulation under isothermal conditions. Hence it shows the deformation mainly due to the externally applied load only, since there is negligible pressure change in the column as the small quantity of the compressible gas is already present in the column.

The “Thermo-Mech” legend displacement plot shows the combined effect of the externally applied load and only the thermal effects. This was achieved by turning off the poroelastic effects using the respective flag in the T2STR record in the TOUGH2 input file.

The “Hydro-Mech (T)” legend indicates the simulation, where in, TOUGH2 run was done using non-isothermal conditions, thus capturing the pressure variation due to the phase changes and increase in pressure due to undrained condition as
explained above. But the thermal effects on displacement were neglected by setting the flag in T2STR record of the TOUGH2 input file to zero. Hence in “Hydro-Mech (T)” legend displacement plot, we see the final deformation exactly equal to the initial deformation, which is solely due to externally applied load.

The simulation results are consistent with the physical understanding of the problem.

**CONCLUSION**

The T2STR, fully coupled code, is implemented to carry out thermo-hydro-mechanical (THM) analysis of porous media under multiphase conditions. The code is tested and verified using various benchmark problems. Multiple materials can be now used in T2STR code to model the reservoir. A user interface is provided to facilitate the pre-processing required to run the T2STR code.

We demonstrated the capability of T2STR code to successfully handle single phase as well as two phase problems and simulate a two phase fluid flow and heat transfer analysis with deformation of the porous media. The analyses of the problems also demonstrated the effectiveness of the ability to turn on-off certain effects provided in the T2STR code. It proves very beneficial to be able to study the individual effects and gain deeper understanding into the physics of the problem.

In general, due to the nature of the THM problem, the selection of timesteps in relation to the density of the mesh for the given domain is important and should be carefully selected. Due to higher condition number of the Jacobian matrix in THM problem, the mesh also plays a vital role in convergence.

**REFERENCES**


