THE USE OF SCALED-DOWN METHOD IN GEOTHERMAL RESERVOIR MODELING

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ABSTRACT

This paper is a report of an initial attempt to conduct laboratory-size, experimental geothermal reservoir modeling. The method is based on the basic physical understanding of a mathematical model of a reservoir. The reservoir model used here is a fluid dominated geothermal reservoir. The hydrostatic pressure and the reference temperature are extracted from the mathematical model, in the form of nondimensional system. The Rayleigh number which is the ratio between the enthalpy of convection to the enthalpy of conduction is kept constant, while the characteristic time, velocity, and pressure are isolated in order to develop temperature and flow patterns. In that way, a real geothermal reservoir can be built in a laboratory-size geothermal reservoir where the temperature and flow patterns can be investigated from the reservoir by means of thermocouple and laser Doppler velocimeter.

A typical example of a laboratory model which can be built from a real reservoir is as follows: when the linear size of the real reservoir is reduced by 10^3 and its permeability is multiplied by 10^4, the resulting velocity will be magnified by 10^2. Consequently, the characteristic time required for the fluid to flow from the bottom to the surface in the real situation will be reduced by the factor of 10^6, meaning that the conditions investigated in one-day experiment in the laboratory model is equivalent to almost 3,000 years conditions depicted from the real reservoir.

INTRODUCTION

The problem of convective fluid flow and mass and heat transport in porous media have become the increasingly fascinating subject of investigations in recent years due to its application for example in wired electrical cable, geothermal activities, etc. Thermal convection around a uniform flux pipe embedded in a box containing a saturated porous medium was studied experimentally and theoretically (K. Himasekhar et al., 1988). The agreement between the theoretical and experimental are reported quite good. In theoretical effort, a simple, two-dimensional, liquid-phase reservoir model was developed and analyzed to gain the basic physical understanding to the fluid flow dynamics and heat transfer mechanism in geothermal system (Sutrisno, 1995). In this study we try to bring them together in terms of geothermal reservoir modeling. Thus, it is one of the objectives of the present work to study the model in both approach, theoretically and experimentally. In this attempt we also try to overcome the difficulties in any experimental modeling of a geothermal reservoir which is in the time scale means also in the fluid velocity scale (Djoko Wintolo et. al., 1996).

In the present work the previously developed (Djoko Wintolo et. al., 1996) is developed further which could transform the conditions used in the mathematical formulation into a physical dimension in the scale of laboratory so the fluid flow dynamics and heat transfer mechanism can be analyzed experimentally and compared it to the numerical results. Another objective of this study is also to establish whether the experimental apparatus may be used to model convection associated with a simple model, as a first step, of a geothermal reservoir.

FORMULATION OF THE MODEL

As mentioned before, the experimental model is based on the basic physical understanding of the mathematical model. Thus we first analyzed the model. In this first effort, the geothermal reservoir is simulated as a liquid dominated reservoir with unsteady convective flow development toward a natural state in homogeneous, isotropic porous
medium filled with saturated liquid. The law of mass conservation, momentum and energy balance could then be expressed as follow

\[ \overrightarrow{V_r} \cdot \nabla \overrightarrow{V} = 0 \quad \text{(1)} \]

\[ \left( \frac{\nabla \rho'}{\rho_o} - \frac{g}{\alpha'} \right) \nabla T' + \alpha' \left(\frac{T' - T_o'}{T' - T_o} \right)^2 \overrightarrow{V'} = \nabla (\alpha' \nabla T') \quad \text{(2)} \]

\[ \left[ 1 - \Phi \right] \rho'_o C'_v + \Phi \rho'_o C'_v \right] \frac{g}{\alpha'} T' = \frac{\rho'_o C'_v}{\alpha'} \nabla T' \quad \text{(3)} \]

with some assumptions that the horst structure matrices \((\Phi', K', K'_m)\) are isotropical, inhomogeneous and independent of temperature.

The Boussinesq approximation is applied as

\[ \rho' = \rho_o \left(1 - \alpha' \left(\frac{T' - T_o}{T' - T_o} \right)^2 \right) \quad \text{(4)} \]

The kinematics viscosity which is dependent of temperature \(\nu_T = \gamma_0 \left(\frac{f(T)}{T'} \right)\) and \(\rho_o', \alpha', T_o', \beta'\) are all constant. The pressure work and the viscous dissipation are ignored here.

The normalized dimension below can then be applied to form the non-dimensional governing equations

\[ \overline{X} = \frac{X'}{L'}, \quad \overline{V} = \frac{V'}{V'}, \quad \overline{t} = \frac{t'}{t'}, \quad \overline{V'} = \overline{V'} (L'/V') \quad \text{(5)} \]

\[ \overline{T} = \frac{\Delta T'}{T_o} - \frac{\rho' - \rho_o' \frac{\Delta T}{T_o}}{\rho_o'} \beta' = \frac{\beta' T_o}{\alpha'} \quad \text{(6)} \]

\[ \overline{\mu} = \frac{\mu'}{\mu_o} = \frac{k'}{k_o} = \frac{g}{g'} = \frac{\tau'}{\tau_o} = \frac{\Delta T'}{T_o} \quad \text{(7)} \]

where \(L'\) is the characteristic length of the reservoir. \(T'\) is the temperature difference, \(g'\) is the gravitational acceleration, \(a'\) is the coefficient of the thermal expansion, \(K'\) is the absolute permeability, \(\rho_o'\) is the density and \(\nu_{v'}\) is the dynamics viscosity.

In that way, the velocity characteristic is,

\[ \nu_{v'} = \frac{g' k_o a' \Delta T}{\nu_o} \]

and

\[ \rho_o' = \rho_o' g' a' \Delta T' \]

is the pressure characteristic and \(t'_{r} = L'/V'_{r}\) is the time characteristic.

The non-dimensional governing equation can then be expressed as

\[ \overline{V} \cdot \nabla \overline{V} = 0 \quad \text{(8)} \]

\[ \overline{\mu} \overline{V} = -\nabla \overline{P} \quad \text{(9)} \]

\[ \frac{\overline{T} - \overline{T}_H}{\tau} \left(1 + \beta (T + \overline{T}_H - 2) \right) \frac{\nabla \overline{V}}{\overline{V}} \quad \text{(10)} \]

where \(R\) is the Rayleigh number

\[ R = \left( g K_o a' \Delta T \right) \left( \frac{\nu_o}{\nu_{v'}} \right) \left( \frac{\rho_o'}{\rho_o} \right) \left( \frac{C_o}{C_o'} \right) \left( \frac{K'}{K} \right) \left( \frac{l_o}{l} \right) \left( \frac{m}{K} \right) \quad \text{(11)} \]

and

\[ C_m = \frac{\frac{\alpha C_v}{\alpha'} + (1 - \Phi) \rho_o' C'_o / \rho_o}{\rho_o} \quad \beta = \frac{\beta'}{\alpha'} \quad \frac{K_m}{K} = \frac{K_m}{K} \quad \frac{C_m}{C_o} = \frac{C_m}{C_o} \quad \frac{\mu}{\mu_o} = \frac{\mu}{\mu_o} \]

**SCALE DOWN PROCEDURE**

The scale down applied here, is a method to isolate the coefficient in the governing equation, Rayleigh number \(R\) equation (11), which is function of variables \(\beta, C_m, C_o, K_m, K, m/K\) to be a certain value and kept constant by choosing any numerical value of the variables which could suit laboratory size requirement. Mathematically, the solution of the governing equation will be unique.

If the mathematical conditions are comply, a typical example of a laboratory model which can be built from a real reservoir is as follow; when the linear size of the real reservoir is reduced by \(10^3\) and its permeability \(k'\) is multiplied by \(10^3\) the resulting velocity, \(v_{v'}\), will be magnified by \(10^3\). Consequently, the characteristic time required for the fluid to flow from the bottom to the surface in the real situation, \(t'_{r}\), will be reduced by the factor of \(10^3\), meaning that the conditions investigated in one-day experiment in the laboratory model is equivalent to almost 3,000 years conditions depicted from the real reservoir.
THE INITIAL EXPERIMENTAL APPARATUS

A preliminary experimental model based on the method was constructed and basic characteristic investigations for the model is currently in progress. The lay-out of the experimental apparatus and its major dimension are as shown in Figure 1.

The apparatus is built based on the experimental apparatus used by Himasekhar et al. (1988). The apparatus consists of a well-insulated Plexiglas box filled with stone crushed and it is structured into three different region, namely region III, IV, and V with different porosity as shown in Table 1. The stone crushed is used to simulate the porous medium. Region I and II simulate impermeable boundaries.

In fact the structured of the porous medium is one of some differences exist between this apparatus to the one used by Himasekhar et al. (1988).

**Table I. Thermophysic parameters of the crushed stone in the apparatus**

<table>
<thead>
<tr>
<th>Region</th>
<th>Porosity %</th>
<th>Density kg/m3</th>
<th>Specific Heat J/kg C</th>
<th>Conductivity W/m°C</th>
<th>Permeability mD</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>3.5</td>
<td>2650</td>
<td>1050</td>
<td>3.01</td>
<td>1.75</td>
</tr>
<tr>
<td>II</td>
<td>3.8</td>
<td>2640</td>
<td>1020</td>
<td>3.01</td>
<td>1.75</td>
</tr>
<tr>
<td>III</td>
<td>3.4</td>
<td>2630</td>
<td>1040</td>
<td>3.04</td>
<td>9.45</td>
</tr>
<tr>
<td>IV</td>
<td>3.7</td>
<td>2540</td>
<td>1050</td>
<td>2.69</td>
<td>7.35</td>
</tr>
<tr>
<td>V</td>
<td>4.5</td>
<td>2550</td>
<td>1030</td>
<td>2.10</td>
<td>8.95</td>
</tr>
</tbody>
</table>

The length of the cylindrical heater spans the box's width. A perforated plate heat exchanger was fitted at the top of the apparatus to pick up the heat from the heater. The perforations are made to accommodate thermal expansion of the fluid inside the apparatus. The permeability of the plate was assumed to be impermeable and isothermal for the purpose of the theoretical modeling. A water pool of about 10 mm depth is maintained above the plate. At the very top of the apparatus is a sealed cover to prevent evaporation.

Experiment are carried out by inputting the heater with electric power and it is changed in a sequence of small steps. A period of several hours is allowed to achieve steady state condition. When the maximum temperature for the apparatus has been monitored, the investigation is repeated by gradually reducing the electric power input to the heater. The flow rate and temperature rise of the cooling water which flows through the heat exchanger plate are continuously monitored and used to calculate the rate of energy outflow from the apparatus. This quantity is then compared to the electrical power input into the heater.

The distribution of the temperature was measured by means of a network of thirty-gage copper constantan thermocouples embedded at various locations within the porous matrix. The temperatures were continuously recorded by using data acquisition system. The laser Doppler apparatus to investigate the flow has not been set up yet.

Figs. 2 and 3 are the two example of the temperature distribution in the box for the heater temperature of 72 and 100°C. The isothermal distribution was drawn from the reading of the thermocouple matrix which was then manipulate by using a program.
flow has been established. Hot fluid is rising above the heater and descending along the side walls. As the temperature increases, the convective effects are predicted more important.

Numerical solution of the temperature distribution in the box was processed by using TOUGH2 program, a numerical program for geothermal reservoir modeling.

Observation of the possibility of transition into a three-dimensional and time dependent flow is still underway.

![Fig 3. The distribution of the temperature in experimental box for temperature 100°C.](image)

NOTES FROM THE STUDY

Preliminary efforts in experimental modeling based on a mathematical approach for a type of geothermal reservoir has been conducted. An apparatus to study the capability of the method in showing the fluid flow dynamics and heat transfer mechanism in the apparatus has also been set up. Investigation of the temperature fields from a heat source embedded and placed in the bottom of the box was carried out.

The approach, which uses simple algebraic operations, shows that experimental modeling for geothermal reservoir in laboratories is theoretically possible. The preliminary experimental evidence shows that there exists temperature fields which tend to follow the numerical results from the TOUGH2.

The adequacy of the experimental apparatus for modeling reservoir with high temperature and pressure conditions is also being examined.

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REFERENCES


