Estimation of Parameters Distribution and Injection Process in Geothermal Reservoir

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Abstract — The objective of this study is to develop a simulator for geothermal energy investigation. Geothermal energy is well known as a renewable and clean energy. The first step to predict the potential of geothermal energy can be estimated by modeling, among others physical and numerical simulation. In this study, we have simulated the geothermal reservoir using different parameters e.g. fluid permeability, porosity and temperature. In this study, a mathematical and numerical modeling are performed to simulate the geothermal reservoir with injection and production well in the reservoir. Mathematical modeling in this simulation is based on Darcy's law, mass balance and energy balance. The model is calculated using finite difference method. Results of the calculation are obtained in form of distribution of temperature, pressure, enthalpy and direction of fluid flow.

Keywords – Physical modeling, injection, production, Darcy's law, mass balance, energy balance.

I. Introduction

Geothermal fluid is derived from water surface (meteoric water) into the rock below the surface through cracks or permeable rock [1]. In reservoir, water from surface will contact with the hot rocks. Because hot water is lighter than cold water, then hot water will tend to move upwards through cracks or permeable rock, and then be appeared on the surface as hot springs, geysers, etc. (Fig. 1).

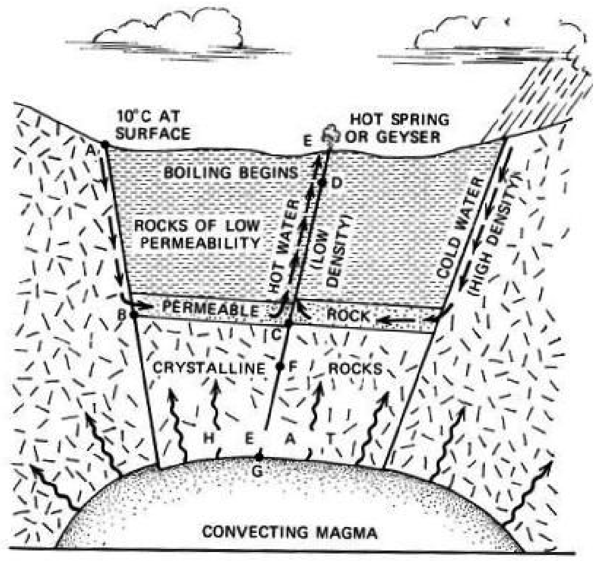

Fig. 1. Hydrothermal Circulation [2]

Geothermal energy is one of the prospect energy in the future, so that it is important to exploit the geothermal energy. For this reason clarifying the thermal processes in a geothermal reservoir is needed. Nowadays, some numerical simulations are available among others from Faust and Mercer [3] that presented the geothermal reservoir simulation for liquid and steam dominated. However almost of them just simulate the fluid condition for liquid and two phase state only, in which the temperature is less or equal to the boiling point depth (BPD) temperature. In one occasion the higher temperature than BPD can be attained at the bottom area of the reservoir. In this research, a simulator is developed that can describe temperature higher than BPD [4]. This aim is achieved by using finite difference method based on mass and heat balance equation. Results of the calculation are obtained

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in form of distribution of temperature, pressure, enthalpy and direction of fluid flow.

II. Basic Concept of Calculation

In Geothermal reservoir modeling there are a lot of variables and formulation to be calculated. These formulation and variables are calculated using mathemathical approach based on the physical modeling. In this paper we use some formulation and variables that relate to fluid flow in the porous medium. Some formulation and variables that related to how fluid flow in the porous mediumnare used.

2.1 Darcy's Law

It is assumed that the movement of fluid in the geothermal reservoir is sufficiently slow. Therefore the darcy's equations for multiphase flow may be used as simplified momentum balances [3]. Darcy Law formulate the fluid flow through a porous medium. The Darcy's model can be simplified as a fluid that flow in a simple porous pipe [5]. According to the Darcy's Law, the fluid discharge Q in a porous medium in a pipe (Fig. 2) that has length L is

$$Q = vA = -\frac{kA}{\mu}\Delta P \tag{1}$$

where A is cross sectional area, ΔP is pressure difference with v is fluid velocity in a porous medium (m^3/s), and μ is fluid dynamic viscosity (kg/m.s), and k is fluid permeabillity.

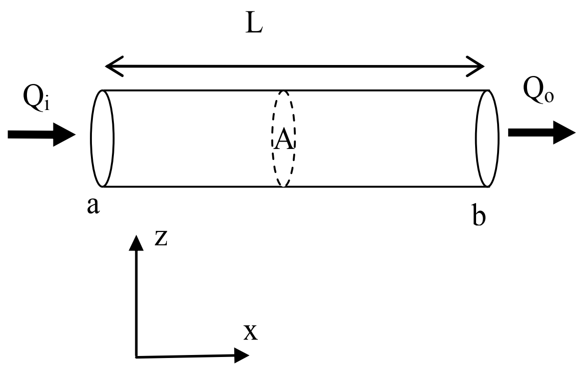

Fig. 2. Pipe's model that describe the Darcy's Law

Darcy's Law can be expressed for a single phase flow as follows [6] :

$$v = -\frac{k}{\mu}(\nabla P - \rho g) \tag{2}$$

In vertical direction, for single phase-flow can be expressed as follows :

$$v_z = -\frac{k_v}{\mu}\left(\frac{\partial P}{\partial z} - \rho g\right) \tag{3a}$$

and for horizontal direction:

$$v_x = -\frac{k_h}{\mu}\frac{\partial P}{\partial x} \tag{3b}$$

In Eq. (3a) and (3b), k_v and k_h are the permeability for vertical and horizontal direction. For two phase fluid flow, the mass flux density of liquid phase is given by [6]:

$$v_w = -k\frac{k_{rw}(S_w)}{\mu_w}(\nabla P - \rho_w g) \tag{4a}$$

and for steam phase is:

$$v_v = -k\frac{k_{rs}(S_s)}{\mu_s}(\nabla P - \rho_s g) \tag{4b}$$

where k_{rw} and k_{rs} are relative permeability for liquid and steam respectively. In a two phase fluid flow case, the k variables have to be defined as follows:

$$k = k_r.k_f \tag{5}$$

with k is effective permeabillty, k_r is a relative permeabillity, and k_f is phase permeabillty [6]. In multiphase flow, the fluid permeabillity is not only depend on the porosity of the rocks but also on the phase. So that the equation (1) can be written as follows:

$$v = -\frac{k_r.k}{\mu}(\nabla P - \rho g \nabla D) \tag{6}$$

with ρ is the fluid density, ϕ is porosity and g is gravity accelaration.

2.2 Mass and Energy Balance

The mass and energy balance for this model is well described by a box of square, where the mass and energy that come in to the box will be same with the mass and energy that going out from the box as visualized in the Fig.3.

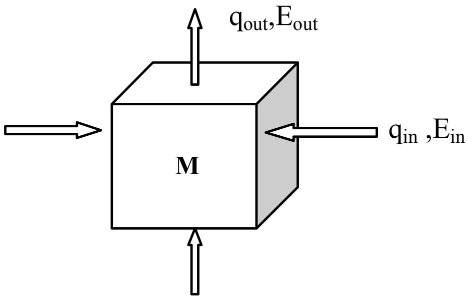

Fig. 3. Mass and energy balance of the box

The mass and energy balance for this modeling are described folows [5] :

$$\frac{\partial M}{\partial t} = -q_{out} + q_{in} \tag{7}$$

$$\frac{\partial Q}{\partial t} = -E_{out} + E_{in} \tag{8}$$

with M is the fluid mass (kg), q_{out} is production mass flux (kg/s), q_{in} is replenishment mass flux (kg/s), Q is total energy in the reservoir (kg.m^2/s^2), E_{out} is discharge energy flux (kg.m^2/s^3), dan E_{in} is replenishment energy flux (kg.m^2/s^3). In geothermal system there are two general classification of hydrothermal fluid, e.g. fluid with one phase and two phase. The difference beetwen this classification will affect the mass and energy definition in the above equation.

Based on Darcy' equation, two main equation of the general mathematical model are derived as mass and heat balance equation ([4] and [6]) as follow:

a. Mass balance equation,

$$\frac{\partial}{\partial t}\left(\phi\rho_w S_w + \phi\rho_s S_s\right) + \nabla \bullet \left(Q_{mw} + Q_{ms}\right) - q_m = 0 \tag{9}$$

where ∇ is the vector differential operator, t is the time, ϕ is the porosity, ρ_w is the density of liquis, ρ_s is the density of steam, S_w is the water saturation, S_s is the steam saturation, Q_{mw} and Q_{ms} are the mass flux of fluid for water and steam and q_m is the mass source term.

b. Heat balance equation

$$\frac{\partial}{\partial t}\left(\phi\rho_w S_w h_w + \phi\rho_s S_s h_s + (1-\phi)\rho_r h_r\right) + \nabla \bullet \left(Q_{mw}h_w + Q_{ms}h_s\right) - \nabla \bullet \begin{bmatrix} K\left(\frac{\partial T}{\partial P}\right)_h \nabla P \\ + K\left(\frac{\partial T}{\partial h}\right)_P \nabla h \end{bmatrix} - q_e = 0 \tag{10}$$

where h is the specific enthalpy, T is the temperature, P is the pressure, K is the thermal conductivity of medium, ρ_r is the rock density, h_r is the rock enthalpy and q_e is the energy source term. In Eq. (9) and (10*), s, w* and *r* refer to steam, liquid and rock.

Furthermore, the mass and energy equation can be described with considering the Darcy's law so that it can be described as follow [6]:

$$\frac{\partial(\phi\rho_f)}{\partial t} + \nabla\left(-\frac{\rho_f k}{\mu_f}\left(\nabla P - \rho_f g \nabla D\right)\right) = 0 \tag{11}$$

If we put $C = \rho(\alpha + \phi\kappa)$, where α is the compressibility constant and and κ compressibility, then Eq. (11) can be formulated as Eq. (12).

$$\nabla\rho_f\left[\frac{k}{\mu_f}\left(\nabla P - \rho g\right)\right] = C\frac{\partial P}{\partial t} \tag{12}$$

Energy balance equation (8) can be described as follows:

$$\left[(1-\phi)\rho_m C_m + \phi\rho_f C_f S_f\right]\frac{\partial T}{\partial t} + \rho_f v_f C.\nabla T = -\nabla.K\nabla T \tag{13}$$

with T is temperature and K is thermal conductivity respectively. The index f denote to fluid phase.

2.3 Reservoir's Presseure Decrease

One problem that always occurs in geothermal reservoir exploitation process is the pressure decrease that can affect another variable such as temperature and density in the reservoir. In this study we use the formulation of pressure decrease to describe the reservoir condition in real condition. We still pass over some variables to simplify the calculation. The pressure decrease in the reservoir depends on three main variables namely gravity, friction and acceleration [5], which is shown in the following equation:

$$\left(\frac{dP}{dz}\right)_{total} = \left(\frac{dP}{dz}\right)_a + \left(\frac{dP}{dz}\right)_f + \left(\frac{dP}{dz}\right)_g \tag{14}$$

The acceleration factor is neglected because of its value contribution on the total pressure drop is too small. The friction factor is also ignored because the process of change in pressure due to the friction influence is not fixed at all points. So the pressure drop equation can be written as follows:

$$\left(\frac{dP}{dZ}\right)_{total} = \rho_w g \sin\theta \tag{15}$$

The principle of the pressure drop is applied along the vertical line of the reservoir so that the value of *sin* θ =1. After integral process of Eq. (15), we will get the pressure on the depth *h* as follows:

$$\int_{P_o}^{P} dP = \int_{0}^{h} \rho_w g dz \tag{16}$$

The influences of friction and acceleration are very small, so that they can be ignored. The pressure can be approached as lithostatic pressure as integration of Eq. (16). Then we find the pressure value as follows:

$$P(h) = P_o + \rho\, g\, h \tag{17}$$

where P_o is pressure at earth's surface and *h* is the depth.

2.4 Finite Difference

Finite Difference is a numeric method that used to approximate the solution of some differential equation by dividing its derivative problem into a square block with a specific interval (Fig. 4).

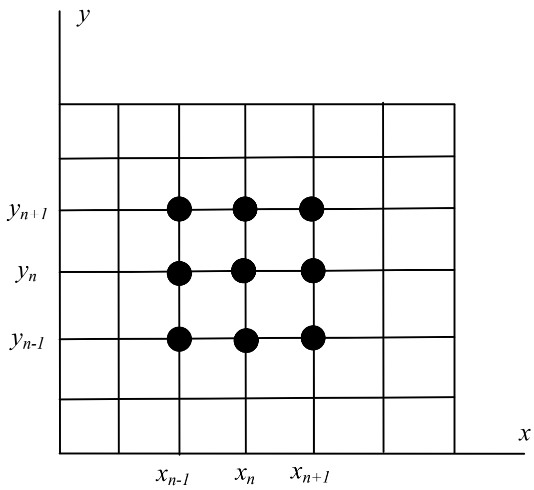

Fig. 4. Finite difference grid system

The variables in finite difference problems are shown in the following notation [5]:

$$u_{i,j} = u(x_0, y_0) \tag{18}$$

$$u_{i\pm m, j\pm n} = u(x_0 \pm m\,\Delta x, y_0 \pm n\,\Delta y) \tag{19}$$

where $u_{i,j}$ is *u* value in (x_o, y_o). The variable *m* and *n* is integer number (-∞,.., -2, -1, 0, 1, 2, …,∞).

Notation in Eq. (18) and (19) further approximated by using Taylor series expansion as follow:

$$u(x) = \sum_{m=0}^{\infty} \frac{(x - x_i)^m}{m!} \left(\frac{\partial^m x}{\partial x^m} \right)_i . \tag{20}$$

Eq. (20) can be approximated using Taylor series up to second order to obtain the following result:

Taylor_1:

$$u_{i+1,j} = u_{i,j} + \Delta x \left(\frac{\partial u}{\partial x} \right)_{i,j} + \frac{(\Delta x)^2}{2} \left(\frac{\partial^2 u}{\partial x^2} \right)_{i,j} + \cdots \tag{21}$$

Taylor_2:

$$u_{i-1,j} = u_{i,j} - \Delta x \left(\frac{\partial u}{\partial x} \right)_{i,j} + \frac{(\Delta x)^2}{2} \left(\frac{\partial^2 u}{\partial x^2} \right)_{i,j} - \cdots \tag{22}$$

Taylor_3:

$$u_{i-2,j} = u_{i,j} - 2\Delta x \left(\frac{\partial u}{\partial x} \right)_{i,j} + \frac{(2\Delta x)^2}{2} \left(\frac{\partial^2 u}{\partial x^2} \right)_{i,j} - \cdots \tag{23}$$

From the Taylor_1 series expansion result in equation (21), a finite-difference numerical methods formulations can be obtained. By expanding the formulation up to first-order formula, we find the following equation:

$$\left(\frac{\partial u}{\partial x} \right)_{i,j} = \frac{u_{i+1,j} - u_{i,j}}{\Delta x} = \frac{u(x_0 + \Delta x, y_0) - u(x_0, y_0)}{\Delta x} \tag{24}$$

The Taylor_2 expansion result up to its first order is known as backward difference as follow:

$$\left(\frac{\partial u}{\partial x} \right)_{i,j} = \frac{u_{i,j} - u_{i-1,j}}{\Delta x} = \frac{u(x_0, y_0) - u(x_0 - \Delta x, y_0)}{\Delta x} \tag{25}$$

By applying a substraction on Eq. (24) and (25), then a finite difference method formulation as central differences can be obtained as the following equation:

$$\left(\frac{\partial u}{\partial x}\right)_{i,j} = \frac{u_{i+1,j} - u_{i-1,j}}{2\Delta x} = \frac{u(x_0 + \Delta x, y_0) - u(x_0 - \Delta x, y_0)}{2\Delta x} \quad (26)$$

The second derivative formulation can be obtained by using two step differentiation process.

$$\left(\frac{\partial^2 u}{\partial x^2}\right)_{i,j} = \frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{(\Delta x)^2} = \frac{u(x_0 + \Delta x, y_0) - 2u(x_0, y_0) + u(x_0 - \Delta x, y_0)}{(\Delta x)^2}. \quad (27)$$

Eq. (27) can be applied to solve a differential equations problems based on the mass and energy flow equation.

III. Discretization and Modeling

The next step for modeling of the geothermal reservoir is to form a discretization formula using finite difference and after that apply it to mass and energy balance equation. The discretization formula is needed for calculating and knowing the value of variables in the reservoir.

3.1 Mass and Energy Equilibirum Discretization

The discretization process using divergence theorem is needed to get the final formulation. The formulation can be applied to find temperature, pressure and enthalpy of the reservoir [6]. For the entire model of the reservoir system, the mass balance of each box should be integrated into the all area of the reservoir, so that Eq. (7) becomes [6].

$$\frac{k}{\mu_f}\sum_m \left(\rho_{f_{n,m}} \frac{P_m - P_n}{d} - \rho_{f_{n,m}}{}^2 g\eta\right) = C\frac{\Delta P_n}{\Delta t} d \quad (28)$$

and also the energy balance becomes:

$$\rho\frac{\Delta H_n}{\Delta t} d = \sum_m \left[\begin{array}{l} K(\mu_{JT}\frac{P_m - P_n}{d} + \frac{1}{C_p}\frac{H_m - H_n}{d}) \\ + \rho_{f\,n,m}\frac{k}{\mu_f}\frac{P_m - P_n}{d}\left(\frac{H_m + H_n}{2}\right) \\ - \frac{k}{\mu_f}\rho_{f\,n,m}{}^2 \bar{g}\left(\frac{H_m + H_n}{2}\right) \end{array}\right] \quad (29)$$

3.2 Reservoir's Modeling and Boundary Conditions

In this study the reservoir is modeled as a square box that located in 500 m underground with the caprock temperature is 100°C, and then the bedrock as a heat source of the reservoir is 500°C. The reservoir dimension is 400m x 1000m and divided into some small partitions with dimension 20m x 20m. The porosity is 10% and the fluid density is 910 kg/m^3. In this model, there are no mass and energy that comes in and out from the reservoir, so the reservoir is a closed system.

In the second modeling, we attach the injection and production well in the reservoir. We picked the injection well of 800 meters below the ground and the production well is 500 meters below the ground. The porosity of the well is assumed by 80%. The injection well is attached under production well to avoid the temperature decrease in the reservoir. Physical parameters that assumed in the reservoir modeling is shown in the **Table 1**.

Table 1 Physical Parameters

Physical Parameters	**Value**
Intrinsict permeabillity (*m*^{2})	1x10^{-14}
Fluid dynamic viscosity (*kg/m s*)	0.0004
Vertical compresibillity in porous medium (*ms*^{2}*/kg*)	4x10^{-11}
Fluid compresibillity (*ms*^{2}*/kg*)	4.5x10^{-9}
Fluid thermal expansivity ($^0C^{-1}$)	5x10^{-4}
Rock thermal conductivity (*kg m/s*$^{3\,0}$*C*)	1.7
Rock density (*kg/m*^{3})	3000
Rock heat specific (*m*^{2}*/ s*^{2}*C*)	800
Fluid heat specific (*m*^{2}*/s*^{2}*C*)	3500
Gravity acceleration (*m/s*^{2})	9.8

The illustration of reservoir model for the first and second step modeling with injection and production well is visualized in Fig.5 and Fig. 6..

3.3 Reservoir Modeling with Injection and Production Well Attached

The first step modeling results is used as an initial condition for the next modeling process by added an injection wells. The wells that attached have a high porosity and permeability. These wells drain a fluid from the surface to the bottom of the reservoir with a fixed velocity. The reservoir geometry illustration can be seen in Fig.6.

The injection wells is placed deeper than a production wells so that the injected fluid will be directly in contact with the hot rocks. From this modeling process, we can get the distribution of temperature, pressure, enthalpy, and fluid flow direction at a specified time range. Flowchart of the modeling can be seen in Fig.7.

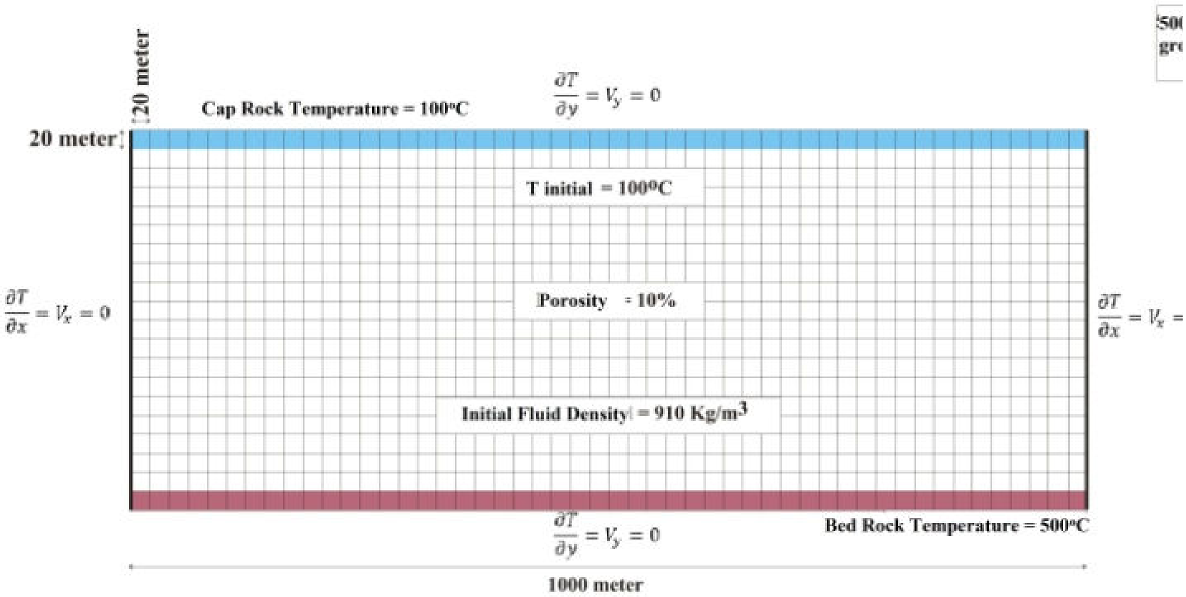

Fig. 5. Model of geothermal reservoir [5]

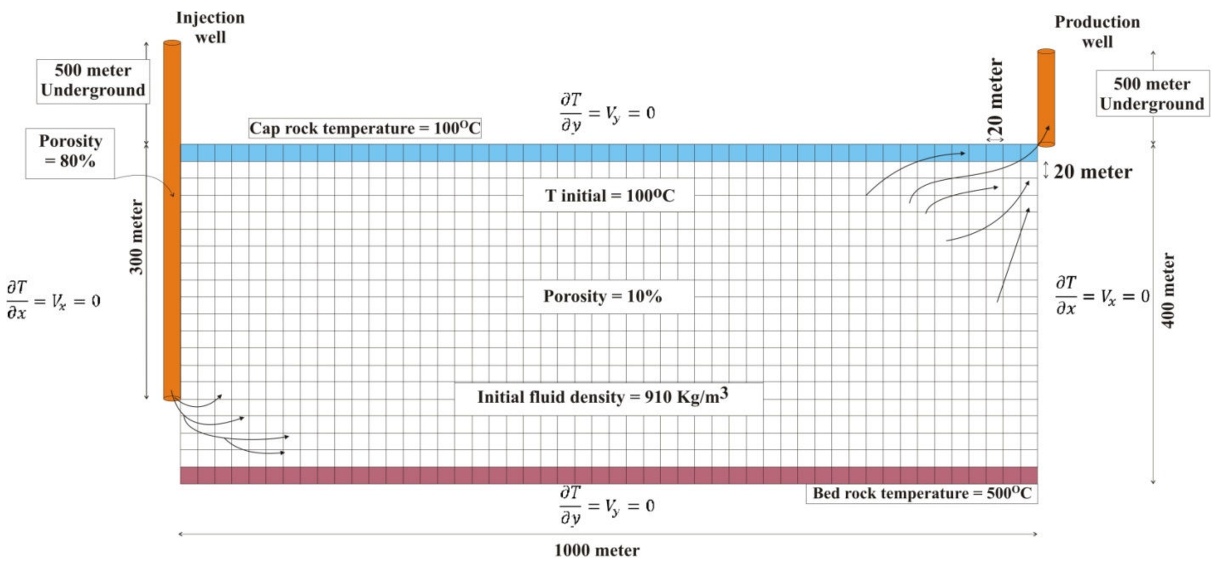

Fig. 6. Reservoir model with injection and production well [5]

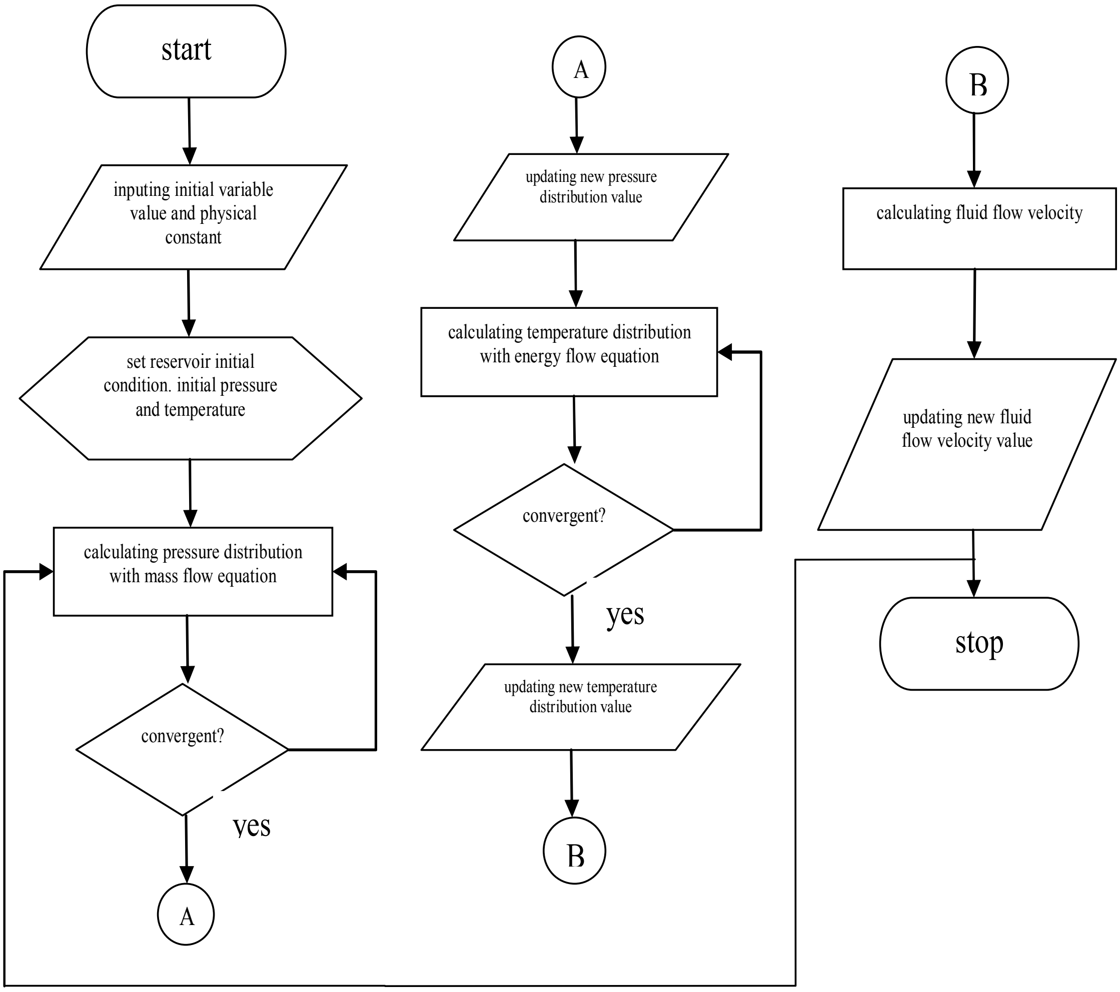

Fig. 7. Reservoir thermodynamics distribution model flowchart

IV. Result and Analysis

By using the above initial condition, physical boundary and the physical parameters in Table 1 into Eq. (28) and (29) iteratively as function of time the observation are carried out. The observation is stopped until 1000th years, because we assumed that the reservoir is ready to be exploited with the high temperature and also high enthalpy and stable pressure distribution that covered the whole reservoir. The result that we got from the reservoir modeling is three main values of variables namely temperature, pressure, and enthalpy distribution.

4.1 Temperature Distribution

Fig. 8 shows the simulation result of temperature at 1000th year.

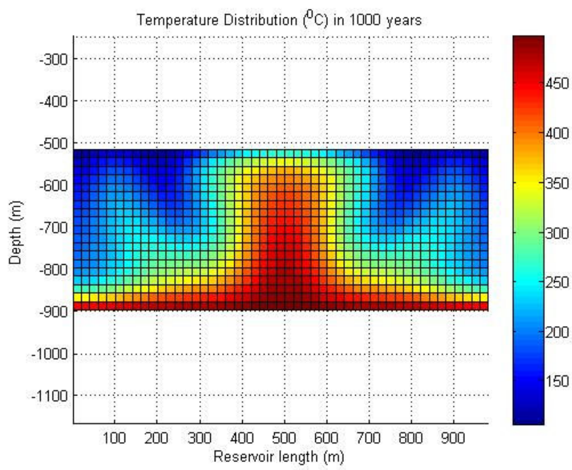

Fig. 8. Temperature contour at 1000th year

The result showed that the temperature distribution is always changing and moving over time in the reservoir. This is because of the convection flow fluid is always moving and there are no state condition in the reservoir model. The mevement of the fluid direction as convective flow in reservoir can be seen in Fig.9.

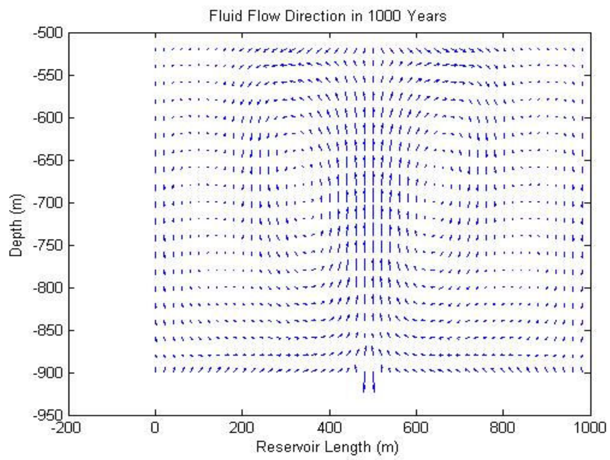

Fig. 9. Fluid flow direction at 1000th year

From the temperature distribution result, then the temperature vs depth curve is also expressed to explain how the relationship of temperature as function of depth. Fig. 10 shows the temperature profile at the center of the reservoir. The curve gives an information about temperature rise in the middle of the reservoir. We see that the temperature value rise for each year as shown in the previous temperature distribution contour model.

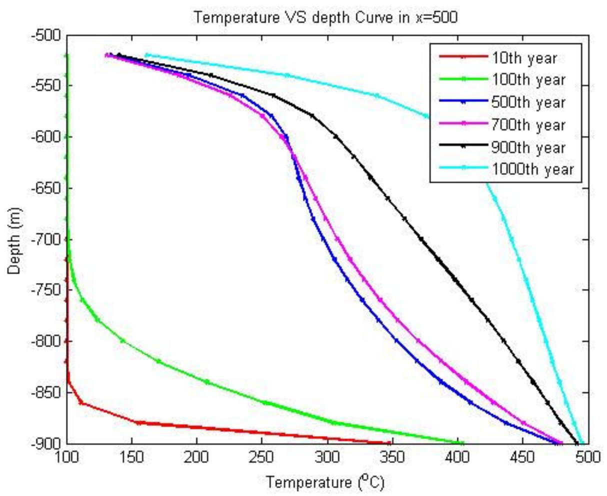

Fig. 10. Temperature vs depth at the centre of reservoir

Geothermal reservoir is ready to be exploited when the temperature distribution condition is reach above 200°C. The heat spreads evenly with temperature about 153°C in the reservoir, and also the heat near the ground. So it will be easy to exploit the energy as heat from the reservoir.

4.2 Pressure Distribution

The pressure distribution is also influenced by temperature change. Fig. 11 shows the pressure distribution at 1000th years. The result shows that the pressure changes in the reservoir model is very small. This is because that there are no mass and energy comes in and out from the reservoir. We also make a pressure vs depth plot to make sure that the pressure changes in the reservoir is really small.

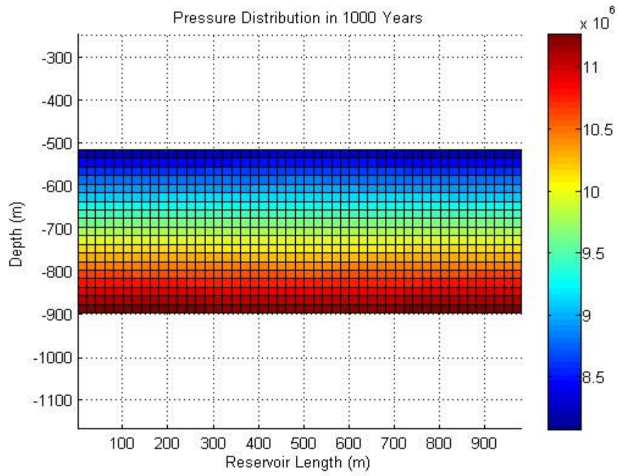

Fig. 11. Pressure Distribution at 1000th year (in Pa)

Fig. 12 shows the pressure profile as function of depth. The pressure change is picked at 10th, 500th, and 1000th year. The result show that in reservoir almost no change for the pressure.

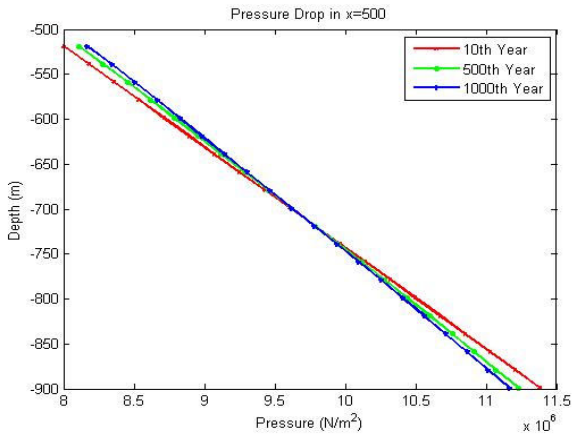

Fig. 12. Pressure vs Depth plot for 1st step modeling

4.3 Enthalpy Distribution

In the first step of calculation, the temperature and pressure distribution are obtained. From both of these distribution, the reservoir enthalpy distribution can be obtained. The distribution of enthalpy in the reservoir is obtained by using steam table based on the temperature and pressure data. Fig. 13 shows the enthalpy distribution at 1000th year. The enthalpy distribution model looks like the temperature distribution result (Fig. 13).

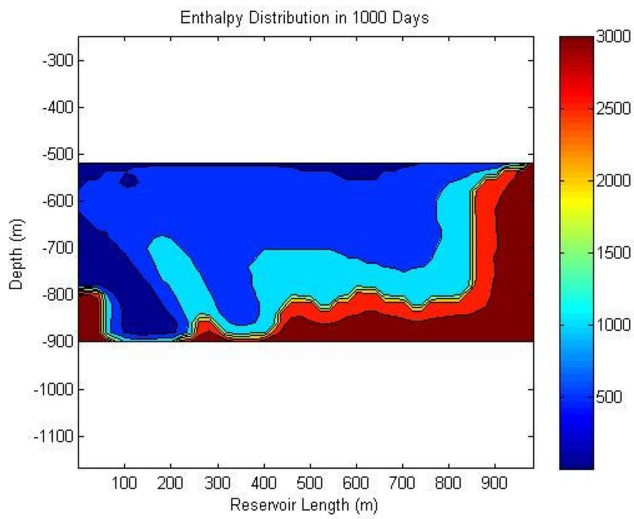

Fig. 13. Enthalpy Distribution at 1000th year

The information that also contained in the enthalpy distribution is phase change in the reservoir. The phase change can be directly explained by enthalpy value because the enthalpy values consist of temperature and pressure variables by using steam table [9]. Figure 14 shows the phase change as function of pressure. From the phase change curve, we know that the phase of fluid in the reservoir will change from liquid to vapor when value of enthalpy is above 2100 kJ/kg, because the fluid phase change from liquid vapor occur when the enthalpy value of about 2000-3000 kJ /kg in reservoir [10].

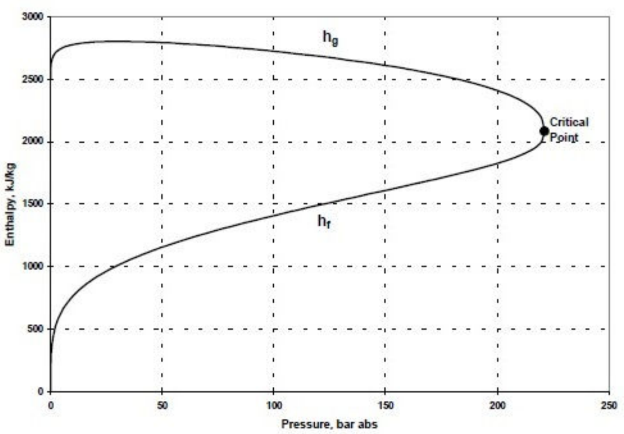

Figure 14. Phase Change Curve [11]

The reservoir fluid could be composed of two-phase fluid. Enthalpy data obtained in the reservoir model provide us that the enthalpy value in the reservoir model has a range of 500-3000 kJ/kg at 80-110 bar pressure. From the phase change curve, we will note that the fluid is in two-phase state. The red-colored contours indicated steam-phase and the blue-colored contours will likely be filled by the liquid phase fluid.

4.4 Temperature distribution affected by injection and production well

When injection and production are added to the modeling, numerical results show a significant temperature distribution changes every day. This is caused by fluid movement. The movement of fluid is very intense due to the injection and production processes. The fluid flux debit value is considered same as the injected value into the reservoir for every day. There is no steady phase in this modeling.

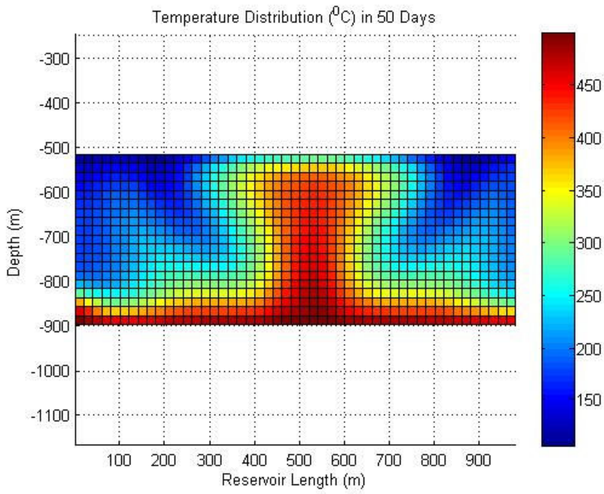

Figure 15. Reservoir temperature distribution at 50 days

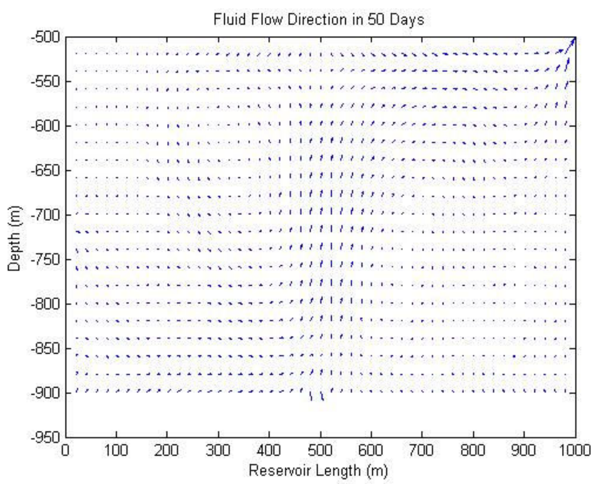

Figure 16. Fluid flow direction at 50 days

The temperature distribution and fluid movement will continue to move every time so that the main purpose of this modeling is to obtain the condition of the reservoir which can be estimated and plan for the further geothermal energy utilization. The result indicate that the production process is carried out by pulling out the fluid into the bottom hole of the production wells, The high temperature in the reservoir moves toward the production wells. Meanwhile, to maintain the fluid mass equilibrium in the reservoir, the waste production fluid is injected back into the reservoir. The fluid temperature becomes suitable for a thermal power with temperature of about 250°C [12]. The withdrawal process of fluid in the reservoir model takes at 50 days as shown in Fig. 15. Under the attached injection and production well, the temeperature of reservoir is increased over time with average temperature is about 245°C.

V. Conclusion

Geothermal reservoir is ready to be exploited when the temperature distribution condition is above 200°. From the modeling of physical and numerical simulation of geothermal reservoir system, we found that at 1000th year, the reservoir reach its steady condition and ready to be exploited with the high temperature and also high enthalpy and stable pressure distribution. Geothermal reservoir has some hotspot. This hotspot is caused by the convection fluid flow in the reservoir. The heat is spread evenly with temperature is about 153°C in the reservoir. The heat is near the ground so that it will be easy to exploit its energy. The modeling study also give an information about phase change by seeing the change of enthalpy of the reservoir.

Under the attached injection and production well, temperature distribution is increase over time with average temperature is about 245°C. It is important to know it because from the data we can make a management system and strategy how to develop the geothermal energy production..

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