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Numerical Modeling on Fluid Dynamics and Phase Changes for a Supercritical Geothermal System

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ABSTRACT

With the development of geothermal energy and the enhancement of drilling capacity, supercritical geothermal resource emerges. It refers to the water that exists in the supercritical state under the condition of ultra-high temperature and pressure in the deep part of the crust (22.064 MPa, 373.946°C), which is beneficial for geothermal resource development and utilization. In this work, we developed a numerical program for supercritical geothermal systems based on the structure of the TOUGH2 simulator. The IAPWS-IF97 is employed as the thermodynamic formulation. Compared to the previous codes, significant improvements have been made. The advantages of our code mainly include: 1) primary variables are unified following EOS 1, which is friendly for users to be familiar with. 2) A novel method is proposed to deal with the flow between supercritical and subcritical, which is more accessible and physically reasonable. 3) The effect of P-T condition on relative permeability and capillary pressure is considered, which makes it smooth and continuous within the whole P-T range, even around the critical point. 4) Wellbore flow function is coupled with the reservoir flow simulation. One example is given for verification and capability test, which proves the reliability of the code.

In our present study, a wellbore-reservoir coupling model is built, to study the fluid dynamics and possible phase changes along wellbores. It is found that water in supercritical condition behaves more like a gas. Production by the siphon phenomenon is also achievable in a supercritical geothermal system. A higher reservoir temperature brings a higher compressibility, more accessible to achieve production by the siphon phenomenon. In addition, under higher temperature conditions, production fluid may present in the steam single-phase state in the early period. In that circumstance, the wellbore friction could be very significant.

1. INTRODUCTION

With increases in climate change and air pollution, renewable and environmental-friendly energy have received more and more attentions. Geothermal energy is a clean and constant energy source that has been exploited for electricity generation and space heating. At present, with the development of geothermal energy and the enhancement of drilling capacity, supercritical geothermal resource emerges. It refers to the water that exists in the supercritical state under the condition of ultra-high temperature and pressure in the deep part of the crust (22.064 MPa, 373.946°C). Different from the normal liquid state, the mobility and heat capacity are much improved, beneficial for heat extraction. According to Cladouhos et al. (2018), at 60 kg/s mass flow rate, energy extraction in a 400°C reservoir could be almost 10 times higher than that of a 200°C reservoir. Until now, many geothermal fields have encountered the supercritical condition (Dobson et al., 2017; Reinsch et al., 2017). For some of them, further studies and field experiments have been conducted, such as DESCRAMBLE Project in Italy (Bertani et al., 2018; Chudaev et al., 2019), JBBP in Japan (Asanuma et al., 2012; Asanuma et al., 2015), Hotter and Deeper Project in New Zealand (Bignall, 2010), GEMex in Mexico, etc. (Jolie et al.). Relatively advanced in the development of supercritical geothermal energy is Iceland. Since the 21st century, the country starts Iceland Deep Drilling Project (IDDP), tried to conduct deep drilling to find a supercritical geothermal body at proper depth for commercial power generation (Friðleifsson et al., 2014; Fridleifsson and Elders, 2005).

The formation of the supercritical geothermal system is often associated with shallow magmatic intrusion (Hayba and Ingebritsen, 1997; Ingebritsen et al., 2010), but the formation mechanism, hydrothermal transport, and chemical properties are not yet well understood. Fournier (1999) built a comprehensive model to demonstrate hydrothermal system formation under control of magma activity. From the perspective of geo-mechanical and geochemical, upward magma surge breaches the self-sealed zone in the ductile zone and drives the fluids to flow up to brittle zone accompanying mineral dissolution and precipitation.

Some investigators assumed that supercritical fluids were formed by isobaric heating of subcritical fluids from shallow magma intrusion, and proved it through geochemical means (Heřmanská et al., 2019a; Heřmanská et al., 2019b). They conducted experiments showing that supercritical fluids have similar volatile element concentrations (B, C, and S) as subcritical fluids and lower non-volatile elements (Si, Na, K, Ca, Mg and Cl) concentration due to mineral precipitation. The same pattern was predicted by the geochemical model and observed at the IDDP-1 project, Krafla, Iceland.

Permeability of host rock is a primary control on heat transport, as the previous study, below a permeability of ~10-16m2, heat transport changes from being advection- to conduction-dominated. Therefore, Scott et al. (2015) defined the supercritical geothermal resources stored in the reservoir where the permeability greater than 10-16 m2 as being "economically exploitable". They analyzed the potentially exploitable supercritical resource distribution and evolution above magma intrusion (Scott et al., 2015). They then discussed the effect of permeability, geometry, and emplacement depth on the thermal structure and temporal evolution of the high-enthalpy geothermal system (Scott et al., 2016). In 2017, they extended to a saline geothermal system, noted that magma intrusion depth would control the phase separation phenomenon via pressure and temperature variation, and then influence the efficiency of heat transfer (Scott et al., 2017).

Many scholars focus on the magma-hydrothermal system, from geological, geochemical, and geomechanical perspective, to understand the link between magma intrusion with the formation of a supercritical geothermal system. There is no so much research work on the fluid-heat flow pattern of supercritical geothermal extraction engineering. In this study, we developed an improved EoS module based on TOUGH2, for numerical simulations covering supercritical geothermal conditions. Similar to AUTOUGH (Croucher and O'Sullivan, 2008) and iTOUGH-EOS1sc (Magnúsdóttir and Finsterle, 2015), IAPWS-IF97 is employed for the calculation of water properties. Our modifications and improvements are as follows. 1) The primary variables were unified as the original EOS1 module. 2) A novel method is proposed for the flow calculation between supercritical and subcritical conditions. 3) A linear function of relative permeability and capillary is given for considering phase merging and separation. 4) Wellbore flow function is coupled to the reservoir flow simulation. We analyzed the fluid-heat flow dynamics in the reservoir, phase change along wellbores, and explored the favorable conditions for supercritical geothermal extraction.

2. MODEL SETUP

2.1 Geological model

The wellbore is an indispensable part of any geological engineering. From the surface to the deep reservoir, it covers a wide P-T range. Therefore, a wellbore-reservoir coupling model is set up, as Figure 1. A doublet geothermal system is assumed with a well spacing of 400 m. The outer boundary is 10,000 meters, large enough to avoid the effects of geothermal development. The reservoir thickness is assumed 100 m with homogeneous thermo-physical properties.

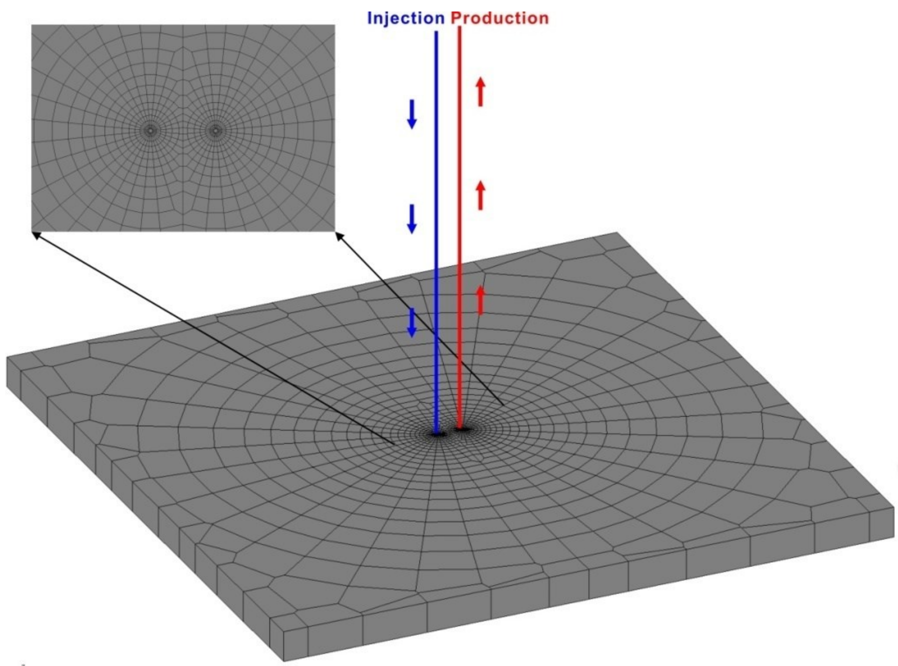

Figure 1: Sketch of a doublet supercritical geothermal system

The permeability of deep geothermal in the natural state is very low. For economic consideration, hydraulic fracturing is needed to create a reservoir with fracture network. In this study, a multiple-interaction-continua method (MIINC) is applied to consider the flow in fractures. The wellbore has a depth of 4600 m with a diameter of 0.18 m. The parameters used for the wellbore and reservoir are shown in Table 1

Table 1: Geometry and hydrothermal parameters of wellbore and reservoir formation

Reservoir formation parameters	
Thickness	100 m
Permeability (Fracture/Matrix)	1×10-14 m^2 / 1×10-17 m^2
Porosity (Fracture/Matrix)	0.5 / 0.01
Heat conductivity	3.0 W/m/^oC
Specific heat capacity	1000 J/kg/^oC
Reservoir pressure	Hydrostatic
Reservoir temperature	400^oC
Wellbore	

Depth	4600 m
Diameter	0.18 m
Roughness	1.0 mm
Well distance	400 m

For this model, different governing equations are applied for different sub-domains, the momentum equation is employed to describe the multiphase flow in the wellbore and the Darcy equation for the reservoir. The drift between different phases is considered using the model proposed by Shi (2005). A semi-analytical solution is considered for the heat exchange between the wellbore and surrounding rock (Ramey Jr, 1962).

2.2 Initial and boundary conditions

The reservoir temperature is taken as 400°C, and the surface temperature is 20°C. The reservoir depth is 4600 m with a hydrostatic pressure condition, about 36.0 MPa at the bottom. A fixed mass flow rate is given, 40 kg/s for both injection and production wells. The operating cycle is set to be 40 years. The detailed parameters are shown in Table 2

Table 2: Initial and boundary condition for the model

Initial condition	
Wellhead pressure	Atmospheric
Wellhead temperature	20°C
Well bottom pressure	Hydrostatic
Well bottom temperature	400°C
Boundary condition	
Injection temperature	60°C
Injection flow rate	40 kg/s
Production flow rate	40 kg/s

3. RESULT AND DISCUSSION

3.1 Hydrothermal flow and phase change along wellbore

The pressure and temperature evolution of wellhead and bottom for both injection and production wellbores are shown in Figure 2. For the pressure, the bottom pressure of both injection and production is relatively stable. The pressure at the wellhead of injection and production goes up and down, respectively. In the first 15 years, the pressure at production wellhead is lower than that of injection. The siphon phenomenon also occurs due to a large density difference between injection and production wells, like CO2-EGS.

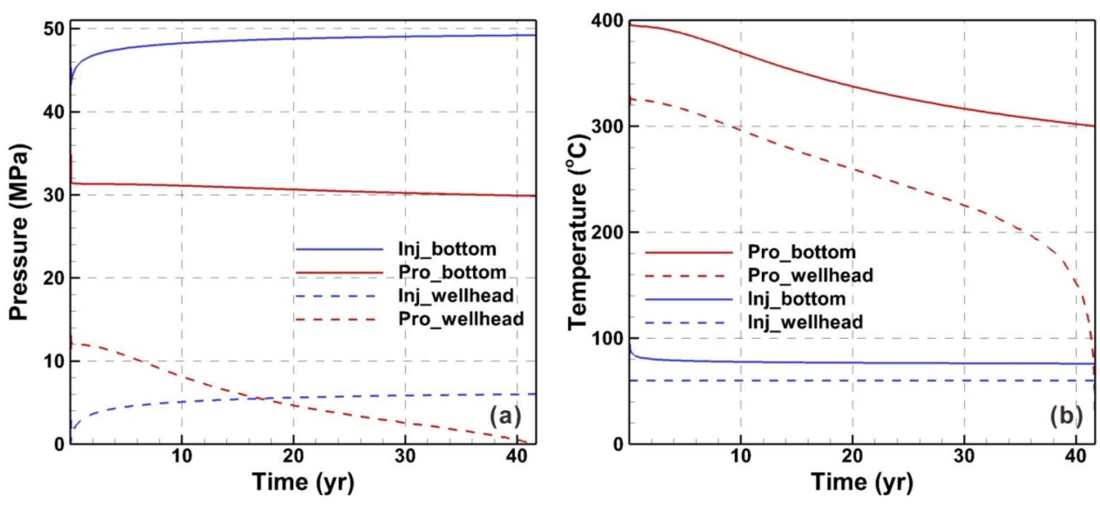

Figure 2: Pressure (a) and temperature (b) evolution of the two ends of both wellbores

The energy flow rate, which is defined as the mass flow rate multiplied by specific enthalpy, is shown in Figure 3a, With the system running, more cold water moves from injection to production well, the energy flow rate decreases with the specific enthalpy of production fluid. The temperature of production fluid decreases over time, as presented in Figure 2b.

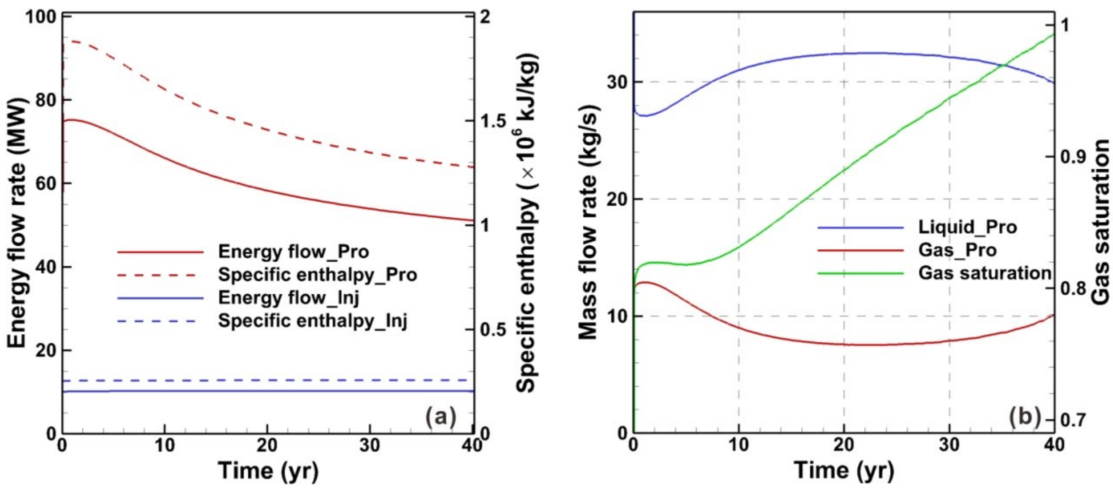

Figure 3: Energy flow rate and specific enthalpy of injection and production wells (a), and mass flow rates of liquid and gas at the production wellhead (b)

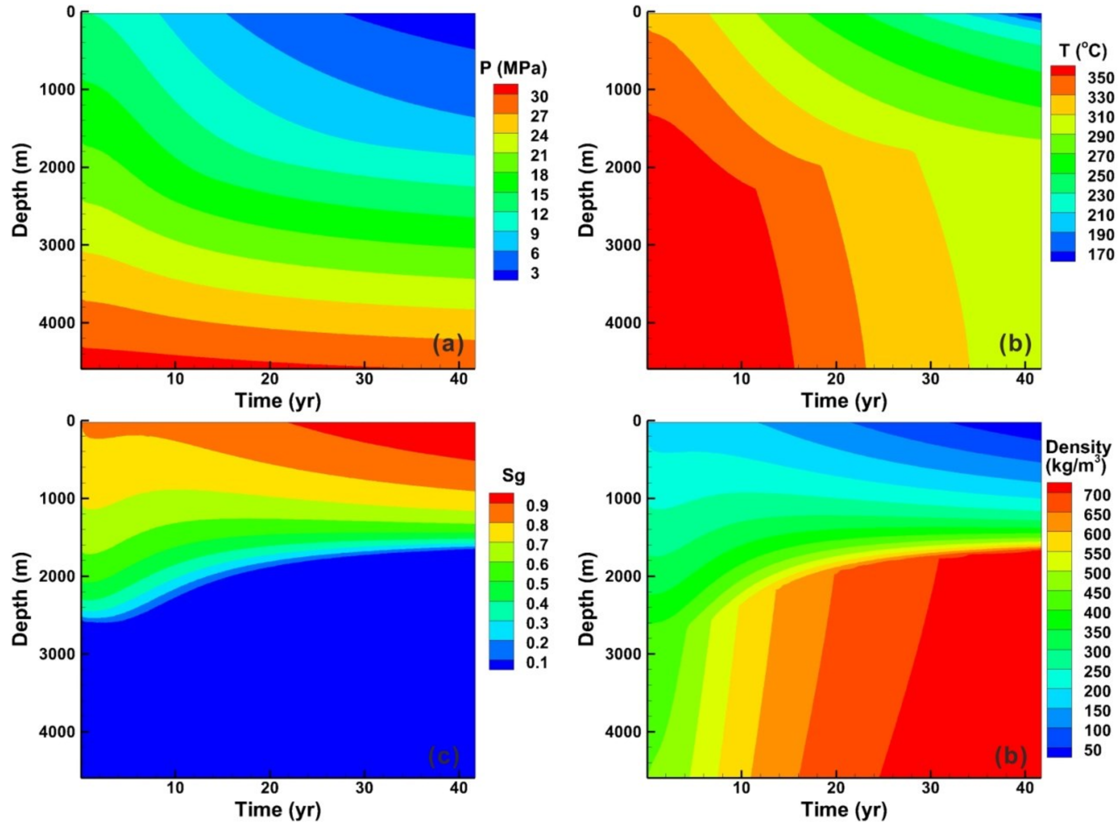

Figure 4: Evolution of some primary variables along production wellbore: (a) Pressure, (b) Temperature, (c) Gas saturation, (d) Density

The hydrothermal flow evolution pattern of production well is the focus of this study. It is more complex than the processes in the injection well. Figure 4 demonstrates the evolution of some primary variables, including pressure, temperature, gas saturation and fluid density. The temperature decline (Figure 4b) causes a considerable increase in density (Figure 4d) and gravity accumulation. The bottom pressure needs to overcome the gravity accumulation to drive the fluid flow upward (it will be discussed later). While the bottom pressure basically keeps constant, as a result, the wellhead pressure decrease over time to guarantee the 40 kg/s output

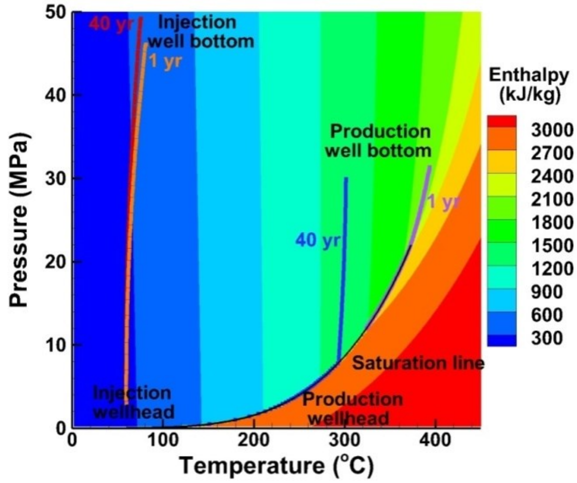

Figure 5: The P-T profile along injection and production wellbores at different times and the corresponding enthalpy

Specific enthalpy is a function of both pressure and temperature, which can help better understand the thermal-hydraulic coupling process. The P-T profiles along wellbores are illustrated in Figure 5. It is an approximately isenthalpic flow along the wellbore. Only the gravitational potential energy conversion and heat exchange with surrounding rocks will affect a little. Along injection well, there is a slight increase in specific enthalpy. Under low temperature and liquid phase, the pressure has a slight effect on specific enthalpy, so the temperature changes slightly. After being heated by reservoir, fluid is extracted along the production well. Under a higher temperature condition, the temperature has a positive relationship with pressure during an isenthalpic process, which is the so-called Joule-Thomson effect. The temperature declines during flowing upward. Besides that, in the upper part of the wellbore, fluid presents in two-phase coexistence. It evolves along the saturation line, causing an additional temperature decline. That is the reason for the temperature to decrease more quickly in the upper part of the wellbore as Figure 4b.

3.2 Sensitivity to reservoir temperature

Because the properties of supercritical water are more similar to those of steam, highly compressible. Here, the purpose of this model is to find out that, if it shares the same pattern as the traditional geothermal field, a reservoir with higher temperature results in a higher heat extraction rate. If not, what condition is more suitable for supercritical geothermal development. Here the sensitivity to reservoir temperature is analyzed. Except for the reservoir temperature, other parameters remain unchanged.

Reservoir temperatures of 500°C and 300°C are considered for discussion. The energy flow rates are shown in Figure 6a. A Higher temperature corresponds to a higher production energy rate. The pressure and temperature evolution at wellhead are shown in Figure 6b and c. As discussed above, the pressure difference between production wellhead and bottom must be larger than the gravitational accumulation. The production fluid density in 300°C case is larger than the base case (400°C). Therefore, after 20 years of operation, the pressure at wellhead deceases to atmospheric. Pumping is needed to extract water, about 1000 m long below the surface in a vacuum. Hence, the pressure and temperature at 1000 m depth is used for comparison. Higher reservoir temperature corresponds to higher production pressure and temperature. It could be drawn that higher temperature brings higher compressibility for water, more accessible to achieve production by the siphon phenomenon. It is worth noting that the pressure evolution pattern of 500°C case is different, rises in the first 5 years and then fall.

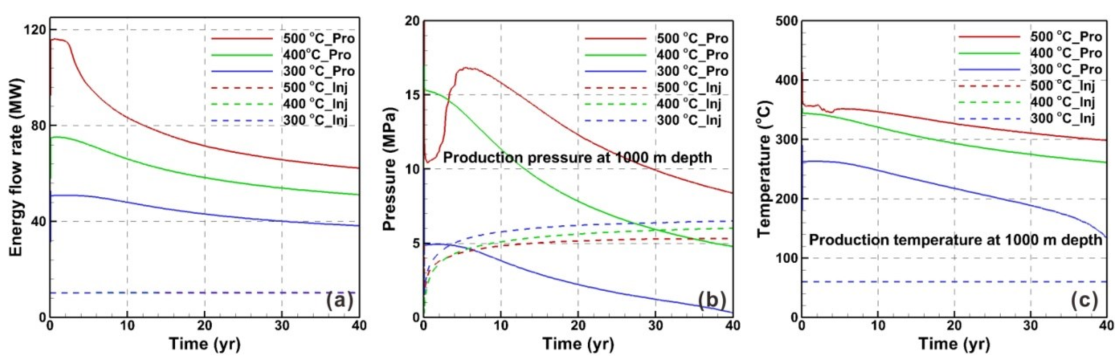

Figure 6: Energy (a) and mass (b) flow rates of injection and production, and production temperature (c) of three scenarios

To explain that, the pressure change mechanics are analyzed in detail. According to the momentum equation, the pressure composition includes the four parts in the bracket, the inertia item, acceleration item, friction item and gravity item, respectively. In the supercritical geothermal system, the first two items, inertia and acceleration is very small, could be neglect. Only the friction and gravity need to be taken into account.

$$\rho_m\left(\frac{\partial v_m}{\partial t}+v_m\frac{\partial v_m}{\partial z}+f\frac{v_m^2}{2d}+g\cos\theta\right)=-\frac{\partial P}{\partial z}$$

As demonstrated in Figure 7, the red line shows the evolution of the difference between wellhead and well bottom, and others are pressure change induced by the mechanics. Integrate the friction and gravity; it fits well with the pressure difference. In the 400^{o}C case, the pressure change induced by friction is relatively stable, around 4 MPa. The pressure change induced by gravity increases from 15 MPa to 25 MPa. While in 500^{o}C case, it can be seen in the first 5 years, the friction takes the dominant, and then drops quickly. The gravity accumulation is only 3 MPa at first.

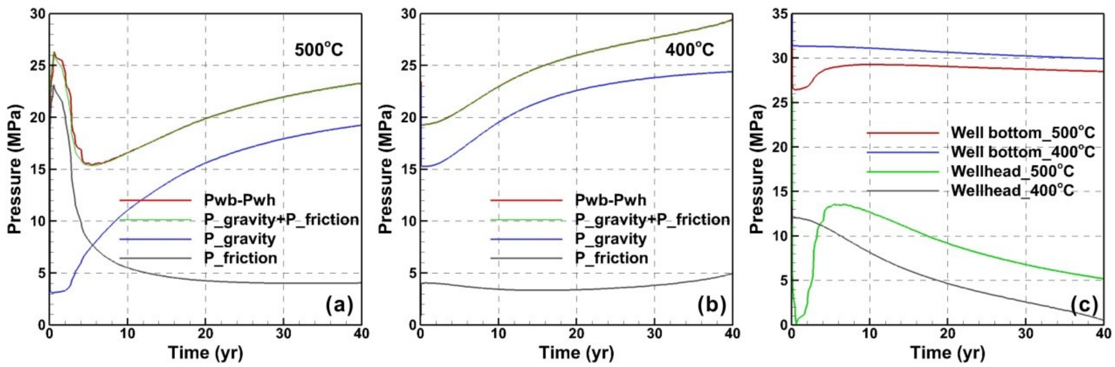

Figure 7: Pressure change mechanics under different conditions

From the equation, the friction item is positively related to the square of velocity. The gas-phase velocity can reach 250 m/s as Figure 8.

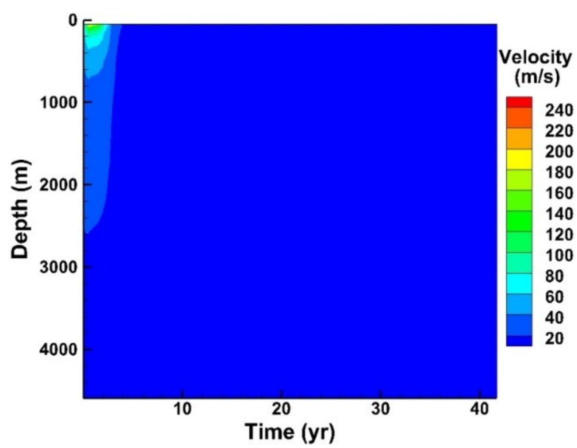

Figure 8: Gas-phase (steam) velocity evolution along production well in the case of 500^{o}C reservoir

The reason for such high velocity in the first 5 years is as illustrated in Figure 9, for the 400^{o}C case, it presents in a two-phase coexistence state after 1 year's operation. While for the 500^{o}C case, the production fluid at wellhead does not present in two-phase coexistence, but a single-phase phase only. Until third year, the P-T profile reaches the saturation line, liquid water appears.

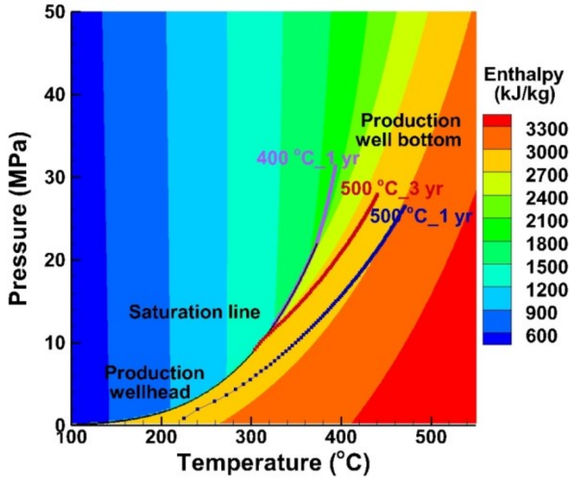

Figure 9: The P-T profile of production well for different times and different cases

The fundamental reason lies in the fluid density. Figure 10 demonstrates the 2-D contour of density within a broad T-P range and the 1-D profile at typical pressures of supercritical geothermal field. It can be seen there is a plummet at around 400°C, especially for lower pressure conditions. In this work, the roughness of wellbore is set to be higher to show the wellbore friction could be very significant, especially near the wellhead, water presents mostly in gas state (steam).

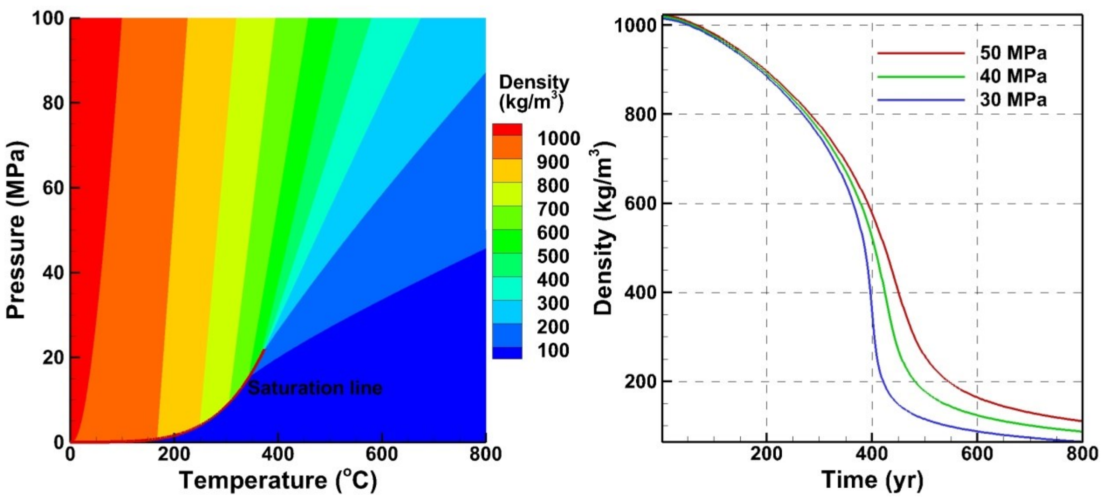

Figure 10: The 2-D contour of density within broad T-P range (left) and the 1-D profile at typical pressures for a supercritical geothermal system (right)

4. CONCLUSION

Water in supercritical condition behaves somewhat more like a gas (steam). Production by the siphon phenomenon is also achievable in supercritical geothermal systems. In the lower part of production well, it presents in the supercritical state. In the upper part, it presents a two-phase state. While for reservoir with high enough temperature, it may present a steam single-phase state. As the system running, production pressure goes down.

Higher reservoir temperature corresponds to a higher energy extraction rate and a higher production pressure. Moreover, it brings higher compressibility for water, more accessible to achieve production by the siphon phenomenon. The wellbore friction could be very significant, especially near the wellhead where water presents in gas state.

5. ACKNOWLEDGMENT

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