The Thermal Phenomena of the Supercritical CO_2 in the Reservoir of the Enhanced Geothermal System based on Brinkman Model

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Abstract-The paper is to discuss the thermal phenomena of the supercritical CO_2 in the geothermal reservoir for the enhanced geothermal system. The transient heat transfer model conjugated with the Brinkman model of employed by the finite element package is used to obtain the dynamic and thermal behavior in the porous medium. The different pressure of the reservoir, the various inlet volumetric flow rate are discussed. The results show that the inlet volumetric flow rate results in the temperature difference between the wall and working fluid on the exit apparently. It can be predicted that the heat extraction will increase as the volumetric flow rate decreases. In addition, the suitable operated pressure will reach the maximum heat extraction for the reason of property of supercritical CO_2.

I. Introduction

Geothermal energy can be considered as one of the important energy in future. It is one kind of renewable energy and emissions very less CO_2 [1]. The geothermal system is divided into traditional geothermal system and non-traditional geothermal system. The non-traditional geothermal system is enhanced geothermal system (EGS) which injects working fluid through injected well into reservoir approximate 3000 m depth. The working fluid is heated in the reservoir through hot rock with 250℃ and flows out ground through the producted well. The water or CO_2 can be chosen as the working fluid. Recently, supercritical CO_2 is suggested be the one of working fluids in the enhanced geothermal system. Brown proposes the CO_2-EGS in 2000 first [2].The advantages of this system are an excellent buoyant driving, the inability of dissolving with mineral species, and without the problem associated with the silica dissolution. Therefore, the thermal behavior of supercritical CO_2 is the important issue at high temperature and pressure reservoir of EGS. For the purpose of practice of CO_2-EGS, the properties of supercritical CO_2 should be studied such as the mechanical, thermal and flow phenomena. Recently, the studies related to CO_2-EGS are flourish published. Wan et al. review the impact of fluid-rock interaction on CO_2-EGS in 2011 [3]. They review many researches about the CO_2-EGS after Brown's propose. Several issues have been discussed to understand the availability of the CO_2-EGS, these include the CO_2 mineralization, such as CO_2 injection in granite and sandstone [4], the CO_2 sequestration in deep-saline aquifers [5], CO_2-rock interaction in elevated temperature [6]. Pruess et al. publish a series of studies of CO_2-EGS, such as heat transmission [7], sequestration of carbon [8], and production behavior [9] from 2006. Pruess et al. build the numerical model TOUGH for the multiphase flow in permeable media in 2004 [10]. In addition, Xu follows the Pruess's research to develop the advanced TOUGH [11] and process a series of numerical modeling about fluid-rock interaction [12], the effects of pH solution [13] and brine [14]. Spycher and Pruess discuss the effect of CO_2-brine mixtures by TOUGH in advance [15]. The heat extraction is still the key role of the CO_2-EGS. To obtain the heat extraction of the CO_2-EGS, many different phenomena have been observed and studied. Several studies investigate the heat transfer phenomena related to this topic. Therefore, several flow and thermal phenomena have understand

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well such as CO_2 flow is well than water in low permeability reservoirs [16], the pressure drop and heat transfer performance of a CO_2 geothermosiphon can be superior to those of water-based systems [17]. The buoyancy of super-critical CO_2 in the vertical mini-tubes and porous media is discussed by Jiang et al. [18]. Liao et al. find that the buoyancy effects are significant for all the flow orientations [19, 20]. However, the above approaches have some limits in this application, for example, few studies on the supercritical fluid, the absence of experimental system for reservoir. The purpose of this study is to obtain the thermal phenomena of the supercritical CO_2 in the geothermal reservoir for the enhanced geothermal system. In general, Brinkmann model, modified Navier Stokes equation, and Darcy model are used to evaluate the thermal and transport phenomena of porous flow. In this study, the transient heat transfer model conjugated with the Brinkman model employed by the finite element package is used to obtain the dynamic and thermal behavior of the supercritical CO_2 in the porous medium. From the above, this paper proposes a supercritical CO_2 model combined with the porous medium to solve the heat problems in order to complete the above absence. This study can reduce the cost of realistic test of enhanced geothermal system and build an effective way to simplify the evaluated procedure in the geothermal system.

II. Modeling

A geothermal model of reservoir is built in this study for examining the thermal phenomena of supercritical CO2 flow in the porous media under high preassure and temperature. 3-D brinkman momentum equation and energy balance equation are used. Fig. 1 presents a schematic illustration of the problem considered in the present analysis. As shown, the pipe combined with the applied heat fluxes on the surface is modeled as the heated CO_2 flow in the geothermal reservoir. The heat applied on the surface of the pipe spreads into the CO_2 flow through conduction and convection, the effect of radiation is neglected. Initially, the temperature of this model is kept as a constant temperature, T_{inf}. The governing equations are listed as below.

Continuity equation is

$$\frac{\partial}{\partial t}(\varepsilon\rho) + \nabla\cdot(\rho u) = Q_{br} \qquad (1)$$

Momentum equation is

$$\frac{\rho}{\varepsilon_p}\left(\frac{\partial u}{\partial t} + (u\cdot\nabla)\frac{u}{\varepsilon_p}\right) = -\nabla p + \nabla\cdot\left[\frac{1}{\varepsilon}\left\{\mu\left(\nabla u + (\nabla u^T)\right) - \frac{2}{3}\mu(\nabla\cdot u)I\right\}\right] - \left(\frac{\mu}{\kappa} + \frac{Q_{br}}{\varepsilon^2}\right)u + F \qquad (2)$$

here, μ is the viscosity, ε is porosity, κ is the permeability, Q_{br} is mass force, F is forced term.

The thermal properties of porous media are obtained by the average volume method for media and fluid in the porous. The heat equation for media is

$$\frac{\partial}{\partial t}\left[(1-\varepsilon)\rho_p C_{p,p} T_p\right] - (1-\varepsilon)\nabla\cdot\left(k_p \nabla T_p\right) = 0 \qquad (3)$$

and the energy balance for fluid is

$$\frac{\partial}{\partial t}\left[\varepsilon\rho_f C_{p,f} T_f\right] + \nabla\cdot\left(\rho_f C_{p,f} D T_f\right) - \varepsilon\nabla\cdot\left(k_f \nabla T_f\right) = 0 \qquad (4)$$

here, T_p,T_f is the temperature of media and fluid, separately. $D$is the Darcy velocity along the main axis of flow direction.

In this model, the heat transfer phenomena are discussed as the supercritical carbon-dioxide flows into the heated porous medium. The conditions of reservior under the depths of up to 3 kilometers are used. A 3D model is established by finite element method – COMSOL multiphy package. The material of tube is stain steel. The length, outer-diameter and inner-diameter is 133 mm, 20 mm and 10 mm, respectively. The wall heating condition is subjected on the wall of tube. The supercritical properties of carbon-dioxide are modelled using interpolation functions based on data from the NIST standard reference database 69.

In addition, the initional and boundary conditions are listed as below

The temperature and inlet velocity boundary of the outer wall of the test section is $-n\cdot(k\nabla T) = q_0$, and u=0 , v=0 , w=0. The temperature boundary of the inner wall of the test section is $-n\cdot(k\nabla T) = 0$. Then, the inlet velocity and temperature is $u = -U_0 n$, and $T = T_0$. The exit pressure and velocity is assumed as $p = p_0$, $[\mu(\nabla u + (\nabla u^T))]n = 0$.

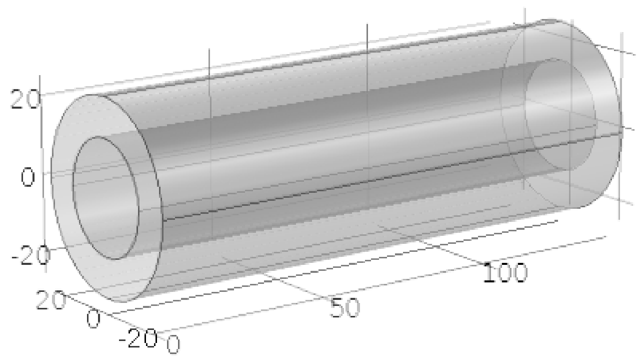

Figure 1. The model of the test section of geothermal reservoir

III. Results and Discussion

In this study, the effects of inlet volumetric flow rate and pressure are concerned. In advance, the model with higher pressure is discussed in this study. It will apply to the non-traditional EGS for higher depth. Different kinds of pressure (10.3 Mpa, 13.8 Mpa, 17.2 Mpa, 20.6 Mpa) and inlet volumetric flow rate (10 ml/min, 30 ml/min, 50 ml/min, 100 ml/min, 300 ml/min and 500 ml/min) are studied, respectively. The heat transfer phenomena are obtained from this 3D porous model.

For the reason of the apparent variation of the thermal properties of supercritical CO_2 with different pressure and temperature, the different kinds of pressure should be discussed in the research of supercritical CO_2. The porous and permeability of this model is assumed as 0.2, and 1E-13 m^2. The heat flux subjected on the surface of the test section is 3160 W/m^2, and the CO_2 temperature on the inlet is 313.15 K. Fig. 2 is the profile of the temperature difference on the exit between the supercritical carbon-dioxide and the tube wall with different pressure. The inlet volumetric flow rate is 50 ml/min. In Fig. 2, we observe that the temperature difference (ΔT) decreases as the pressure decreases. In addition, the temperature difference on the 10.3 MPa is more larger the ones on other pressure apparently. This is the reason of the special property of supercritical CO_2. The specific heat of supercritical CO_2 on 10.3 MPa and 313.15K is 1.75-2.5 times of the ones on the other pressure. In addition the temperature contours of test section under 10.3MPa and 20.6MPa are shown in the Figs. 3 and 4. The temperature increases gradually from inlet to exit and boundary part to inner part obviously. It represents that the heat extraction is available as the supercritical CO_2 flows through the porous media. The distribution is similiar as the pressure is 10.3 MPa and 20.6 MPa. The major discrepancy is the temperature of exit, which is 420K and 370K under 10.3MPa and 20.6 MPa, respectively. It will illustratte the effect of specific heat of supercritical CO_2 in advance.

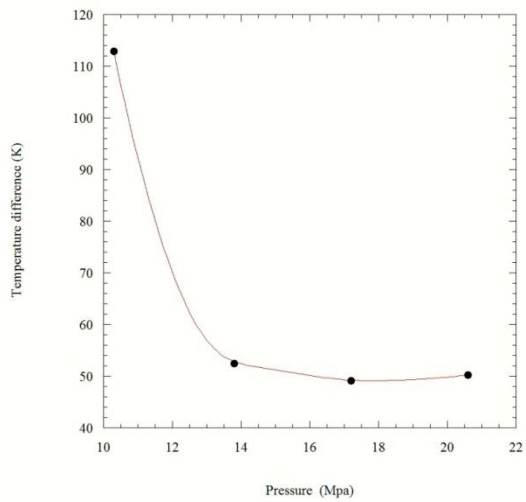

Figure 2. The temperature difference between inlet and exit with the different pressure (volumetric flow rate is 50ml/min).

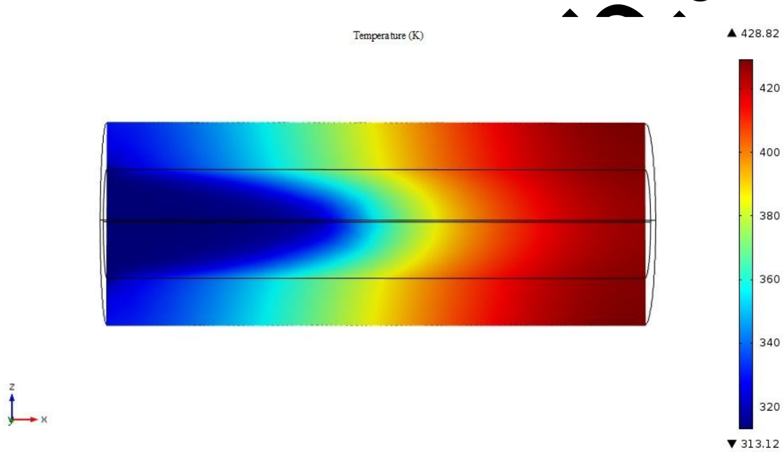

Figure 3.The temperature contour of test section (P is 10.3 MPa, volumetric flow rate is 50ml/min).

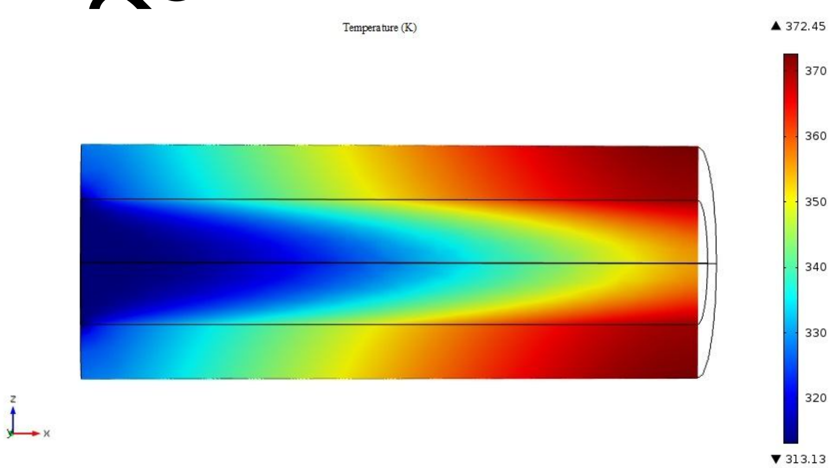

Figure 4. The temperature contour of test section (P is 20.6 MPa, volumetric flow rate is 50ml/min).

For EGS, the pump work is important to inject the working fluid. Therefore, the discussions of the effect of the volumetric flow rate is necessary for the efficiency of EGS. This study will observe the temperature difference and heat extraction affected by the volumetric flow rate. The volumetric flow rate discussed in this study is 10 ml/min, 30 ml/min, 50 ml/min, 100 ml/min, 300 ml/min and 500 ml/min, separately. The profiles of temperature difference with different volumetric flow rate and pressure are shown in Fig. 5. We observe clearly that the temperature difference decreases as the volumetric flow rate decreases. We can find that ΔT is 10 K at 500 ml/min, and approaches to 250K at 10 ml/min. It illustrates that the volumetric flow rate will affect the heat extraction apparently. The behaviour of supercritical fluid is similar to the general fluid. The slower flow can extract the more heat from the environment. It can apply to the better heat extraction under the lower inlet velocity. Slower the flow is, more heat absorption are.

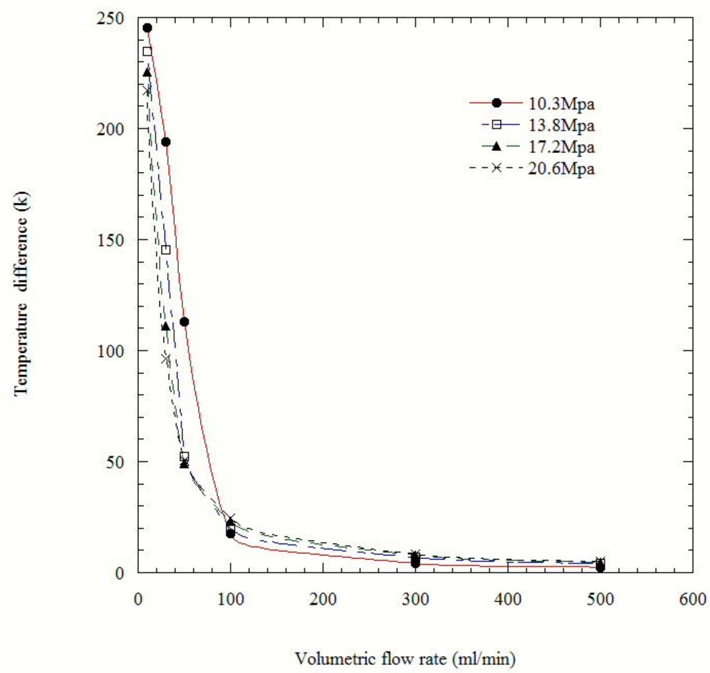

Figure 5. The temperature difference between inlet and exit with the different pressure and volumetric flow rate (q_w is 3160W/m^2).

Through the comparison with Fig. 2, we find that the temperature difference decreases as the pressure decreases for the condition is that the volumetric flow rate is lower than 100ml/min. As the volumetric flow rate is larger than 100ml/min, the variation of temperature difference is not apparent with the different pressure but increases as slightly as the pressure decreases. The major reason is the faster velocity results in the negative effect of the heat extraction.

To examine the effects of inlet volumetric flow rate and pressure more clearly, Fig. 6 presents the heat extraction related to the inlet volumetric flow rate and pressure. According to Fig. 6, the heat extraction is 0.145 W as the volumetric flow rate is 50 ml/min and pressure is 10.3 MPa. Here, a maximun heat extraction is reached. Therefore, we prove that the heat extraction will reach an optimal value for the suitable volumetric flow rate. This conclusion can be suggested to the realistic EGS. The suitable combination of depth and inlet volumetric flow rate will reach the maximun heat extraction and provide the maximun geothermal source.

This study will model the heat extraction of CO_2-EGS on the porous media. We expect these results can result in the better operating conditions for the improvement of the efficiency of the CO_2-EGS.

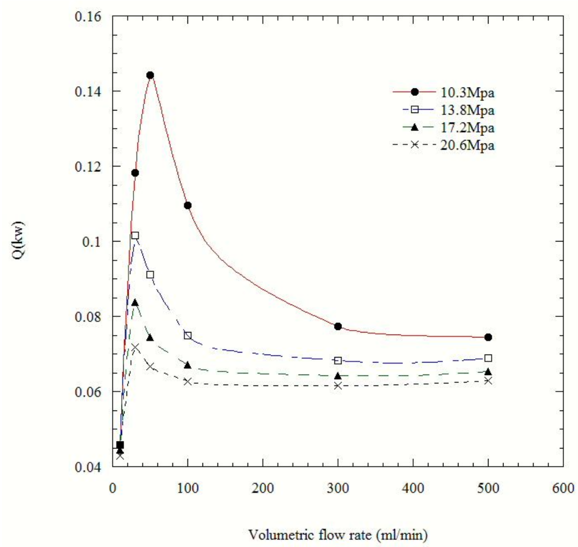

Figure 6. The heat extraction with the different pressure and volume flow rate (q_w is 3160W/m^2).

IV. Conclusions

This study is to discuss the thermal phenomena of the supercritical CO_2 in the geothermal reservoir for the enhanced geothermal system. In this study, the transient heat transfer model conjugated with the model of Brinkman equation employed by the finite element package is used to obtain the dynamic and thermal behavior in the porous medium. The sensitivity parameter study under the various inlet volumetric flow rate and pressure are discussed. The effects of lower pressure and slower flow will increases the heat extraction effectively. This study can enhance the heat extraction and reduce the cost of realistic test of enhanced geothermal system. We expect these results can result in the better operating conditions for the improvement of the efficiency of the CO_2-EGS. In addition, this proposed model will build an effective way to simplify the evaluated procedure in the geothermal system.

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