

The heat transfer phenomena of supercritical CO₂ porous flow based on the Darcy model

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Abstract – The purpose of this study is to obtain the heat transfer phenomena of the supercritical CO₂ in the porous medium. In this study, the transient heat transfer model conjugated with the model of Darcy's law employed by the finite element package is used to obtain the dynamic and thermal behavior in the porous medium. The validated results for the heat extraction are obtained from the comparison between the simulated results and previous study. The sensitivity parameter study under the various inlet velocities and porosities of the porous medium are discussed. The results show that the inlet velocity is the most important effect for the heat extraction. In addition, it proves that the operating conditions are important in the supercritical flow for the different tendency of the temperature difference and heat extraction. The reason is that the specific heat of the CO₂ supercritical characteristics. The heat extraction will increase as the velocity increases and the porosity decreases. The supercritical porous flow will apply on the enhanced geothermal system and high efficient waste heat recycle system.

Keywords – supercritical CO₂, porous medium, Heat extraction, Darcy model

I. INTRODUCTION

To obtain the heat extraction of the supercritical CO₂ flow, many different phenomena and parameters have been observed and studied. Several studies investigate the heat transfer phenomena related to this topic. Therefore, several flow and thermal phenomena have understand well such as CO₂ flow is well than water in low permeability reservoirs [1], the pressure drop and heat transfer performance of a CO₂ geothermosiphon can be superior to those of water-based systems [2]. The buoyancy of super-critical CO₂ in the vertical mini-tubes and porous media is discussed by Jiang et al. [3]. Liao et al. find that the buoyancy effects are significant for all the flow orientations [4, 5]. One of the applications of supercritical CO₂ porous flow is CO₂-enhanced geothermal system. Geothermal energy is one kind of renewable energy and emissions very less CO₂ [6]. Geothermal energy can be considered as one of the important

energy in future. 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 °C and flows out ground through the produced well. The water or CO₂ can be chosen as the working fluid. Recently, supercritical CO₂ is suggested be the one of working fluids in the enhanced geothermal system. Therefore, the thermal behavior of supercritical CO₂ is the important issue at high temperature and pressure reservoir of EGS. Brown proposes the CO₂-EGS in 2000 first [7]. 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. For the purpose of practice of CO₂-EGS, the properties of supercritical CO₂ should be studied such as the mechanical, thermal and flow phenomena. Recently, the studies related to CO₂-EGS are flourished published. Wan et al. review the impact of fluid-rock interaction on CO₂-EGS in 2011 [8]. They review many researches about the CO₂-EGS after Brown's propose. Several issues have been discussed to understand the availability of the CO₂-EGS, these include the CO₂ mineralization, such as CO₂ injection in granite and sandstone [9], the CO₂ sequestration in deep-saline aquifers [10], CO₂-rock interaction in elevated temperature [11]. Pruess et al. publish a series of studies of CO₂-EGS, such as heat transmission [12], sequestration of carbon [13], and production behavior [14] from 2006. Pruess et al. build the numerical model TOUGH for the multiphase flow in permeable media in 2004 [15]. In addition, Xu follows the Pruess's research to develop the advanced TOUGH [16] and process a series of numerical modeling about fluid-rock interaction [17], the effects of pH solution [18] and brine [19]. Spycher and Pruess discuss the effect of CO₂-brine mixtures by TOUGH in advance [20]. However, the above approaches have some limits in this application, for example, the few study on the supercritical fluid, the absence of experimental system for reservoir. This study belongs to a series of researches included experiment, simulation and optimization. The purpose of this study is to obtain the heat transfer

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phenomena of the supercritical CO₂ in the porous medium. 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 model of Darcy's law employed by the finite element package is used to obtain the dynamic and thermal behavior of the supercritical CO₂ in the porous medium. The Darcy model is capable of obtaining the thermal phenomena easily, and calculating fast than the Brinkmann model and the Navier Stokes equation. The optimal design can then be carried out without overwhelming mathematical derivation during the iterative optimal process. From the above, this paper proposes a supercritical CO₂ 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

The model of geothermal reservoir is considered in this study for examining the performance of the heat extraction of supercritical CO₂ flow in the porous media. 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 CO₂ flow in the geothermal reservoir. The heat applied on the surface of the pipe spreads into the CO₂ 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 CO₂ flow in the pipe with the porous media is assumed as the Darcy flow. The governing equations are listed as below.

Continuity equation is

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla \cdot (\rho\bar{u}) = 0 \quad (1)$$

$$\bar{u} = -\frac{\kappa}{\mu} \nabla p$$

The momentum equation is obtained by Darcy flow model is:

$$\frac{\mu}{\kappa} \bar{u} + \nabla p - \nabla \frac{\mu}{\varepsilon} (\nabla \bar{u} + (\nabla \bar{u})^T) = \rho g \beta \nabla T \quad (2)$$

Energy equation is

$$\rho C_p \bar{u} \cdot \nabla T - (k_{eq} \nabla T) - q_w = 0 \quad (3)$$

where

$$k_{eq} = (1 - \varepsilon)k_s + \varepsilon k_f \quad (4)$$

$$\rho C_p = (1 - \varepsilon)\rho_s C_{ps} + \varepsilon \rho C_{pf}$$

In this model, the heat transfer phenomena are discussed as the supercritical carbon-dioxide flows into the heated porous medium. The conditions of reservoir under the depths of up to 3 kilometers. A 3D model combined with Darcy

flow model and heat transfer model is established by finite element method – COMSOL multiply package. The material of tube is stain steel. The length, outer-diameter and inner-diameter is 133mm, 20mm and 10mm, 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. A reliable numerical solution requires that the solution be independent of the numerical grid. Grids of progressively finer resolution were generated and consisted of nine kinds of mesh respectively which resulted in exit temperature from 327.36K to 320.56K respectively. After grid independence studies shown in Fig.2 and Table 1, the 50628 meshes that yielded the convergent temperature is selected for further simulations.

Table 1 The mesh independent study.

Mesh No.	Exit Temperature(°C)	Error(%)
154486	47.41	0.34
50628	47.57	0.30
21656	47.71	0.58
12950	47.99	0.07
8179	47.96	0.43
6253	48.16	0.85
3265	48.57	0.16
2395	48.65	11.51
1699	54.25	

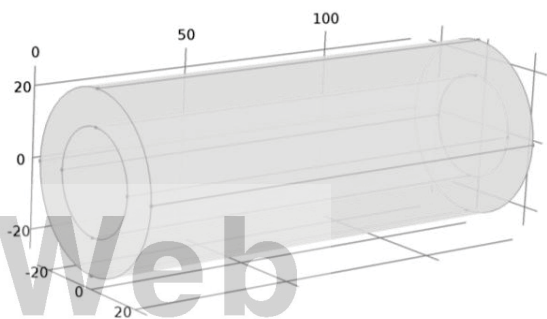


Fig. 1 The schematic diagram of the test pipe model.

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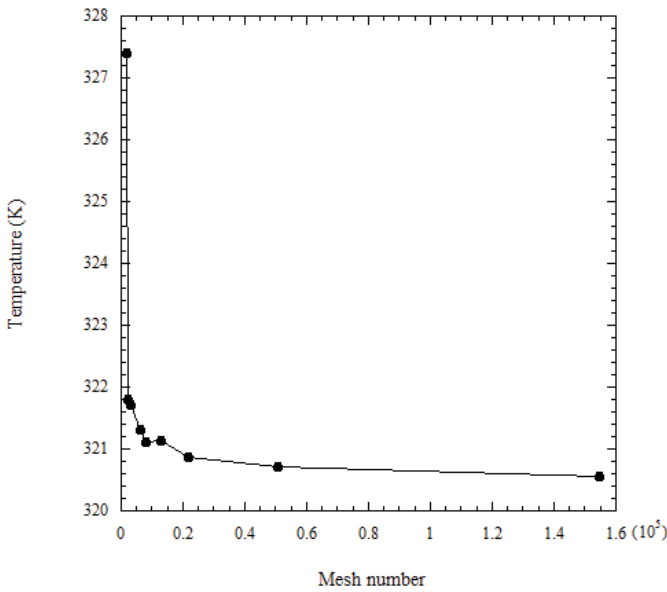


Fig. 2 The mesh independent study.
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III. RESULTS AND DISCUSSIONS

The validated case is shown in Fig.3. The temperature distribution is agreed with the previous study [21]. Here, the inlet velocity is assumed as 0.0038 m/s. The error between the present result and previous result is discussed first. In Fig.3, the absolute average error of temperature at the exit is 2.12%, 0.477%, 1.96% as the heat flux is $2.2e^4$, $4.0e^4$, and $6.2e^4$ W/m². A more detailed understanding of this relationship can be gained from Table 2. From Table 2, it is clear that the absolute average error is about 1.24% between the present study and the previous study.

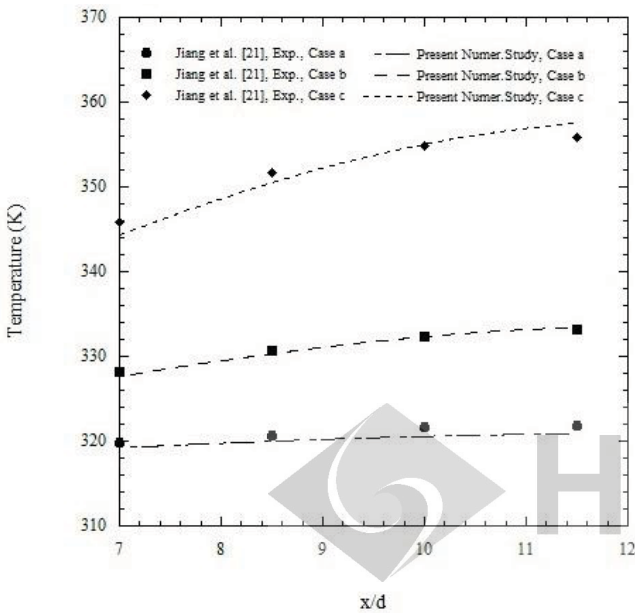


Fig. 3 The temperature profiles of the test section between the present study and previous study [21].

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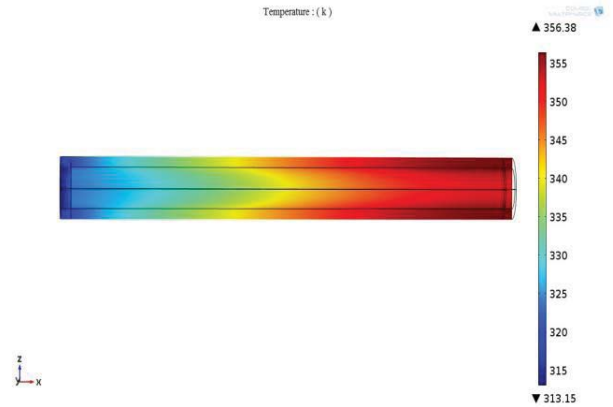


Fig. 4 The temperature contour of the test section ($u=0.8$ m/s, $\epsilon=0.4$).

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Table 2 The temperature of the test section of the present study and previous study [21].

	x/D	Temp.(K) (Jiang et al. [21], Exp.)	Temp.(K) (Present, Numer.)	Error(%)
Case a	7	319.9	319.22	1.46
	8.5	320.65	320.0	1.37
	10	321.65	320.57	2.24
	11.5	321.9	320.87	2.12
Case b	7	328.15	327.65	0.916
	8.5	330.65	330.34	0.544
	10	332.4	332.32	0.128
	11.5	333.15	333.43	0.477
Case c	7	345.9	344.33	2.16
	8.5	351.65	350.56	1.39
	10	354.9	355.03	0.162
	11.5	355.9	357.52	1.96

Four kinds of inlet velocity (0.2, 0.4, 0.6, 0.8) and porous porosity (0.2, 0.4, 0.6 and 0.8) under pressure 1100psi are studied, respectively. The heat transfer phenomena are obtained from this 3D porous model. First, the temperature contour is shown in Fig.4. Here, the inlet velocity, the porosity, permeability, and the pressure is 0.8, 0.2, $5e^{-13}m^2$, and 1100psi, respectively. Throughout Fig.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 CO₂ flows through the porous media. In this study, the effects of inlet velocity and porosity are concerned. The temperature

difference (ΔT) on the exit with the various velocity between the supercritical carbon-dioxide and the tube wall is shown in Fig.5. Here, the porosity and pressure is 0.2 and 1100psi. We can find that ΔT is 42.4K at 0.8 m/s, and approaches to 110K at 0.2 m/s. Obviously, ΔT decreases as the inlet velocity increases. 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.

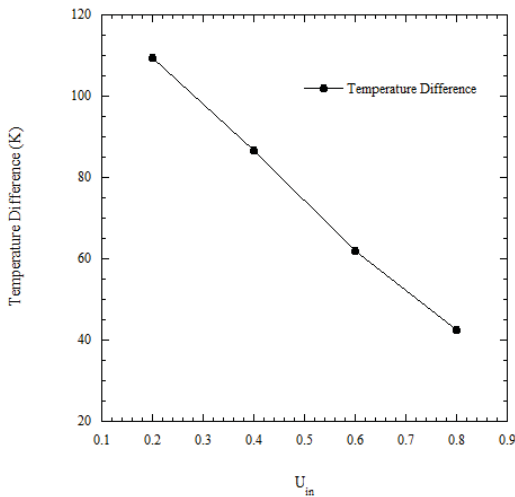
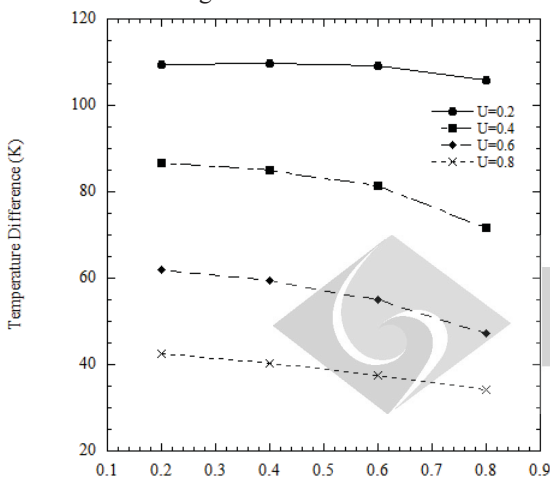


Fig. 5 The temperature difference between the fluid and tube wall on the exit with various inlet velocity.

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Fig. 6 The temperature difference between the fluid and tube wall on the exit with various inlet velocity and porosity.

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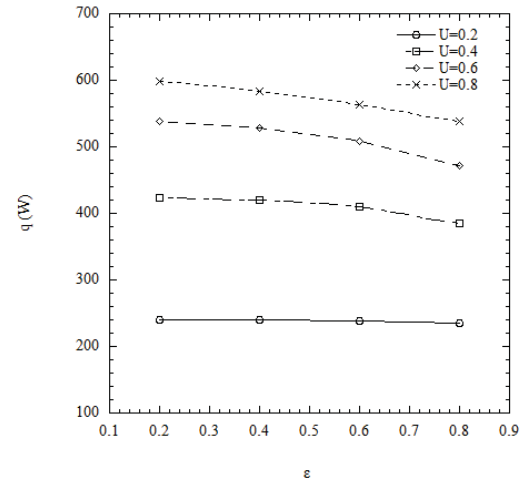


Fig. 7 The heat extraction on the exit with various inlet velocity and porosity.

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In addition, the effects of the porosity are discussed. The profiles of temperature difference with the different inlet velocity and the various porosity are shown in Fig.6. Throughout the Fig.6, the temperature difference is 42.4K, 34.3K at the porosity is 0.2, and 0.8, under the velocity is 0.8 m/s. Furthermore, the temperature difference is 110K, 105.8K at the porosity is 0.2, and 0.8, under the velocity is 0.2 m/s. Therefore, it is obviously that the heat extraction will affect by the porosity. In advance, the inlet velocity is the major parameter for the heat extraction and the minor effect of the porosity should be considered. The small porosity presents the larger heat transfer area. Therefore, the effects of larger heat transfer area and slower flow will increase the heat extraction effectively. The heat extraction with various inlet velocity and various porosity are shown in Fig.7. To examine the effect of inlet velocity and porosity more clearly, Fig. 7 and Table 3 present the heat extraction related to the inlet velocity and porosity. The heat extraction will increase as the inlet velocity increases, the porosity decreases. Compare with Figs.6 and 7, the temperature difference and heat extraction states the different tendency under the different inlet velocity. The reason is that the specific heat at the higher velocity is higher than the one at the lower velocity. It decides by the thermal properties of supercritical CO₂. It proves that the operating conditions are important in the supercritical flow. In details, the heat extraction in Table 3 increases from 234.87 to 239.3 about 1.85% as the porosity is from 0.8 to 0.2 at the inlet velocity is 0.2 m/s, and 9.88% at inlet velocity is 0.8 m/s. The heat extraction is 597.6kW and 538.6 kW at the porosity is 0.2, and 0.8, under the velocity is 0.8 m/s, and, 239.3kW, 234.8kW at the porosity is 0.2, and 0.8, under the velocity is 0.2 m/s. Therefore, we notice that the effect of the porosity is negligible as the porosity is lower than 0.4. It illustrates that the decreased porosity will respond to the increasing flow

resistance. It results that the effect of contact surface resulted from the decreased porosity is limited. In other words, the decreased porosity is benefit to the heat extraction but it is limited. This study will model the heat extraction of CO₂-EGS on the porous media. We expect these results can result in the better operating conditions for the improvement of the efficiency of the CO₂-EGS.

In advance, the model with higher wall temperature (473K, 523K) is discussed in future. It will apply to the non-traditional EGS for higher depth.

Table 3 The heat extraction (kW) on the exit with various inlet velocity and porosity.

	porosity=0.2	porosity=0.4	porosity=0.6	porosity=0.8
U=0.2 m/s	239.3	239.46	238.72	234.87
U=0.4 m/s	423.58	419.35	410.56	385.21
U=0.6 m/s	538.95	527.9	508.21	472.08
U=0.8 m/s	597.65	583.77	562.89	538.61

IV. CONCLUSION

This study is to discuss the heat extraction of the supercritical CO₂ in the geothermal reservoir for the enhanced geothermal system. In this study, the transient heat transfer model conjugated with the model of Darcy's law 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 velocities and porosities of the porous medium are discussed. Four kinds of inlet velocity and porosity are studied, respectively. The inlet velocity is the major parameter for the heat extraction and the minor effect of the porosity should be considered. In general, the effects of larger heat transfer area and slower flow will increases the heat extraction effectively. In addition, the temperature and pressure of working fluid are the important conditions for the supercritical thermal properties. 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 CO₂-EGS. In addition, this proposed model will build an effective way to simplify the evaluated procedure in the geothermal system.

V. ACKNOWLEDGMENTS

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Nomenclature

C_p specific heat capacity

D Diameter of tube

u Velocity

β Heat expansion coefficient

ε Porosity

κ Permeability

k Thermal conductivity

μ Viscosity

Subscript

ex Outlet

eq Equivalent

f Fluid

int initial

i Inlet

s solid

p Porous

w Wall

