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Heat transfer and fluid transport of supercritical CO_2 in enhanced geothermal system with local thermal non-equilibrium model

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Abstract

The heat transfer and fluid transport of supercritical CO_2 in enhanced geothermal system (EGS) is studied numerically with local thermal non-equilibrium model, which accounts for the temperature difference between solid matrix and fluid components in porous media and uses two energy equations to describe heat transfer in the solid matrix and in the fluid, respectively. As compared with the previous results of our research group, the effect of local thermal non-equilibrium mainly depends on the volumetric heat transfer coefficient *ah*, which has a significant effect on the production temperature at reservoir outlet and thermal breakthrough time. The uniformity of volumetric heat transfer coefficient *ah* has little influence on the thermal breakthrough time, but the temperature difference become more obvious with time after thermal breakthrough with this simulation model. The thermal breakthrough time reduces and the effect of local thermal non-equilibrium becomes significant with decreasing *ah*.

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Keywords: Enhanced geothermal system; CO_2; local thermal non-equilibrium

1. Introduction

In recent years, with the accelerated reduction of fossil fuels and the greenhouse effect brought by the utilization of fossil fuels, it is urgent to develop renewable low carbon-emitting energy. The enhanced geothermal system (EGS) is aimed to extract geothermal energy from the hot dry rock (HDR) artificial fracture reservoir at a depth from 3km to 10km by circulating the heat transmission fluid flow through the reservoir. Field scale numerical simulation of

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geothermal reservoir is a very important tool to evaluate the heat extraction performance with heat transmission fluid. Brown proposed a novel CO_2-EGS concept using supercritical CO_2 instead of water as heat transmission fluid to extract geothermal energy from hot dry rock [1]. Many studies have shown that CO_2-EGS system not only produces greater power due to the favorable transport properties of CO_2, but also sequestrates carbon and minimizes water loss due to working fluid losses at large depths [2-4].

The geothermal reservoir is always treated as porous media in the extensive simulations of EGS heat extraction performance. There are two models to describe the fluid flow and heat transfer in the porous media: local thermal equilibrium model (LTE) and local thermal non-equilibrium model (LTNE). The LTE model assumes there is no temperature difference between the solid matrix and fluid, however, the LTNE model describes the heat transfer in porous media with consideration of temperature difference. Shaik et al [5] investigated the effects of heat transfer between rock matrix and fluid and fracture connectivity in naturally fractured geothermal system and showed that the heat transfer coefficient has a profound effect on the economic potential of a geothermal reservoir. Jiang and Chen [6-7] develop a novel three-dimensional transient model with local thermal non-equilibrium model for the study of the subsurface heat exchange process in EGS. The studies showed that the results of local thermal non-equilibrium model has scarcely any differences from that of local thermal equilibrium model and the parameter has very little effect on the production temperature. However, the heterogeneity of permeability of different layers and the fracture zone are not considered in the studies. Therefore, it is very important to develop numerical modeling with local thermal non-equilibrium model to predict the heat extraction behaviors of CO_2-EGS system with fracture zone and heterogeneity layers.

The present work is a continuation to our previous work [4]. This paper presents a numerical model to simulate heat transfer and fluid flow of supercritical CO_2 in EGS with two wells after conditions at the European EGS site at Groβ Schonebekc using the CFD (computational fluid dynamics) code FLUENT 6.3. This study compares the results of local thermal non-equilibrium model with that of local thermal equilibrium model, which has been presented in the paper of Luo et al [4]. And it shows that the effect of local thermal non-equilibrium on the heat extraction depends on the volumetric heat transfer coefficient.

Nomenclature

γ	porosity
ρ_f	density of fluid, kg/m^3
μ_f	viscosity of fluid, Pa· s
λ_f	thermal conductivity of fluid, W/m·K
E_f	internal energy of fluid, J/kg
V	velocity vector, m/s
P	pressure, Pa
ρ_s	density of rock, kg/m^3
λ_s	thermal conductivity of rock, W/m·K
C_{ps}	isobaric specific heat, J/kg·K
k	permeability, m^2
C	inertial flow resistance factor
h	internal convective heat transfer coefficient between the rock matrix and fluid, W/m^2·K
a	the specific surface area, m^{-1}

2. Numerical approach

This study numerically simulates CO_2 flow and heat transfer in 3D CO_2-EGS system with a reservoir with fractures over a 25 year period, based on the parameters of the European EGS site at Groβ Schonebekc. The modeled reservoir shown in figure 1 was divided into five layers and two hydraulic fracture regions around the wells. The characteristic parameters of the reservoir and the hydraulic and thermal properties of reservoir rock were taken from Luo's study [4].

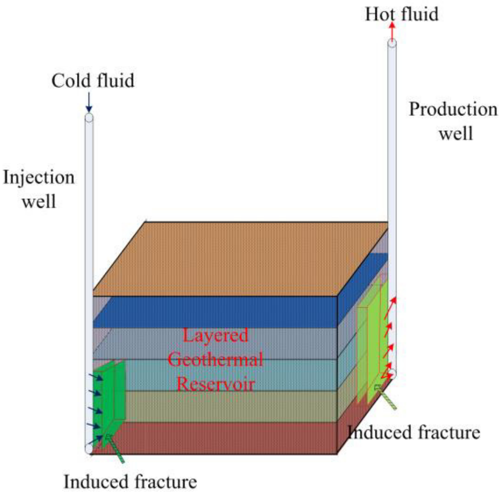


Fig.1. Schematic diagram of a doublet CO_2-EGS [4]

The reservoir was modelled as porous media, and the laminar flow and heat transfer in the reservoir were solved by Navier- Stokes equation and local thermal-equilibrium model. The governing equations are listed as followed.

Continuity equation:

$$\frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f \bar{V}) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial(\rho_f \bar{V})}{\partial t} + \nabla \cdot (\rho_f \bar{V}\bar{V}) = -\nabla P + \nabla \cdot (\mu_f (\nabla \bar{V} + \nabla \bar{V}^T - \frac{2}{3} \nabla \cdot \bar{V} I)) + \rho_f \bar{g} - (\frac{\mu_f}{k} \bar{V} + C \frac{1}{2} \rho_f \left|\bar{V}\right| \bar{V}) \tag{2}$$

Energy equation of fluid:

$$\frac{\partial(\gamma \rho_f E_f)}{\partial t} + \nabla \cdot (\bar{V}(\rho_f E_f + P)) = \nabla \cdot (\gamma \lambda_f \nabla T_f + \mu_f \bar{V}(\nabla \bar{V} + \nabla \bar{V}^T - \frac{2}{3} \nabla \cdot \bar{V} I)) + ha(T_s - T_f) \tag{3}$$

Energy equation of rock matrix:

$$(1-\gamma)\rho_s C_{ps} \frac{\partial T_s}{\partial t} = \nabla \cdot ((1-\gamma)\lambda_s \nabla T_s) - ha(T_s - T_f) \tag{4}$$

Where ρ_f is the fluid density, μ_f is the fluid viscosity, λ_f is the fluid thermal conductivity, V is the velocity vector, P is the pressure, E_f is the internal energy of fluid per kilogram, ρ_s is the solid matrix density, λ_s is the solid thermal conductivity, C_{ps} is the isobaric specific heat, k is the permeability, C is the inertial flow resistance factor, γ is the porosity, h is the internal convective heat transfer coefficient between the rock matrix and fluid. a is the specific surface area. The main flow channel in EGS is the fracture with aperture of mm magnitude. According to the previous research, layer 4 is the main heat transfer path because of the largest permeability. So the specific surface area of layer 4 is assumed as 0.001, while the specific surface area of other layers is calculated by porosity, listed in Table 1.

Table 1. Specific surface area of the reservoir in each layer.

	Fracture region	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
a	0.01	4.5×10^{-6}	4×10^{-5}	2.85×10^{-4}	0.001	4.5×10^{-8}

According to the existing results, the injection rate of CO_2 is 20 kg/s. The injection temperature of CO_2 flowing in the reservoir is 70 ℃. Luo et al suggested that placing the injection well perforation only in layer 3 with the production well perforated only in layer 2 gives the longest thermal breakthrough time and the greatest cumulative heat extraction from the reservoir before thermal breakthrough. This study numerically simulates the unsteady heat transfer and fluid transport of CO_2 in the geothermal reservoir with fractures and layers for 25 years utilization lifetime with FLUENT software. The PISO (Pressure-Implicit with Splitting of Operators) algorithm, which is suitable for transient calculation especially with large time step, was used to couple the pressure and velocity. And PRESTO! (PREssure Staggering Option) scheme was used for pressure discretization and second-order discretization scheme was used for advection and energy terms.

3. Results and discussion

This study is aimed to investigate the effect of local thermal non-equilibrium on the heat extraction of EGS fractured reservoir. *ah* is a parameter which describes the heat transfer between the rock matrix and fluid. The larger *ah* enhances the rock matrix-fluid heat exchange in the reservoir and generally diminishes the rock-fluid temperature difference. When the volumetric heat transfer coefficient *ah* tends to infinity, the temperature difference is zero, which is called local thermal equilibrium model. The CO_2 temperature at the reservoir outlet through the reservoir with LTE model and LTNE model are shown in Fig. 2. From the Fig. 2, it is concluded that the results of LTNE model with non-uniform *ah* has little difference from that of LTE model. The effect of local thermal non-equilibrium is not important for this simulation model. The case with constant *ah* in different layers indicates that the uniformity of *ah* has little influence on the thermal breakthrough time, but the differences of temperature become more obvious with time after thermal breakthrough.

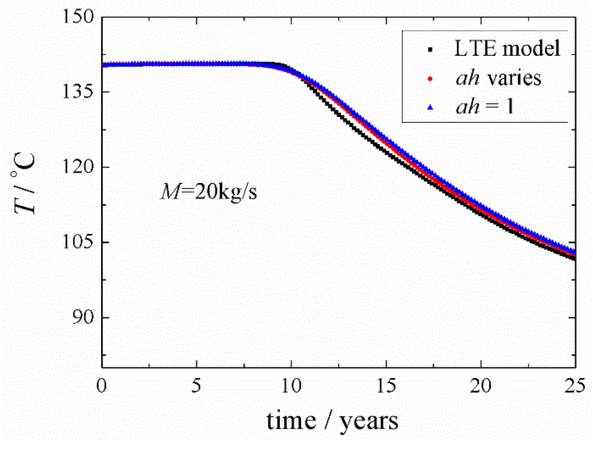
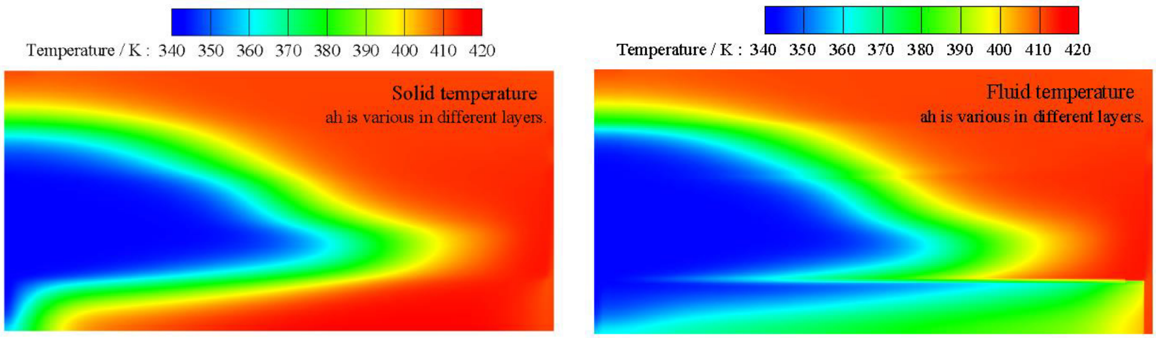


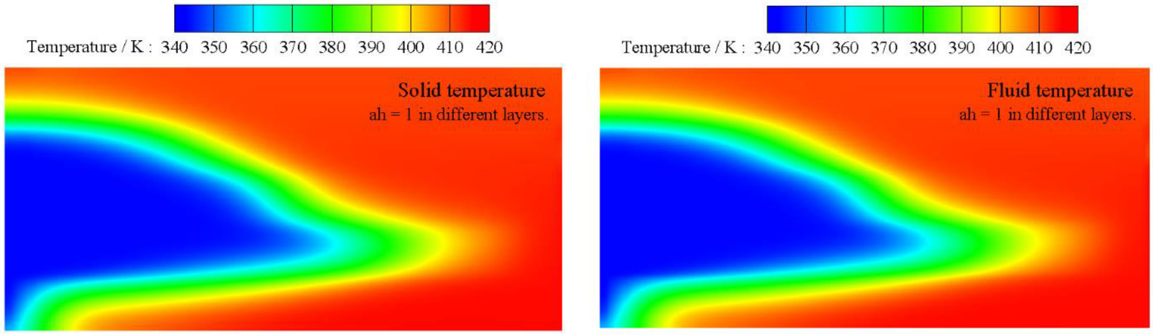
Fig. 2. CO_2 temperature variation with time for different models

Fig. 3 and Fig. 4 show the temperature distributions in the reservoir along a slice linking the injection and production wells after 9.5 years of CO_2 injection for various *ah* and constant *ah* in different layers with local thermal non-equilibrium model. As shown in Fig. 3, the temperature differences between rock matrix and fluid in the different layers are very different. The temperature distributions of rock matrix and fluid in layer 4 are almost the same, while the temperature difference between rock matrix and fluid in layer 5 is significant. This is because that the specific surface area a of different layers varies greatly. For example, the specific surface area a of layer 5 is smaller 5 orders of magnitude than that of layer 4, so the effect of local thermal non-equilibrium is more remarkable in layer 5. It should be noted that the injection CO_2 mainly flow through the layer 4 channel because of largest permeability, and the effect of local thermal non-equilibrium of the whole reservoir depends on the effect of local thermal non-equilibrium of layer 4. The fluid flow and heat transfer in the layer 5 has little impact on the production temperature at the reservoir outlet. This is the reason that the results of LTNE model with non-uniform *ah* has little difference from that of LTE model. When *ah* is uniform and equals 1 in the reservoir, the temperature differences of rock matrix and fluid in different layers are all small, and the effect of local thermal non-equilibrium can be ignored, shown in Fig. 4.



(a) Solid temperature distribution (b) Fluid temperature distribution

Fig. 3. Temperature distribution in the reservoir along a slice after 9.5 years of CO_2 injection with ah is various in different layers (a) solid temperature distribution (b) fluid temperature distribution



(a) Solid temperature distribution (b) Fluid temperature distribution

Fig. 4. Temperature distribution in the reservoir along a slice after 9.5 years of CO_2 injection with constant *ah*=1 in different layers (a) solid temperature distribution (b) fluid temperature distribution

Three another cases with *ah* values of 0.1, 0.01, 0.001, respectively, are simulated for the further study of the effect of local thermal non-equilibrium on the fluid flow and heat transfer in the rock matrix of EGS. The CO_2 temperature variations in 25 years for different *ah* are presented in Fig.5. The thermal breakthrough time is reduced to 6.5 years, 0.8 years, 0.5 years when *ah* equals 0.1, 0.01, 0.001, respectively. Fig. 6 shows the temperature distributions of rock matrix and fluid in the reservoir along a slice linking the injection and production wells after 9.5 years of CO_2 injection for various *ah* with local thermal non-equilibrium model. The temperature difference becomes larger and the effect of local thermal non-equilibrium becomes significant with decreasing *ah*. It shows the effect of local thermal non-equilibrium on the CO_2-EGS heat extraction mainly depends on the volumetric heat transfer coefficient *ah*. Therefore, the accurate prediction of volumetric heat transfer coefficient *ah* is very necessary to predict the heat extraction rate and operation lifetime of a given CO_2-EGS reservoir.

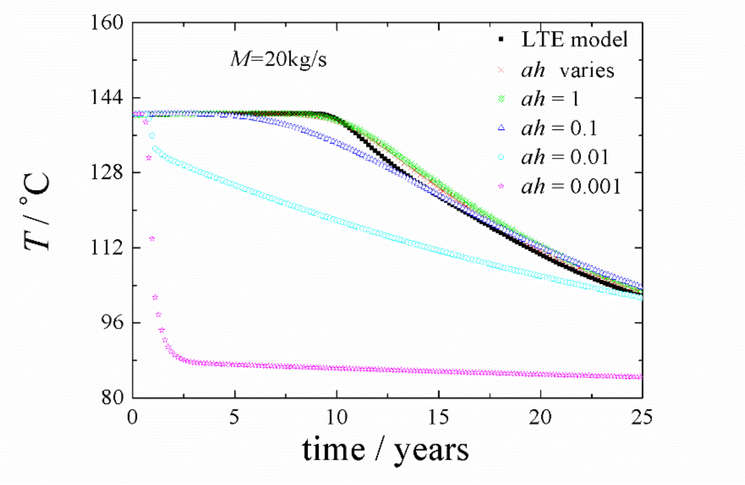
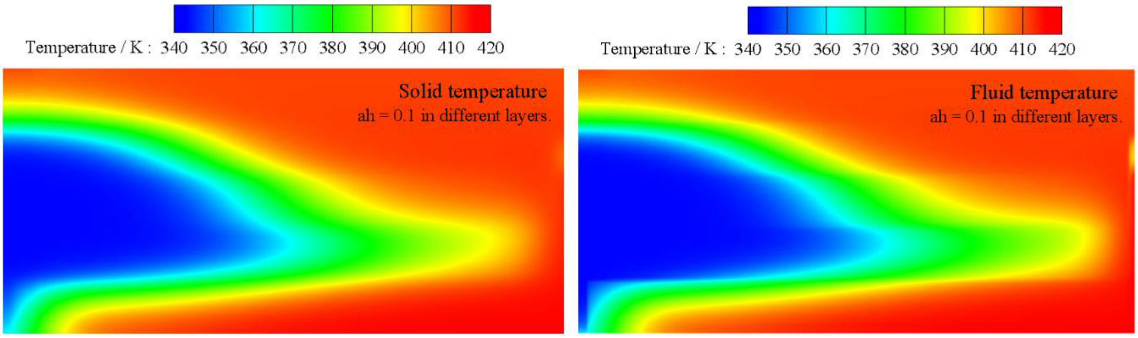
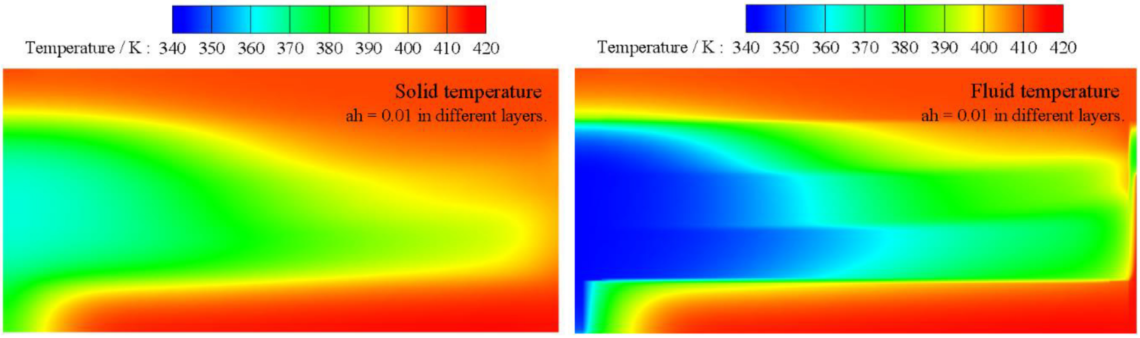


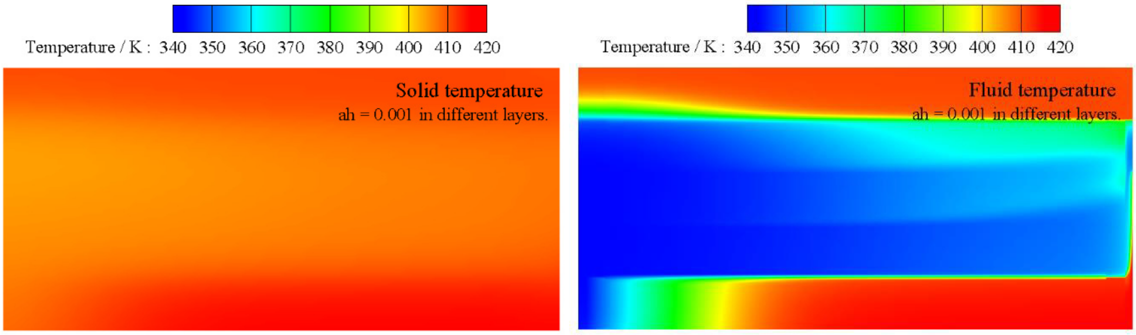
Fig. 5. CO_2 temperature variation with time for different *ah* in the reservoir



(a) Solid and fluid temperature with constant *ah*=0.1



(b) Solid and fluid temperature with constant *ah*=0.01



(c) Solid and fluid temperature with constant *ah*=0.001

Fig. 6. Temperature distribution in the reservoir along a slice after 9.5 years of CO_2 injection with constant *ah* in different layers (a) *ah*=0.1 (b) *ah*=0.01 (c) *ah*=0.001

4. Conclusions

This study presents a numerical model of CO_2-EGS with fracture zones and different layers with two wells to study the effect of local thermal non-equilibrium on the heat transfer and fluid transport of supercritical CO_2 in enhanced geothermal system. This study is a continuation of our previous research. As compared with the previous results of our research group, the effect of local thermal non-equilibrium has a profound effect on the production temperature at reservoir outlet and thermal breakthrough time of a given EGS reservoir. The effect of local thermal non-equilibrium becomes significant with increasing *ah*. Moreover, the uniformity of volumetric heat transfer coefficient *ah* has little influence on the thermal breakthrough time, but the temperature differences become more obvious with time after thermal breakthrough. The thermal breakthrough time reduces and the effect of local thermal non-equilibrium becomes significant with decreasing *ah*. The accurate prediction of volumetric heat transfer coefficient *ah* is very necessary to predict the heat extraction rate and operation lifetime of a given CO_2-EGS reservoir.

Acknowledgements

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