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Research Paper

Experimental study of convective heat transfer of carbon dioxide at supercritical pressures in a horizontal rock fracture and its application to enhanced geothermal systems

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HIGHLIGHTS

- A laboratory apparatus and a corresponding data reduction method was presented.
- Heat transfer performance of supercritical pressure CO_2 in a fracture was analyzed.
- A correlation was provided for improving field-scale simulation models for EGS.

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ABSTRACT

Enhanced geothermal systems create fractured reservoirs to extract economic quantities of heat from low-permeability and/or low-porosity geothermal resources. Convective heat transfer characteristics of fluids at supercritical pressures in rock fractures are important for optimizing the heat transfer model, which is a key tool for simulating heat extraction and improving the heat recovery factor for such projects. This paper presents the results of experimental investigations of laminar convective heat transfer of CO_2 at supercritical pressures in a horizontal fracture with an aperture of 0.2 mm. The laboratory apparatus operated at temperatures up to 280 °C, fluid pressures up to 14 MPa, and confining pressures up to 28 MPa. The effects of mass flow rate and initial rock temperature on the rock wall and fluid temperatures were examined. A method was proposed for processing the experimental data and local heat transfer performance in the fracture was obtained. Considering the effects of variations in thermophysical properties, a correlation of heat transfer performance in the rock fracture was proposed to improve field simulation models for enhanced geothermal systems.

1. Introduction

Urgent demands for clean and renewable energy resources can be addressed by the enormous potential and low emissions of geothermal energy, which can provide long-term sustainable use for electricity generation, heating, and other applications [1–6]. Enhanced geothermal systems (EGS) are defined as engineered reservoirs that are created to extract economic quantities of heat from low-permeability and/or low-porosity geothermal resources [1]. EGS enable the utilization of geothermal energy from conductive hot dry rock (HDR) with low permeability and low porosity and from low-productivity convective and aquifer systems by creating fluid connectivity through stimulation methods [3]. According to official assessments by China Geological Survey, the total HDR resources distributed at depths of 3–10 km are equivalent to 8.6×10^{14} tons of standard coal, which is approximately 260,000 times China's 2010 national energy consumption [7,8]. These rocks are almost impermeable in their natural state, so an artificial interconnected fracture network that connects injection and production wells is stimulated. A heat transfer fluid, such as water or CO_2, is pumped into injection wells, flows through the fractured reservoir, and the heated fluid is extracted from production wells for electricity generation or other applications.

In 2000, Brown [9] proposed a novel CO_2–EGS concept using supercritical CO_2 instead of water as the heat transfer fluid in a closed-loop HDR system. Many subsequent performance comparisons between CO_2–EGS and water–EGS using field-scale numerical simulations have shown that the former not only produces greater power owing to the favorable transport properties of CO_2, but also

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Nomenclature

C_p	specific heat at constant pressure [J/(kg K)]
d	fracture aperture [mm]
E	total energy [J]
h	heat transfer coefficient [W/(m^2 K)]
H	specific enthalpy [J/kg]
I	unit tensor
M	mass flow rate [kg/s]
Nu	Nusselt number
P	fluid pressure [MPa]
Pr	Prandtl number
Q	overall heat extraction rate [W]
Re	Reynolds number
t	time [s]
T	temperature [°C]
u	x component of velocity [m/s]
v	y component of velocity [m/s]
$\vec{v}$	velocity vector [m/s]
x	axial coordinate [m]

Greek symbols

λ	thermal conductivity [W/m K]
μ	fluid viscosity [Pa s]
ρ	fluid density [kg/m^3]

Subscripts

0	initial time
b	bulk
exp	experiment
f	fluid
in	inlet
out	outlet
p,c	pseudo critical
x	axial location
w	wall

sequestrates CO_2 underground [9–16]. An effective numerical simulation model of CO_2–EGS is therefore necessary to predict the overall performance for demonstration or commercial projects [5]. There are two main numerical simulation models used to describe flow and heat transfer in an EGS reservoir: the fracture network model and the equivalent continuous porous media model [17,18].

The fracture network model generates a discrete fracture network reservoir based on measured project data, such as fracture aperture and length distribution, orientation, and spacing [19–21]. For simplicity, many researchers represent an EGS fractured reservoir as one single fracture [22–26] or multiple fractures [27–29] to obtain analytical solutions or effective numerical simulations. For modeling of fluid flow and heat transfer processes in fractured rocks, the most common assumption is that an instantaneous local thermodynamic equilibrium exists between the fluid and surfaces of the neighboring rock matrix [23–25,27]. Lu et al. [30] analyzed the effects of assuming instantaneous local thermodynamic equilibrium on heat transfer in a single-fracture impermeable rock and observed that the ratio of the convective coefficient and the grain size is the major factor influencing the validity of this assumption. Shaik [31] generated a discrete fracture network geothermal system and showed that the heat transfer coefficient between the rock matrix and working fluid has a profound effect on the production temperature. Therefore, heat transfer between the rock matrix and fluid has a significant effect on the production performance of a geothermal system.

Many field-scale numerical studies of EGS heat extraction performance regard the fractured reservoir as a continuous porous medium and average the flow and thermal transport properties of individual fractures in the reservoir over a representative element volume; the flow and thermal transport in the discrete fracture network can then be represented by continuous equations. It is well known that there are two models to describe convective heat transfer in porous media: the local thermal equilibrium (LTE) model and the local thermal non-equilibrium (LTNE) model. In the former, the temperature of the rock and fluid are assumed to be the same: only one energy balance equation is solved. For application of the LTE model in EGS simulations, the porous medium temperature represents the temperature of the fracture surface, the rock matrix, and the circulating fluid [9–11,32–34]. In contrast, the LTNE model uses two energy equations to describe heat transport of the solid matrix and the fluid individually, with consideration given to the temperature difference between them in a representative element volume. The internal heat transfer coefficient in this model is important for the overall performance of a geothermal system [35–41]. Our research group [37] presented an LTNE model with a broad range of more reasonable internal heat-transfer coefficients to simulate the flow and heat transfer of supercritical CO_2 under conditions pertaining at the European EGS site at Groβ Schönebeck, Germany. The results showed that, with decreasing internal heat transfer coefficient, the thermal breakthrough time was reduced and the effect of local thermal non-equilibrium became significant. Gelet et al. [38,39] proposed a fully coupled thermo–hydro–mechanical model combined with the LTNE model and calibrated the specific solid-to-fracture heat transfer coefficients at about 33 W/m^3/K and their range as 60–120 W/m^3/K by comparing the simulation results with field data collected from Fenton Hill HDR and Rosemanowes Reservoirs [38].

Knowledge of the heat transfer coefficient in a rock fracture is important for both the fracture network and LTNE models in EGS field simulations; however, few exact and systematic empirical solutions for heat transfer coefficients in rock fractures are available [30]. A few experiments have been conducted on convective heat transfer in rock fractures to obtain their internal heat transfer coefficients. Zhao [42] conducted hydro–thermal–mechanical experiments with flowing water: in several studies the heat-transfer coefficients between a single fracture and granite were calculated as 200–1400 W/m^2/K [42,44], 5–200 W/m^2/K [43] and 9–960 W/m^2/K [45]. Ogino et al. [26] determined the heat transfer coefficients between fluid and particles and between fluid and the fracture wall for unidirectional flow in the packed slit by analogy with mass transfer experiments. For CO_2–EGS applications, Magliocco et al. [46] established an experimental apparatus to investigate heat extraction by flowing dry supercritical CO_2 and water through a heated porous medium and the numerical model using TOUGH2 with ECO2N module was validated by comparison with the experimental results. However, no correlation of internal heat transfer coefficients has been obtained from experiments taking into consideration the variations of supercritical CO_2 properties in porous media.

According to Potter et al. [47], the most suitable HDR rock type is granite or other crystalline basement rock, where temperatures vary from 150 °C to 500 °C at depths of 5–6 km. In most regions of the reservoir described by Potter, the water temperature is much lower than the pseudocritical temperature at pressures corre-