Experimental Study of Heat Transfer for Supercritical Carbon Dioxide with Upward Flow in Vertical Tube

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Abstract
In this study heat transfer of supercritical carbon dioxide in vertical tube with 10 mm of inner diameter and 1800 mm of length was investigated experimentally. The initial temperature of tube wall was set to 150 and 200°C. The system pressures of supercritical carbon dioxide are 1100, 1500 and 2000 psi, respectively. The experimental results show that the heat transfer coefficient and heat transfer rate increase with Reynolds number. The maximum heat transfer coefficient and heat transfer rate was occurred in 1500 psi of system pressure. The heat transfer coefficient for 150°C is higher than that of 200°C resulted from effect of specific heat.

Keywords: *Supercritical fluid, Enhanced Geothermal System (EGS), Carbon dioxide*

1 Introduction

Recently, the global warming of the earth becomes more and more serious. The renewable energy is used to replace fossil fuels gradually. Therefore, considered to be a very important factor in reduce to CO_2 emissions while to enhance energy security and sustainability [1,2]. Geothermal power is a kind of renewable energy and less CO_2 emission [3].

Enhanced geothermal system which injects working fluid through inject well into reservoir approximate 3000 m depth. The working fluid is heated in the reservoir through hot rock and flows out ground through the production well. Because unique and thermodynamic properties for supercritical CO_2, Brown [4] proposed that supercritical CO_2 is used as working fluid in enhanced geothermal system. In addition, carbon dioxide can sequestrations and recycled in the reservoir, does not cause to environment pollution.

Atrens et al. [5] demonstrate the CO_2 can perform well than water in low permeability reservoirs. Haghshenas Fard et al. [6] observe that the pressure drop and heat transfer performance of a CO_2 geo thermosiphon can be superior to those of water-based systems. Yun et al. [7] results show the effects of heat flux on the heat transfer coefficient are much significant than those of mass flux. Niu et al. [8] show the thermo physical properties of CO_2 near the critical point have significant effects on the supercritical local heat transfer behaviors. Heat transfer of supercritical local CO_2 is also dependent on the mass flow rate, input heat flux and pressure. Jiang et al. [9] propose that the thermo physical properties of super-critical CO_2 and buoyancy are influenced by the convection in the vertical mini-tubes and porous media significantly. Liao and Zhao. [10] found that the buoyancy effects are significant for all the flow orientations. In addition their experiments reveal that, a significant impairment of heat transfer is discerned under the pseudo critical region in downward flow direction. Although heat transfer for horizontal and upward flow both are enhanced under the same conditions. Cao et al. [11] found that the buoyancy is significant and enhances the heat transfer, especially near the pseudo critical point, unless the fluid and the tube wall are under the thermal equilibrium condition. Bruch et al. [12] experimental results illustrated the influence of buoyancy forces on the heat transfer process. Kim et al. [13] found the flow acceleration predominantly affected the heat transfer phenomena. This purpose of this study is to study the heat transfer of supercritical CO_2 flowing in vertical tube at higher temperature.

2 Experimental Apparatus

2.1 *Experimental parameters*

This study investigates the efficiency of heat extraction of the Supercritical carbon dioxide at different pressure, temperature. The efficiency of heat extraction depend on pressure and temperature, therefore operating conditions is set for pressure 1100, 1500 and 2000 psi, Reynolds number from 1.5 to 7.6 and 150 and 200°C of initial wall temperature during experiment.

The heat transfer rate from tube wall to supercritical carbon dioxide at steady state is calculated.

$$\dot{q} = \dot{m}(h_{out} - h_{in}) \tag{1}$$

where $\dot{m}$ indicates the mass flow rate, h_{in} is the test section inlet enthalpy, h_{out} is the test section outlet enthalpy of supercritical carbon dioxide.

Heat transfer coefficient of Supercritical carbon dioxide in the test section is defined, as follow:

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{2}$$

where ΔT_1 indicates the temperature difference between inlet temperature and tube wall, ΔT_2 is the temperature difference between outlet temperature and tube wall. The average heat transfer coefficient is determined from:

$$h = \frac{\dot{q}}{A \cdot LMTD} \tag{3}$$

where A is inner surface of test section.

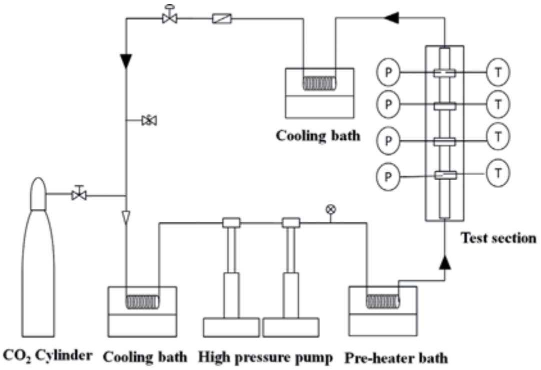


Figure 1: schematic diagram of experimental system.

2.2 *Experimental apparatus*

The schematic diagram of experimental system is shown in Figure1. It consists of a CO_2 cylinder, high pressure pump, pre-heater water bath, cooling water bath, test section, computer and data logger. The test section is made of stainless steel with inside and outside diameters of 1 cm and 1.27 cm and length of 1.8 m. The test section is heated by heating unit. The heating unit is consists of copper, resistance heater, power supply and thermal insulator. The heat is provided by resistance heater through copper to test section. The temperature of outside tube wall and supercritical CO_2 are measured by TC and RTD. The ten TCs are fixed on outside of tube wall. The RTDs placed in inside of tube for each 450 mm are measured to evaluate heat transfer coefficient and rate.

To study supercritical carbon dioxide heat extraction efficiency at different pressures, flow rate and temperature. The processes are using power supply input power to heated test section and the apparatus was allowed to thermally equilibrate. After carbon dioxide was pressurize in high pressure pump, then injection to the test section before to be heated at pre-heater bath, this aim is for carbon dioxide reached to supercritical state. Resistance Temperature Detector and T-type thermocouple will immediate record variation in temperature within tube and tube wall when fluid through to test section. Last, supercritical carbon dioxide was cooling in the cooling bath when leave for test section, the aim is for supercritical carbon dioxide were cycled in this manner until the test section achieve the thermal equilibrium state.

3 Experimental Results and Discussion

All the experimental data reported in this study were processed based on the data for the physical properties of CO_2 provided by the NIST Refrigerants Database [14]. As supercritical CO_2 at constant pressure, the specific heat reaches peak value as supercritical CO_2 at constant pressure. The temperature at this peak value of specific heat is called pseudo-critical temperature. When temperature of supercritical CO_2 approaches the pseudo-critical temperature at constant supercritical pressure, the heat transfer coefficient is higher, relatively. In this study measurements were carried out at CO_2 pressures ranging from 1100 to 2000 psi, temperatures from 150 to 200°C, and Reynolds number from 1.5 to 7.6. Figures 2–4 present the experimental results for the heat transfer coefficients, heat transfer rate, Reynolds number and heat transfer coefficient of CO_2 at supercritical pressures in the tube.

3.1 *Effects of Reynolds number*

Figure 2 (a) and (b) show that the heat transfer coefficient and heat transfer rate affected by Reynolds number. Heat transfer coefficient and heat transfer rate both are increased with Reynolds number. However, for x/L=0.25 the performance of super-critical CO_2 is the highest for all Reynolds numbers resulted from effect of specific heat of super-critical CO_2 at pseudo-critical temperature.

3.2 *Effects of different pressure*

Figure 3 shows that the influence of system pressure on the heat transfer coefficient and heat transfer rate at Re=7.6 and 150°C of initial wall temperature. The highest value for specific heat of supercritical CO_2 appears at 1100 psi and 31°C. However, the initial wall temperature is set at 150°C and the temperature of supercritical CO_2 is higher than 31°C in the test section at steady state. For local and average heat transfer coefficient 1500 psi of the system pressure is optimal operating conditions for CO_2-EGS. It is noted that above 1100 psi the heat transfer rate insignificantly affected by system pressure despite higher specific heat for 1500 psi. Nevertheless, it is mean that for lower system pressure the power consumption is lower during EGS.

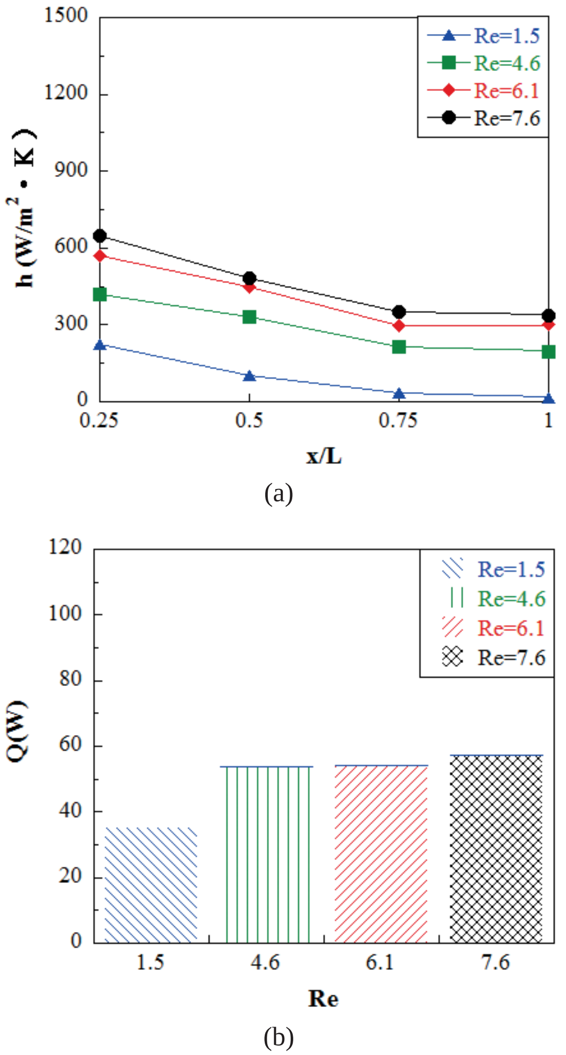
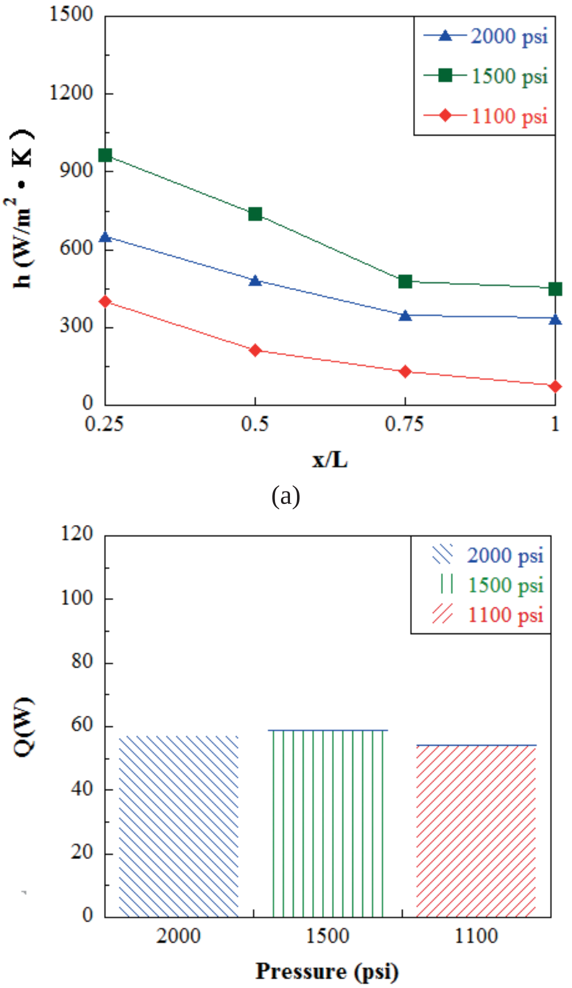


Figure 2: Effects of Reynolds number on the heat transfer coefficient (a) and heat transfer rate (b) at pressure=2000 psi and temperature=150°C.

3.3 *Effects of initial wall temperature*

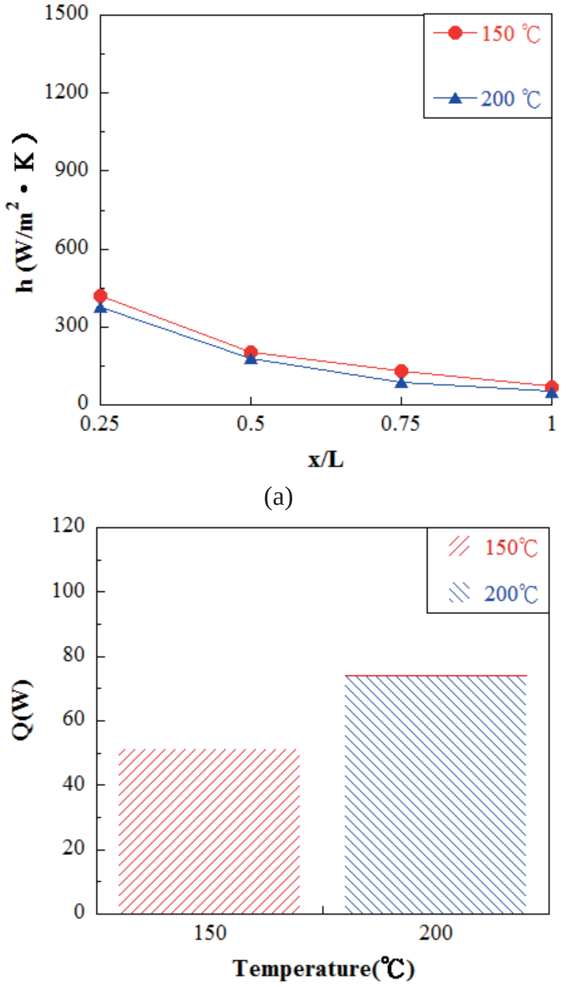
Figure 4 shows that the influence of initial wall temperature on the heat transfer coefficient and heat transfer rate at Re=6.3 and 1100 psi of system pressure. The heat transfer coefficient at 200°C of initial wall temperature is lower than that at 150°C, but the heat transfer rate is higher than 150°C, the resulted from effect of specific heat with temperature and have enthalpy difference between inlet and outlet of the test section.



(a)

(b)

Figure 3: Effects of pressure on the heat transfer coefficient (a) and heat transfer rate (b) at Re=7.6 and temperature=150°C.



(a)

(b)

Figure 4: Effects of temperature on the heat transfer coefficient (a) and heat transfer rate (b) at Re=6.3 and pressure=1100 psi.

4 Conclusions

This paper purpose is investigated performance of heat transfer for CO_2. The results show that the 1500 psi of system pressure is better on heat transfer coefficient. It is attributed to specific heat is higher at 1500 psi of system pressure. In addition, the heat transfer coefficient and heat transfer rate both are increased with Reynolds number. The current geothermal energy and sequestration of carbon dioxide is important issue, therefore the more experiment parameters can be investigated in the future, such as increased pressure, temperature, change flow direction and inserted in-situ porous medium into test section to model supercritical carbon dioxide injection enhanced geothermal system operating conditions.

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