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# Heat Transfer Characteristics of Supercritical Carbon Dioxide in a Horizontal Tube

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**Abstract.** The convection heat transfer characteristics of supercritical $CO_2$ in a horizontal tube were investigated experimentally. The experimental parameters were supercritical pressures and volumetric flow rates. The experimental results show that the heat transfer coefficient increased with flow rate. Furthermore, the pseudo-critical point had a significant influence on the heat transfer coefficient. In the study, the supercritical pressure of 10MPaconstituted an optimal operating condition for $CO_2$-EGS because of the high heat transfer performance at 200 ℃.

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

## 1. Introduction

Renewable energy technology has created a lot of discussion ever since the issue of carbon-reduction and environmental protection was raised. Geothermal energy is a type of renewable energy that releases few $CO_2$ emissions [1], and can be considered as one of the important energy in future. Geothermal systems can be divided into traditional and nontraditional geothermal systems. Nontraditional geothermal systems are normally called enhanced geothermal system (EGS). The operation process of Enhanced Geothermal System (EGS) had two stages. First, the injection well shall be at least drilled three kilometers deep and the temperature shall be more than 250℃. Second, the high pressure working fluid composed of chemical component (depend on geologic condition) is used to create the fracture in the reservoir though the injection well. The high pressure water is used to absorb the heat from the fracture in the reservoir and then flow out from the production well. Finally, the extracted heat from the working fluid can be used to generate power. In the past, water and carbon dioxide can be used as working fluids, but studies have been suggested as an EGS working fluid because of its thermal behavior is better than water's at high temperatures and pressure in reservoir. Furthermore, the special characteristic of $CO_2$makes is more satisfactory than that of water in the reservoirs which has low-permeability condition [2]. Brown first proposed $CO_2$-EGS in 2000 [3], which leads the research of EGS proliferated recently. Wan et al. investigated the impact of fluid-rock interaction on $CO_2$-EGS in 2011 [4], while the buoyancy of super-critical $CO_2$ in the vertical mini-tubes and porous media were discussed by Jiang et al. [5]. To determine the availability of $CO_2$-EGS, researchers have discussed several topics, including $CO_2$ mineralization by injecting $CO_2$ into granite and sandstone [6]. The EGS can not only product power but also let $CO_2$ sequester in deep-saline aquifers.[7].In 2006, Pruess et al. extensively investigated the heat transmission [8], sequestration of carbon [9], and production behavior [10] of $CO_2$-EGS.

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Heat extraction is the main parameter for $CO_2$-EGS to determine the efficiency of the system. In order to extract the heat from the reservoir, numerous phenomena have been observed and studied. Several studies have investigated heat transfer phenomena related to $CO_2$-EGS: Liao et al. determine that buoyancy effects are significant for all flow orientations [11, 12]. Most of these studies show that the flow rate and pressure are the most important parameters in the EGS. However, these results are nearly based on the simulation and limited by the absence of an experimental system used to investigate the performance of supercritical CO2 in artificial conditions of reservoir. In order to obtain more precise result, the study determined the efficiency of supercritical CO2-EGS by using a horizontal tube to perform the heat extraction.

# 2. Experiment

## 2.1 Experiment apparatus

The heat transfer characteristics of supercritical $CO_2$ in a horizontal tube were investigated experimentally. Fig. 1 shows the experimental system, which included a compressed $CO_2$ cylinder, a cooling water bath, a high pressure $CO_2$ pump, a pre-heater, a test section, heating unit, cooler, differential pressure transmitter, heater and measurement systems, a computer, and a data acquisition system (YOKOGAWA MA100). The test section was composed of stainless steel tube with the length of 208.0 mm. The inner and outer diameter of test section is 30 mm and 55 mm, respectively. The heating unit that is connected to a power supply is composed of a resistor, copper, and thermal insulator. A syringe pump (Teledyne ISCO pumps 520D) was used to provide a precise flow rate and high static pressure. To determine the behavior of supercritical $CO_2$, various experimental parameters were applied during the experiment including the system pressure (7.5, 10, and12.5 MPa), and the flow rate (20, 40, 60, and80 mL/min). In addition, the initial test section temperature was pre-set at 200℃ by a constant heat flux to simulate the actual reservoir temperature.

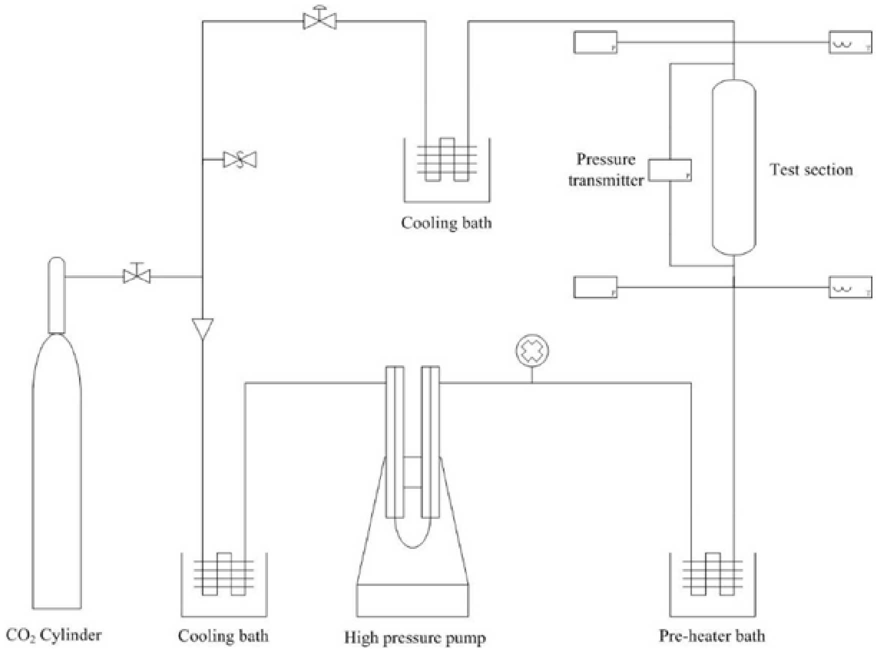

Fig. 1: Schematic of experimental apparatus

## 2.2 Experimental parameters

The heat transfer rate is calculated by the following equation.

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

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

$$T_{w,i(x)} = T_{w,o(x)} - \frac{q_w d}{2k_s} \ln \frac{d+2\delta}{d} \quad (2)$$

Where $T_{w,i}$ is the local inner surface temperature, $T_{w,o.}$ is the local well temperature, d is the tube inner diameter, $k_d$ is thermal conductivity of the solid wall, $\delta$ is the distance from thermocouples to the inner surface.

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

$$h_x = \frac{q_w(x)}{T_{w,i}(x) - T_{f,b}(x)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where $h_x$ is the local heat transfer coefficient in the tube, the local inner surface temperature, $T_{w,i}$ is calculated by $T_{w,o.}$ The local bulk fluid temperature, $T_{f,b}$ (x), was obtained from the local bulk fluid enthalpy, $h_f$(x), which was in turn calculated by:

$$h_f(x) = h_{f,in} + \frac{q_w(x)\pi dx}{G} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where $h_{f,in}$ is the inlet enthalpy , $q_w$ is the local heat flux on the inner surface, π is the circular ratio, d is the tube diameter, x is axial coordinate.

## 3. Experimental Results and Discussion

In the present study, the experiments were carried out with various supercritical pressures from 7.5 to 12.5 MPa, and various volumetric flow rates from 20 to 80mL/min at the initial wall temperature 200℃. All the experimental data reported in this study was processed based on the physical properties of $CO_2$ provided by the NIST Refrigerants Database [13]. Fig. 2 shows the relationship of specific heat with temperature in the critical region under different pressure by using the NIST Refrigerants Database. As shown in the figure, the pseudo critical temperatures are 31.7 ℃ (7.5 MPa), 45.02 ℃ (10 MPa), and 55.95 ℃ (12.5 MPa) for $CO_2$ at these pressures. The thermo physical properties of $CO_2$ at supercritical pressures vary with pressure and fluid temperature with the specific heat having a maximum at the pseudo critical temperature.

Figure 3 illustrates that influence of flow rates and supercritical pressure on the heat extraction. The heat extraction rate at 10MPa was better than that of at 7.5 and 12.5MPa. When supercritical pressure was at 10 MPa, the heat extraction rate for flow rate of 60 mL/min reached the highest value. For example, the heat extraction rate at 10 MPa and flow rate of 60 mL/min was approximately 66% higher than that of 7.5 MPa. This was because the effects of the properties of supercritical $CO_2$.

Figure 4 shows the heat transfer coefficient of test section affected by different pressure under the flow rate of 60 mL/min. As shown in the figure, the heat transfer coefficient increases significantly at the position (x/L) beyond 0.66, the highest increase value at 10 MPa are 2.84 times and 2.03 times more than that at 7.5 MPa and 12.5 MPa due to the strong variations of the thermo physical properties of supercritical $CO_2$ with temperature. This phenomenon can be easily observed in Fig. 2. According to the experimental results, the temperature of test section after steady state at x/L = 0.88 under the flow rate of 60 mL/min is 64.2 ℃ (7.5 MPa), 49.9 ℃ (10MPa), and 54.1 ℃ (12.5 MPa) respectively. The temperature difference between the pseudo critical temperatures show in Fig. 2 and experimental result is 32.5 ℃ (7.5 MPa), 4.88 ℃ (10 MPa), and 1.85 ℃(12.5 MPa) respectively. It is obvious that the temperature under the condition of 7.5 MPa is the one closest to the pseudo critical temperature. However, since the Cp at 7.5 MPa is much lower than that at 10 MPa and the steady temperature at 12.5 MPa is very different from its pseudo critical temperature, the heat transfer coefficient in the test section at 10 MPa shows the relatively high value in these three cases.

The heat transfer coefficient was examined at supercritical pressure of 10 MPa to determine the effects of the volumetric flow rates as shown in Fig. 5. At region of flow rate from 20 to 60 mL/min, the heat transfer coefficient increased as the volumetric flow rate increased and reached a peak value at 60 mL/min which is 10.94 times more than that at 20 mL/min. However, as the flow rate increases to 80 mL/min, the heat transfer coefficient decreases from the position x/L = 0.88. As we mentioned above, the thermal performance of super-critical $CO_2$ can reach an optimal value if the condition of test section is close to pseudo-critical status. The temperature of test section after steady state at x/L = 0.99 under the pressure of 10 MPa is 68.1 ℃ (20 mL/min), 53.1 ℃ (40 mL/min), 50.9 ℃(60 mL/min) and 49.3 ℃ (80 mL/min). The pseudo critical temperatures in Fig. 2 is 45.02 ℃ (10 MPa). Fig. 2 also shows the temperature difference between the pseudo critical temperatures and experimental results, which is 23.68 ℃ (20 mL/min), 8.08 ℃ (40 mL/min), 5.88 ℃ (60 mL/min) and 4.28 ℃ (80 mL/min). Although the temperature difference at 80mL/min is much closer than that at 60 mL/min, the temperature difference between the local bulk fluid temperature ($T_{f,b}$) and the local inner surface temperature ($T_{w,i}$) is 0.66 (60 mL/min) and 0.93 (80 mL/min). The heat transfer coefficient in the test section at 60 mL/min shows the relatively high value in these three cases.

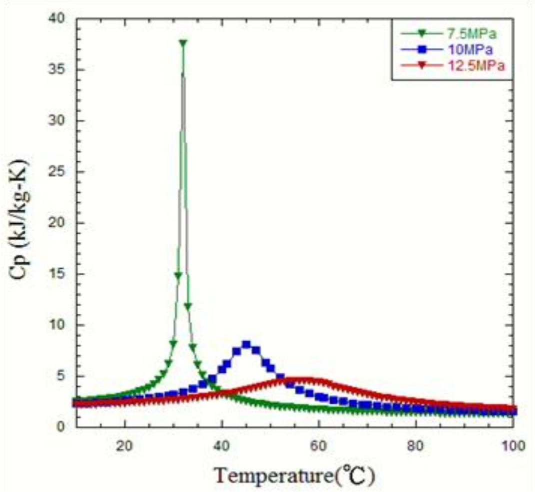

Fig. 4: Effects of pressure on the heat transfer coefficient at volumetric flow rate is 60 mL/min

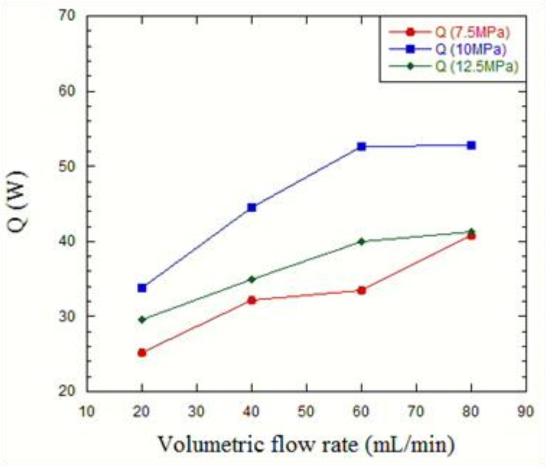

Fig. 3: Effects of pressure and volumetric flow rate on the heat extraction.

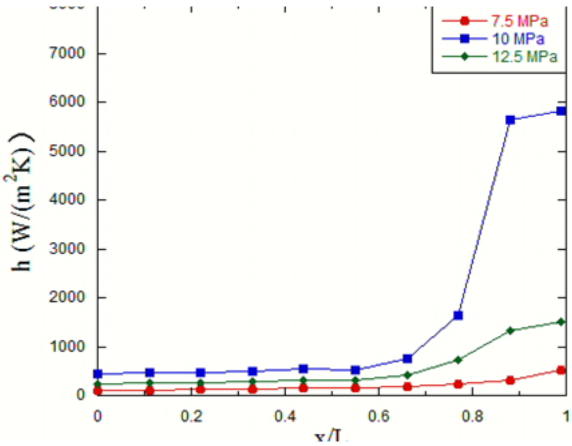

Fig. 4: Effects of pressure on the heat transfer coefficient at volumetric flow rate is 60 mL/min

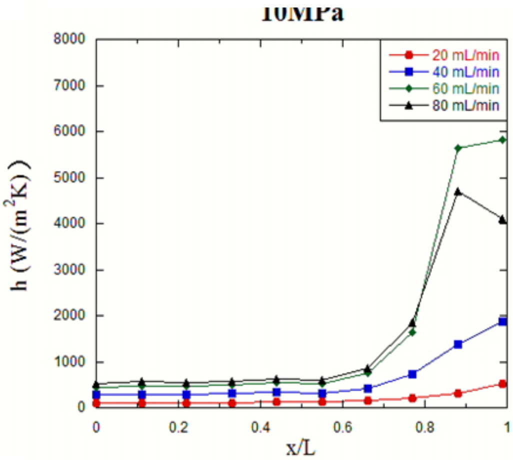

Fig. 5: Effects of volumetric flow rate on the heat transfer coefficient at pressure is 10MPa

## 4. Conclusions

In the study, the heat transfer performances for supercritical CO2 were experimentally investigated. The results show that the 10MPa of system pressure on heat transfer coefficient was better than that of 7.5 and 12.5 MPa. The heat transfer coefficient and heat extraction rate at supercritical pressure of 10 MPa and flow rate of 60 mL/min was higher than 7.5 MPa approximately 8.35 times and 66%, respectively. The heat transfer performance and heat transfer rate both increased with flow rate. And the heat transfer performance and heat transfer rate both increased with the temperature difference that between the pseudo critical temperatures and experimental results decrease.

According to the experiment results, we can find that the thermal performance of $CO_2$-EGS is strongly affect by the steady temperature of test section, that is, the amount of heat extraction is higher if the temperature is close to pseudo-critical temperature of $CO_2$. In conclusion, the best property is 10 MPa pressure and 60 mL/min volumetric flow rate in our research.

The current geothermal energy and sequestration of carbon dioxide is an important issue. Therefore, the more experiment parameters can be investigated in the future. Such as inlet temperature, pressure, flow direction. In addition, we can inserted in-situ porous medium into test section to model supercritical carbon dioxide injection enhanced geothermal system operating conditions and simulate some fracture inside the test section.

The best parameter of this research can be compared with the data of in-site reservoir in the future, such as pressure, flow rate. We expect it can apply the better parameter of EGS.

## 5. Acknowledgements

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