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Research Paper

Heat transfer of supercritical carbon dioxide flowing in a rectangular circulation loop

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HIGHLIGHTS

- Heat transfer of supercritical CO_2 flowing in circulation loop was studied.
- Parametric effects on heat transfer were carefully discussed.
- Buoyancy force has apparent effect on deteriorated heat transfer.
- A heat transfer correlation with reasonable performance was obtained.

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ABSTRACT

Experiments were conducted to investigate the heat transfer of supercritical carbon dioxide flowing in a rectangular circulation loop. The effects of heat flux, pressure, buoyancy force on heat transfer of supercritical carbon dioxide were carefully discussed. A heat transfer correlation for supercritical fluid was developed based on experimental data. Distinct heat transfer enhancement and heat transfer deterioration were observed in the present experiments. The maximum of heat transfer coefficient decreased with the increase of heat flux and pressure. Noticeable heat transfer deterioration was only observed in conditions of buoyancy parameter higher than 2.2×10^{-5}, $T_{w,int}/T_{pc}$ higher than 1.4, T_b/T_{pc} less than 0.95. The mechanisms of the effects of heat flux, pressure and buoyancy force on heat transfer of supercritical carbon dioxide were discussed in detail. Results indicated that the steep gradient of physical property over the tube cross-section is the key reason for heat transfer deterioration. The new heat transfer correlation showed reasonably satisfactory prediction performance.

1. Introduction

In natural circulation loop, the fluid is driven by buoyancy force resulted from the density difference between the hot source and cold sink in the circulation loop. Due to the elimination of driven components, such as pumps, natural circulation systems are simple and reliable, and thus they have advantages over forced circulation systems in terms of cost and system reliability. The local and system characteristics of natural circulation systems are significantly affected by physical properties of the working fluid. Water is one of the most widely used natural circulation working fluids, which has been used in solar energy collector and nuclear reactor. However, the circulation rate of water based natural circulation is relatively low [1]. In recent years, supercritical carbon dioxide has been attracting growing attention in thermal engineering due to its favorable physical properties, and it has been proposed for various industrial applications such as chemical extraction [2], generation IV nuclear reactor [3], refrigeration systems [4] and heat pump [5].

An interesting feature of supercritical fluid is the temperature-sensitive physical properties near the critical or pseudo-critical point. The temperature-sensitive physical properties near the pseudo-critical point could generate a considerable driving head in the system, and a high circulation rate would be achieved in supercritical carbon dioxide based natural circulation system. However, the unique behavior of supercritical carbon dioxide near the critical (or pseudo-critical) point would make the local and system characteristics of supercritical carbon dioxide natural circulation distinctly different from those of subcritical fluid natural circulation.

Literature reveals that very few experimental studies on supercritical carbon dioxide natural circulation have been conducted. The steady-state and stability behavior of supercritical carbon dioxide natural circulation have been experimentally investigated by Lomperski et al. [6], Yokhikawa et al. [7], Sharma et al. [8,9], Zhang et al. [1,10]. The effects of system pressure, inlet temperature and heater orientation on the steady-state and stability behavior of natural circulation loop have been investigated. Chen et al. [11]

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experimentally investigated the flow and heat transfer of supercritical carbon dioxide flowing in a natural circulation loop with horizontally positioned heating section. Various researchers have investigated the characteristics of supercritical carbon dioxide natural circulation. Most of them focused on the stability of natural circulation system. Chatoorgoon [12,13], Jain and Rizwan-uddin [14] investigated the stability of supercritical carbon dioxide natural circulation loop with one-dimensional model. One-dimensional model may be less capable in the analysis of the local behavior of supercritical fluids natural circulation [15]. Yadav and Gopal group [16–18], Zhang and Chen group [19–22] have conducted numerical studies on the transcritical and supercritical carbon dioxide natural circulation with two-dimensional or three-dimensional model.

It is important to note that most of the studies were numerical ones, and the emphasis was on the system stability of natural circulation. Very few experimental studies on the heat transfer of supercritical carbon dioxide flowing in natural circulation loop have been performed. Besides, the heating section of the natural circulation loop was usually horizontally positioned, and constant wall temperature boundary condition was applied to the heating section [16–18,20–22]. In applications such as nuclear reactor, the heating section is usually vertically positioned, and the constant heat flux boundary condition is reasonable. The orientation of heating section and the boundary condition are expected to affect the characteristics of supercritical fluids natural circulation [19]. For a thorough understanding of the heat transfer of supercritical carbon dioxide flowing in natural circulation loop, it is necessary to investigate the heat transfer of supercritical carbon dioxide flowing in a circulation loop with the vertical heating section and constant heat flux boundary condition, which is critical for the design and safety of natural circulation system.

In this study, the heat transfer of supercritical carbon dioxide in the heating section of a circulation loop was experimentally investigated. The general trends of heat transfer coefficient and wall temperature, and parametric effects on heat transfer were discussed in detail. The aim of the study is to research the heat transfer of supercritical carbon dioxide flowing in natural circulation system and to improve the understanding on the characteristics of supercritical carbon dioxide based natural circulation system.

2. Experimental apparatus and method

2.1. Experimental loop

The schematic diagram of the test loop was shown in Fig. 1. The test loop can sustain a maximum pressure of 30 MPa and a maximum temperature of 550 °C, which can operate with either supercritical water or supercritical carbon dioxide. The test loop is consisted of a test section, a cooler, a carbon dioxide storage tank, a pressurizer, a flow meter, a vacuum pump, an air-driven gas booster pump, a cooling water system and a DC power supply system.

The test section was an inconel 625 circular tube with a length of 2410 mm. The outside diameter and inside diameter of the test section were 11.50 mm and 5.98 mm, respectively. The voltage was applied on two copper plates with the help of the DC power supply system to obtain the desired heating power on the test section. The total test-section power was obtained by measuring the current and the voltage across the test section. It was assumed that the volumetric heat generation rate in the test section was uniform. The cooler was a counter-flow heat exchanger with carbon dioxide flowing in the internal tube and cooling water flowing in the external tube. The whole loop was wrapped with compound silicate insulation material ($k = 0.01$ W/m/K) to minimize heat lose. More details about the test loop can be found in Fig. 1.

2.2. Instrumentation

The pressures of the loop were measured by ST3000-type pressure transmitters with a range from 0.1 to 20.7 MPa and an accuracy of ±0.1% (of full scale). The flow rate of the primary loop was measured by a Venturi meter with a range from 10 to 100 kg/h and an accuracy of ±0.5% (of full scale). Platinum resistance thermometers with an accuracy of ±0.2 °C were used to measure the inlet and outlet fluid temperatures of the test section. Thermocouples

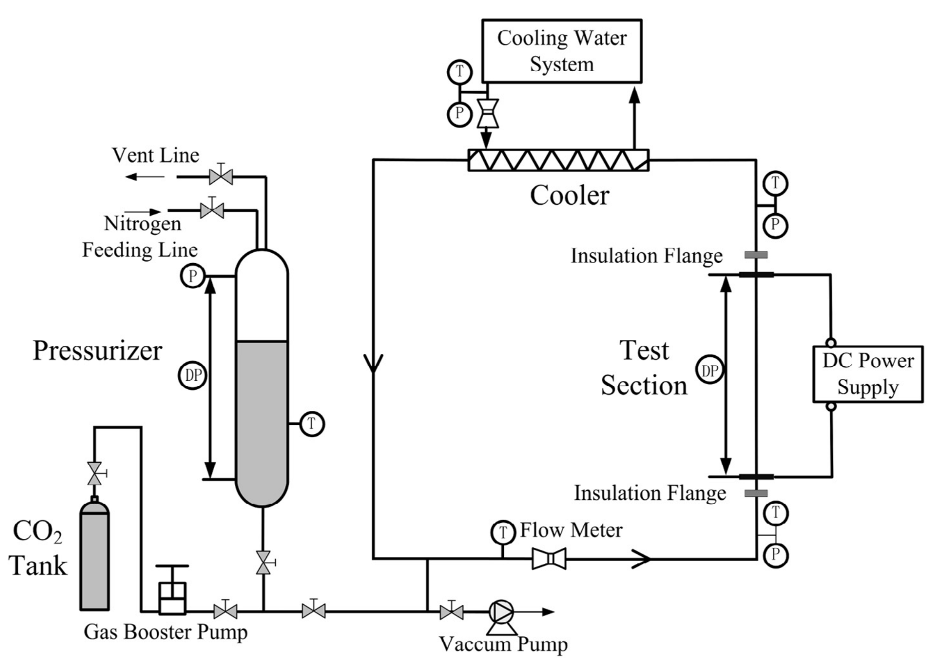

Fig. 1. Schematic diagram of the test loop.