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Flow and heat transfer characteristics of supercritical CO_2 in a natural circulation loop

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ABSTRACT

Owing to the environmentally benign nature and the special property variation at supercritical pressure, CO_2 attracts considerable attention in both science and engineering. The CO_2 utilization is regarded as a sustainable way in long term and has become an important global issue. In the present study, a two-dimensional numerical model is used to study the convective flow and heat transfer characteristics of supercritical CO_2 natural circulation in a uniform diameter rectangular loop. Parametric influences of the heat sink temperature, the inclination angle of the loop and the temperature difference on the convection motion and heat transfer performance have been studied. For a given temperature difference, the heat sink temperature has great effect on both flow and heat transfer performance. Increasing the inclination angle decelerates the convective flow and heat transfer processes due to the gradual decrease in buoyancy. With the increase of the temperature difference, both the flow rate and heat transfer performance are found to initially increase, reach a peak, and then decrease gradually. The underlying physics is explored.

1. Introduction

CO_2 seems to be the best retrofit to meet the future demand of long-term environment friendly working fluid. The key advantages of CO_2 include the fact that it is not explosive and non-toxic, which makes CO_2 an excellent alternative, especially in applications where toxicity and flammability of ammonia and hydrocarbons may be a problem. Another advantage of essential importance is that the heat transfer performance of CO_2 is outstanding, even in some cases of the supercritical region. The volumetric capacity of CO_2 is in the order of 5–10 times higher than that of common alternatives. Considerable efforts have been devoted to discussing the application potential of CO_2 in convection-based energy systems [1–8]. As suggested by Lorentzen and Pettersen [9], the use of CO_2 as a working fluid may provide a totally safe, economical and cost-effective 'natural' solution in many applications.

Owing to the reliability and simplicity, natural circulation loop is a promising option in many practical applications, such as nuclear power generation [10], geothermal processes [11], solar heaters [12], cooling of electronic devices [13], etc. The simplest conditions are those in which the loop lies in a vertical plane and is made of a bottom-placed heat source and a heat sink on the top. In the past few decades, many efforts have been devoted to the study about the primary characteristics of the natural convection of conventional fluids in circulation loops and parametric effects on the steady state stability and performance. Welander [14] gave a theoretical discussion of the flow instability of a fluid contained in a rectangular loop. Cammarata et al. [15] proposed a methodology based on the linear stability analysis for the construction of stability maps of rectangular natural circulation loop. Based on numerical simulations, Linzer & Walter [16] discussed how to avoid flow reversal in natural circulation systems. Vijayan et al. [17] studied the effect of loop diameters on the steady state and stability behavior of single- and two-phase natural circulation loops both experimentally and numerically. Sharma et al. [18] gave linear and nonlinear analysis of a supercritical water-based natural circulation loop. Using a one-dimensional theoretical model, Vijayan et al. [19] recently analyzed the steady state and stability performance of a single-phase, two-phase, and supercritical natural circulation in a uniform diameter rectangular loop and studied parametric effects. These improve the understanding about the flow and heat transfer process in rectangular circulation loops.

There is a growing research interest in CO_2-based natural circulation loops. Under supercritical pressure conditions, the

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thermodynamic and transport properties of CO_2 are very sensitive to the change of temperature, making CO_2 a promising working fluid in natural convection systems and of great interest in fundamental research. Lomperski et al. [20] studied the closed-loop natural circulation of supercritical CO_2 through experiments and numerical simulations, and discussed the stability behavior for operating conditions where CO_2 is heated so that its temperature passes through the pseudo-critical point. Yoshikawa et al. [21] carried out experiments to study the heat transfer characteristics of CO_2 in a natural circulation loop. Rieberer [22] studied the ground-coupled heat pumps that use CO_2-based thermosyphons for extracting geothermal energy. Chatoorgoon et al. [23] defined non-dimensional parameters to describe the effects of geometric parameters and the fluid temperature on the flow instability in CO_2-based circulation loops. Jain and Rizwan-uddin [24] reported the stability threshold through numerical simulation. Kumar and Gopal [25] discussed the effects of several parameters on the heat transfer performance of the CO_2 natural circulation loops through numerical simulation. However, one-dimensional models were often used in the numerical studies mentioned above. The one-dimensional model may be too simplified to unveil the true flow and heat transfer behaviors because it neglects the wall–fluid interaction and assumes a uniform distribution of fluid properties along the direction perpendicular to the flow. Recently, we studied the supercritical CO_2 natural convection using a two-dimensional numerical model [26]. Primary results indicate that the tube diameter has significant effects on the instability of the flow in supercritical CO_2-based natural circulation loops.

Based on our recent research work, in this paper, the convective flow and heat transfer characteristics of supercritical CO_2 in a natural circulation loop is numerically studied using a two-dimensional model. The operating pressure is always fixed at 9.0 MPa. The effects of several controlling parameters, such as the heat sink temperature, the inclination angle of the loop and the heat source to heat sink temperature difference, on the flow and heat transfer characteristics are discussed. The underlying physics is explored.

2. Physical model and numerical scheme

2.1. Physical model

Fig. 1 shows the schematic of the two-dimensional model of the natural circulation loop studied here. The loop has a uniform inner diameter d of 0.005 m, with the width and height of 0.25 m and 1.0 m, respectively. The aspect ratio AR (ratio of the vertical to horizontal length of the tube) of the rectangular loop is 4.0. AR is an important parameter affecting the flow stability of conventional fluids in natural circulation loops [15]. It may also have significant effects on the flow and heat transfer characteristics of the supercritical CO_2 natural circulation, which is out of the scope of the present paper and will be reported elsewhere. The loop has horizontally-oriented heating and cooling sections. Both the heat source and heat sink are isothermal with a horizontal length of 0.14 m. Here, the Cartesian coordinate is used with the origin located at the left lower corner of the loop (see Fig. 1). The heat source and heat sink temperatures are denoted by T_h and T_c, respectively. Other parts of the tube wall are adiabatic. The buoyancy force resulting from the vertical temperature difference ΔT, equal to $T_h - T_c$, is the only driving force for the natural circulation of the CO_2 fluid in the rectangular loop. The gravity acceleration g is also shown in Fig. 1. To avoid the occurrence of abrupt turnings, quarter annuluses are used at corners with the inner diameter of the outer circle of 0.025 m. The middle cross section of the heat sink is chosen as the monitoring cross section, where the fluid velocity

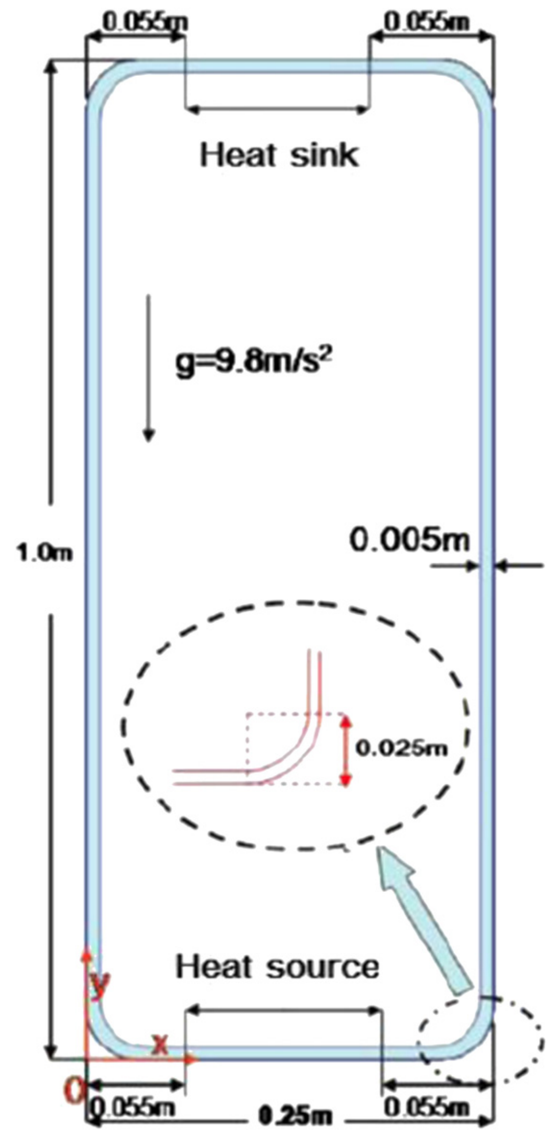

Fig. 1. The schematic of the two-dimensional model of the natural circulation loop. The loop has the width and length of 0.25 m and 1.0 m, respectively. The inner diameter of the tube is 0.005 m. The cooling (upper) and heating (lower) sections are isothermal, with a length of 0.14 m. Other parts are adiabatic.

and temperature will be used for discussion. The loop can rotate about the bottom tube to change its inclination angle θ. Here, θ is defined as 0° when the loop is in the vertical plane, while θ is 90° when the loop lies in the horizontal plane.

Using a two-dimensional model to study the flow in the supercritical CO_2-based natural circulation loop is a meaningful attempt to improve the understanding about the flow and heat transfer characteristics of supercritical fluids. Different from the one-dimensional model, the two-dimensional model is capable of considering the wall–fluid interaction and the influence of the non-uniform distribution of fluid properties along the direction perpendicular to the flow. Therefore, more information about the flow and heat transfer characteristics can be expected from the two-dimensional analysis. However, it is worth mentioning that the two-dimensional model is also a simplified model, where the flow and heat transfer characteristics are assumed independent of the azimuth of the longitudinal section in the tube. The error introduced by the assumption is acceptable when the tube diameter is small compared to the height and width of the circulation