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Heat transfer model for horizontal flows of CO_2 at supercritical pressures in terms of mixed convection

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ABSTRACT

When a material crosses its critical point or a pseudocritical temperature at which the specific heat of the material at a constant pressure is maximal, the thermal and hydraulic properties vary significantly. Buoyancy, induced by a great density variation of near-wall fluid, results in asymmetric heat transfer coefficients at the top and bottom walls of a horizontal circular channel. However, flow acceleration, which occurs in the flow direction because of significant density variations, has an identical effect on heat transfer regardless of the flow direction. For this reason, only the acceleration effect can be investigated in terms of a turbulent shear stress variation for horizontal flows. Therefore, a study on the buoyancy effect for horizontal flows is required with respect to not the shear stress variation but different aspects between the top and bottom walls.

In this study, semi-empirical and empirical heat transfer models were proposed based on a mixed convection. The models were evaluated using experimental data. The semi-empirical model has a mean absolute difference (MAD), the average error, of 21.73% for the top wall and 22.35% for the bottom wall. However, the empirical model has a MAD of 10.00% for the top wall and 10.44% for the bottom wall. The proposed models significantly improve the prediction accuracy of the Nusselt number at each wall, as well as for the average Nusselt number compared to the previous correlations.

1. Introduction

Supercritical fluid have numerous applications because of their unique thermodynamic characteristics. When the pressure and temperature of a material exceed the critical point, the distinction between the liquid and vapor (or gas) phases disappears. However, when the material crosses the critical point, or a pseudocritical temperature at which the specific heat of the material at constant pressure is maximal, the thermal and hydraulic properties change significantly as shown in Fig. 1.

Flow acceleration and buoyancy induced by the density variations change the heat transfer behavior of supercritical fluids from normal heat transfer behavior. Numerous studies have been conducted to investigate these phenomena for vertical and horizontal flows. In vertical flow, buoyancy and flow acceleration act in a direction parallel to the flow. Therefore, there is no difference in heat transfer characteristics at the circumference. However, in horizontal flow, the heat transfer characteristics are more complex as buoyancy is induced in a direction perpendicular to the flow while the flow acceleration still acts in the flow direction. Therefore, different heat transfer characteristics are observed at the circumference [1–3]. A number of experimental studies reported on the heat transfer characteristics according to heat flux, mass flux, pressure, flow direction, tube diameter, and inlet temperature. Most of such studies published up to 2016 were collated by Pioro and Duffey [4,5], Cabeza et al. [6] and Thiwaan Rao et al. [7].

Based on the results of parametric studies, researchers have been striving to develop an accurate heat transfer correlation. Early studies proposed modifying the Dittus–Boelter-based or the Gnielinski-based correlations by taking into account the properties evaluated at wall temperature or film temperature, $T_f = (T_b + T_i)/2$, or the property ratios between the wall and the bulk mean temperatures. Chen et al. [8] and Shen et al. [9] assessed the existing correlations by using experimental data limited to vertical upward flow for supercritical water. Among the correlations, the correlations of Swenson et al. [10] and Morky et al. [11] exhibited the most accurate predictions. In addition, a number of researchers attempted to define the buoyancy and flow acceleration parameters and draw correlations involving the parameters as correction factors. Jackson [12,13] and Kim and Kim [14,15]

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