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CFD analysis of a CO_2 based natural circulation loop with end heat exchangers

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ABSTRACT

3-D steady flow simulation of a CO_2 based, single-phase (subcritical and supercritical) rectangular natural circulation loop (NCL) with end heat exchangers is presented. Viscous dissipation in fluid and axial conduction in fluid as well as in solid wall are considered. Results are obtained for various inlet temperatures of water in the hot heat exchanger, for a fixed inlet temperature of cooling water in the cold heat exchanger. Effect of loop operating pressure (60–100 bar) on system performance is also investigated. Results show that due to the presence of bends and strong buoyancy effects near pseudo-critical zone, local velocity and temperature vary in all three dimensions. It is noticed that at a given loop pressure, the variation of heat transfer rate with loop fluid temperature changes sign in the vicinity of pseudo-critical region. Steady-state Reynolds number and heat transfer coefficients obtained through the CFD analysis are compared with those calculated using available correlations. Although qualitative trends match, quantitative differences exist that may be attributed to difference in configuration. Additionally, new correlations are proposed for *Re* in terms of modified *Gr*, and *Nu* in terms of *Re* and *Pr* which are expected to be useful in the design and analysis of NCLs with end heat exchangers.

1. Introduction

Natural circulation loop (NCL) based secondary fluid systems are simple and reliable due to the absence of any moving components such as pumps. While water based NCLs are widely used in applications such as solar collectors, nuclear reactors, etc, a wide variety of brines is used for low temperature applications. In recent years, a growing popularity of carbon dioxide as the secondary fluid has been witnessed in both forced as well as in natural circulation loops. This may be attributed to the favourable thermo-physical properties of CO_2 in addition to its environment friendliness. Studies show that for low temperature refrigeration and air-conditioning applications, CO_2 based NCLs are very compact in comparison to other conventional working fluids [1] and have been proposed for various heat transfer application such as new generation nuclear reactors [2], in chemical extraction [3,4], cryogenic refrigeration [5], heat pump [6], electronic cooling systems [7], in geothermal applications [8,9], etc. However, detailed modelling and analyses of CO_2 based NCLs are relatively sparse in the literature. Kiran Kumar and Ram Gopal [10] reported one-dimensional steady-state analysis of a rectangular NCL with end heat exchangers for low temperature applications. Recently Zhang et al. [11] and Chen et al. [12] reported studies on the effects of heat transfer and the instabilities of supercritical CO_2 flow in a 2-D NCL at a fixed operating pressure of 90 bar operating over a large heat source temperature range. However, their analysis considered the case of isothermal heat source and heat sink only. There are many practical applications in which end heat exchangers are used for heat source and sink (e.g. refrigeration and air-conditioning systems, solar collectors, solar power plants). In studies on estimation of in-tube cooling heat transfer coefficient for turbulent forced convection of supercritical CO_2, correlations developed by Pitla et al. [13] and Du et al. [14] are usually employed. However, Du et al. [14] suggested the use of 3-D model to study the behaviour of supercritical CO_2 near the pseudo-critical point. Studies on heat transfer coefficient for supercritical CO_2 based NCLs are scarce in literature. In addition, to account for the strong buoyancy effects (local) near pseudo-critical zone, and the effect of bends in pipe etc., it becomes essential to consider a three-dimensional model for greater accuracy. However, investigations employing 3-D models of CO_2 based NCLs with end heat exchangers are not available in the open literature. To fill in that void, this study presents CFD analysis of a 3-D CO_2 based NCL with end heat exchangers. Results are presented on the steady-state behaviour of the loop at various operating pressures and temperatures. Operating parameter range is chosen such that the loop fluid (CO_2) exists either as a subcritical single-phase fluid or as a supercritical single-phase fluid.

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