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Original Article

Numerical Comparison of Thermalhydraulic Aspects of Supercritical Carbon Dioxide and Subcritical Water-Based Natural Circulation Loop

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ABSTRACT

Application of the supercritical condition in reactor core cooling needs to be properly justified based on the extreme level of parameters involved. Therefore, a numerical study is presented to compare the thermalhydraulic performance of supercritical and single-phase natural circulation loops under low-to-intermediate power levels. Carbon dioxide and water are selected as respective working fluids, operating under an identical set of conditions. Accordingly, a three-dimensional computational model was developed, and solved with an appropriate turbulence model and equations of state. Large asymmetry in velocity and temperature profiles was observed in a single cross section due to local buoyancy effect, which is more prominent for supercritical fluids. Mass flow rate in a supercritical loop increases with power until a maximum is reached, which subsequently corresponds to a rapid deterioration in heat transfer coefficient. That can be identified as the limit of operation for such loops to avoid a high temperature, and therefore, the use of a supercritical loop is suggested only until the appearance of such maxima. Flow-induced heat transfer deterioration can be delayed by increasing system pressure or lowering sink temperature. Bulk temperature level throughout the loop with water as working fluid is higher than supercritical carbon dioxide. This is until the heat transfer deterioration, and hence the use of a single-phase loop is prescribed beyond that limit.

1. Introduction

The basic concept of a natural circulation loop (NCL) is to have energy transmission from a heat source to a heat sink, connected by adiabatic arms through a closed circuit, without bringing them in direct contact and also without involving any rotating machinery. The density difference between the fluids flowing through two vertical sections of the loop develops buoyancy, which acts as the driving potential. It is mandatory to locate the sink at a higher elevation than the source, to take advantage of the favorable density gradient. Geometrical simplicity and enhanced passive safety of NCLs have attracted

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diverse technical applications including solar water heaters, refrigeration systems, thermosyphon reboilers, and cooling of rotating machineries as well as transformers, electronic chips, and nuclear reactor core. Inherent reliability of such loops, due to the absence of moving elements, makes them particularly suitable for large-scale nuclear systems, and hence adoption of both single- and two-phase versions of NCLs can be observed in industries. A supercritical natural circulation loop (SCNCL) is a relatively newer concept and is expected to lead nuclear reactors toward higher thermal efficiency in comparison with the other versions, owing to its higher range of operating pressure and temperature. The system is also more compact due to the elimination of bulky components such as steam generator, dryer, and steam separator. Therefore, the concept of a supercritical water reactor has evolved as one of the most promising technologies under the generation-IV reactors. Water remains the most common working fluid in applications involving temperature above 0°C, whereas various brines are employed for low-temperature cases. However, the nontoxic and nonexplosive nature of supercritical CO_2 (sCO_2), coupled with its excellent heat transfer performance, has projected sCO_2 as the next-generation coolant. It is safe, chemically stable, economically viable, and environment friendly [1], which has encouraged several research groups to explore sCO_2-based SCNCLs.

While most of the experimental and theoretical investigations focused on high-power operation of SCNCLs, a few of the recent efforts were directed toward medium-to-low power applications. Chen et al [2,3] experimented on a CO_2-based SCNCL in the power range of 65–189 W, to study the steady-state thermalhydraulics and stability behavior at different pressures. Heat transfer coefficient on the heater side was found to decrease with an increase in bulk temperature. Consequently, loop thermalhydraulics was found to depend on several parameters inclusive of the temperature differential between the heater and cooler, operating pressure, channel diameter, relative orientation of the heater and cooler, and inclination angle [4]. Heat transfer efficiency of the loop was reported to decrease with increasing operating temperature and is higher for larger-diameter loops, as was numerically identified by Chen et al [5]. In fact, with a continuous increase in input power, SCNCLs can exhibit heat transfer deterioration (HTD), characterized by a rapid decline in mass flow rate and heat transfer coefficient, accompanied by a sharp increase in maximum fluid temperature, as was demonstrated by Sarkar and Basu [6]. Appearance of HTD was found to depend on both system pressure and sink temperature. Sharma et al [7–9] conducted an experimental, as well as numerical, study to analyze the effect of heater and cooler orientation on steady-state behavior. Mass flow rate was found to increase until the heater inlet temperature reached a pseudocritical value. Successful use of commercial software for the simulation of an SCNCL was demonstrated by Yadav et al [10,11]. Asymmetry in velocity and temperature profiles was observed, which was attributed to the three-dimensional (3-D) variation in fluid parameters owing to the presence of bends and local buoyancy. Effects of unsteady heat input and inclination angle (0–90°) were numerically studied by Chen et al. [12,13] over a wide range of input heat flux. Influence of inclination on the average Nusselt number was found to be of lesser significance at lower heat fluxes, but very important for higher powers. A periodic change in the pressure field was observed due to the typical distribution of temperature-sensitive thermophysical properties of sCO_2, which led to repetitive flow reversals [5,14]. More comprehensive discussion on the steady-state thermalhydraulics of an SCNCL can be found in the study by Sarkar et al [15].

A systematic literature survey, therefore, suggests that the thermalhydraulic aspects of an SCNCL have received considerable attention over the last decade, with particular emphasis on high-power systems for nuclear core cooling. However, with the advent of portable reactors [16], loops operating at low-to-intermediate power levels definitely have an enormous scope, along with possible applications in solar heaters and refrigerators. It is common to employ single-phase NCLs for such systems, despite the saturation temperature constraint and low flow limitation. As a single-phase loop is a well-explored device, its thermalhydraulic and stability responses are generally well documented [17], which is its prime advantage over SCNCLs, along with the moderate levels of working parameters. Therefore, implementation of supercritical loops for low-power situations over its single-phase counterpart needs to be justified, and the present work attempts precisely the same. A comparative thermal-hydraulic analysis was performed by developing a 3-D computational model of a rectangular NCL. Water was selected as the working fluid for the single-phase loop and CO_2 for the supercritical one. Operating conditions were selected so that the respective states can be maintained for both the fluids under an identical set of working parameters. Effects of system pressure, heater power, and sink temperature were examined to explore the relative merits of either loops and make a final recommendation accordingly.

2. Computational model and numerical procedure

2.1. Physical geometry

A rectangular loop of uniform diameter was chosen for the present analysis, as shown in Fig. 1. The diameter (D), height (H), and width (L) of the loop are 8 mm, 800 mm, and 600 mm, respectively. The heater and cooler were placed in the middle of the opposite horizontal arms, with both having identical length ($L_h = L_c$) of 400 mm. Stainless steel was selected as the wall material with 1 mm thickness. Accordingly, a 3-D numerical model was developed using ANSYS-Fluent 15 (ANSYS Inc., Canonsburg, PA, USA). The focus of the present study being thermalhydraulic analysis at low-to-intermediate powers, selected power levels are limited to 700 W.

2.2. Conservation equations

Steady-state versions of 3-D mass, momentum, and energy conservation equations were solved using ANSYS-Fluent 15 (ANSYS Inc.), along with the equations of state for the concerned fluids. The operating range of Reynolds number being invariably in the turbulence regime, a renormalized group