International Journal of Thermal Sciences 111 (2017) 30–40

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Numerical appraisal on the suitability of supercritical condition in natural circulation loop with isothermal boundary conditions

Milan K.S. Sarkar, Dipankar N. Basu*

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

A R T I C L E I N F O

Article history:
Received 22 June 2015
Received in revised form
18 April 2016
Accepted 2 August 2016

Keywords:
Natural circulation loop
Supercritical
Heat transfer
Thermalhydraulics

A B S T R A C T

It is essential to understand the advantages gained on imposing supercritical condition in a natural circulation loop under a given set of operating condition. Therefore a computational investigation is presented for thermalhydraulic comparison of water, CO_2 and R134a as working fluids in a temperature-coupled rectangular natural circulation loop. Operating conditions are selected to maintain water as single-phase liquid, R134a as supercritical and CO_2 as sub- to supercritical. A 3d model is developed, which shows amicable agreement with relevant literature for both single-phase and supercritical loops. Presence of local convective effects is found to induce asymmetry in velocity and temperature profiles across any cross-section, which increases with larger source-to-sink temperature differential and system pressure. CO_2 exhibits the largest asymmetry, while large heat transfer rate with single-phase water results in near-uniform profiles. CO_2 loop also provides the lowest mass inventory requirement and largest rate of heat transfer, particularly when the sink-side temperature is well below the pseudocritical value and at higher system pressures. Therefore the use of supercritical CO_2 as working medium is suggested with high pressure and specifically when the sink temperature is reasonably low. Otherwise single-phase water is the better option.

1. Introduction

Basic operating principle of any natural circulation loop (NCL) involves the development of flow field by thermally-induced buoyancy force. Density difference is created in different sections of a closed circuit commonly by connecting a heat source and a heat sink through adiabatic arms, heat sink being located at a higher elevation than the source. Geometrical simplicity and enhanced passive safety of NCLs have attracted diverse technical applications, employing both single-phase and two-phase working mediums. Operating regime of single-phase NCLs is limited by the constraints of saturation temperature and low flow rate, whereas the possibility of dry-out and appearance of different flow regimes with contrasting heat transfer behavior are of great concern in two-phase loops. Both the single- and two-phase versions are also susceptible to several kinds of static and dynamic instabilities. Supercritical fluid offers a potent alternative due to its good heat transport capability and large volumetric expansion, thereby coupling the advantages of single- and two-phase versions. Accordingly the concept of supercritical natural circulation loop (SCNCL) has evolved in the present millennium as one of the most important initiatives under generation-IV nuclear reactors. Attractive features like high projected efficiency and compact design due to the elimination of bulky accessories have fascinated several research groups towards SCNCL over the last decade, leading to some development in understanding of the involved phenomena. Still the technology is relatively a fresh one and its numerous aspects requires further investigation, exposing a wide domain of research.

Chatoorgoon [1] was one of the pioneers in proposing analytical model of single-channel SCNCL with distributed, as well as point, heat source and sink. Closed form expression for mass flux was proposed and existence of a maxima of loop flow rate was predicted. That methodology was extended by Chatoorgoon et al. [2] to investigate the relative influence of several geometric variables on steady-state and stability behavior, as they compared the performances of CO_2 and H_2 as working medium with water. Similar steady-state profile was also predicted by the implicit finite difference model of Jain and Rizwan-uddin [3]. The 1-D model of a closed loop with horizontal-heater-horizontal-cooler (HHHC) orientation by Vijayan et al. [4] identified the steady-state profile of SCNCL to behave similar to single-phase loops at lower powers. At

* Corresponding author.
E-mail address: dipankar.n.basu@gmail.com (D.N. Basu).

http://dx.doi.org/10.1016/j.ijthermalsci.2016.08.002
1290-0729/

higher powers, however, mass flow rate variation resembled two-phase systems, with pseudo-critical zone corresponding to the maxima in mass flux. Subsequent studies of Sharma et al. [5,6] showed rapid growth in flow rate with increased diameter and height, and moderate enhancement with system pressure. Flow rate, however, decreased substantially at higher heater inlet temperatures. Impact of loop orientation was also explored, identifying HHHC configuration as the one to produce the largest flow rate [7]. Swapnalee et al. [8] proposed an experimental correlation of steady-state flow rate by involving dimensionless density and enthalpy, by a sigmoidal curve relationship.

The heat transfer aspect of SCNCL has received more attention in recent times, as the role of heat structures and nature of energy addition/removal on the stability response is under scrutiny [9]. Due to the strong temperature dependence of thermo-physical properties under supercritical conditions, around the pseudocritical point in particular, both buoyancy and frictional forces contemplate non-linear relationship with temperature. Accordingly the thermalhydraulic behavior is decided by the involved temperature range. Yadav et al. [10,11] found enhancement in both flow rate and heat transfer rate at higher temperature levels for a rectangular SCNCL. Larger temperature differential between heater and cooler was observed to decrease the mass flow rate. Similar effect was predicted by Chen et al. [12] with increase in heater power. In a subsequent work [13], large values of heat transfer coefficient were estimated in the heating section, nearly comparable with boiling loops, which was also in consensus with the experimental study of Tokanai et al. [14]. 2-D numerical model of Cao and Zhang [15] correlated loop thermalhydraulics to several factors inclusive of heater-to-cooler temperature differential, system pressure, pipe diameter, geometric orientation and loop inclination. Reduction in Nusselt number was predicted for the inclined loops. Inclination angle was found to have a stronger role at lower heat input conditions [16]. The role of local buoyancy forces, developed due to asymmetric temperature distribution across any particular cross-section in both heating and cooling sections, was stressed upon by Zhang et al. [17]. Periodic variation in Nusselt number was reported across flow section, leading to possible flow reversal. Nusselt number was also found to increase significantly with larger tube diameter [18]. A more elaborate discussion on heat transfer aspect of SCNCL is available in Sarkar et al. [19].

Scrupulous analyses of relevant literature identifies SCNCL as an open field of research, as the knowledge database is still a work in progress and several reported observations about the thermalhydraulic behavior are contrasting to each other, alongside incomplete stability appraisal. Therefore, despite all the promising features, application of SCNCL comes with some apprehension and generally gets restricted to a small range of operating variables. Single-phase NCL, however, is a well-studied device and invariably exhibits very regular thermalhydraulic behavior, with well-documented stability performance. Hence it is imperative that the supercritical condition can be employed only when it comes with some specific advantage over its single-phase counterpart under a given set of operating conditions. It is more relevant for heat transport devices involving low-to-moderate temperature levels. Single-phase water is the most preferred fluid there due to its availability and non-toxic nature. Excellent heat transport capabilities of transcritical CO_2 and low critical pressure levels of R134a have also attracted engineers as possible alternatives. Another important factor to consider here is the practical difficulty in handling extreme operating parameters associated with supercritical water in smaller facilities or in laboratory conditions, because of very high critical pressure and temperature. On the contrary, CO_2 identifies itself as one of the fluids with very low critical temperature, whereas R134a is characterized by low critical pressure. Critical point parameters for all the three fluids are summarized in Table 1. Therefore either of them can be viewed to be a potent alternative to water as heat transport fluid in NCLs. They can also be employed as model fluid in scaled-down SCWR test facilities, provided they satisfy the thermalhydraulic scaling rules. Here the focus is primarily on the former application, thereby necessitating a comprehensive analysis of NCLs with each of the three fluids.

Present work, therefore, focuses on the thermalhydraulic comparison of the performance of water, CO_2 and R134a as the working medium in NCL under identical set of operating conditions. Parameters are selected so as to maintain water under single-phase liquid condition, while R134a is at supercritical pressure. Selected temperature ranges generally allow R134a to remain below concerned pseudocritical limit, thereby ensuring “liquid-like” density level for this fluid. State of CO_2 remains sub- to supercritical based on selected system pressure. Velocity and temperature profiles at different sections of the loop are compared, along with heat transfer coefficient at specific locations. Effort is made to identify the best working fluid from heat transfer point of view.

2. Mathematical modeling

2.1. Physical geometry

A rectangular loop is considered for numerical simulation and schematic representation of the same is shown in Fig. 1. Heater and cooler are located in the opposite horizontal arms, whereas other sections of the loop are ideally insulated. Dimension of the loop is set as $D = 8$ mm, $H = 2.12$ m, $W = 1.58$ m, $L_h = 1.4$ m and $L_c = 1.25$ m. The loop wall is made of stainless steel of 1 mm thickness. Here the loop dimensions are taken from an indigenous test facility, developed through fluid-to-fluid scaling, with the geometry of [7] as prototype. Characterizing dimensionless groups are identified from the conservation equations and dimensions are finalized by equating these numbers. Walls of both heater and cooler are maintained isothermal, allowing to investigate the effect of heater and cooler temperatures. It is important here to note that constant temperature boundary conditions are only idealization, as it is extremely difficult to maintain a perfect wall temperature during any experimentation. However, it may be possible to restrict the temperature variation within a narrow range and so the isothermal condition can be viewed as an idealization for the same.

2.2. Conservation equations

Steady-state versions of 3-D conservation equations are solved using ANSYS-Fluent 15 [20], which are summarized below.

2.2.1. Conservation of mass

$$\frac{\partial}{\partial x_j}(\rho u_j) = 0 \tag{1}$$

Table 1
Critical properties for selected working fluids.

Fluid	Pressure (MPa)	Temperature (K)	Density (kg/m^3)
Water	22.064	647.096	322.0
CO_2	7.377	304.128	467.6
R134a	4.059	374.21	511.9