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Thermo-hydraulic characteristics and second-law analysis of a single-phase natural circulation loop with end heat exchangers

Haojie Cheng, Haiyan Lei, Chuanshan Dai*

Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, School of Mechanical Engineering, Tianjin University, 135 Yaguan Road, Jinnan District, Tianjin 300350, China

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ABSTRACT

In this work, a three-dimensional transient numerical simulation of heat transfer characteristics in a single-phase natural circulation loop (SPNCL) with water as the working fluid in the loop and end heat exchangers is performed. A 3-D computational model of a SPNCL with end heat exchangers is developed. The second-law analysis for the SPNCL is presented and total entropy generation is given. Meanwhile, the transient response is obtained based on the finite difference method solving the one-dimensional momentum and energy equations. Firstly, a mesh dependence test and a model verification with the laminar correlation presented by Vijayan are conducted. Then the effects of driving temperature difference and heating or cooling fluid velocity on the thermos-hydraulic performance and dimensionless entropy generation number are investigated by fixing the cooling fluids temperature of 273K. Results show that a stable flow can be reached for all the cases. The formation of the stable natural circulation is the consequence of coupling between heating and cooling fluid. The time of quiescent state is relatively short due to the thermal asymmetry of the SPNCL. The mass flow rate and heat transfer rate at steady state increase with the increase of driving temperature difference and heating or cooling fluid velocity. It is obviously shown the internal heat transfer coefficient is mainly dependent on the driving temperature difference and increases with the increase of driving temperature difference. The thermal effectiveness and dimensionless entropy generation number also increase with the increase of driving temperature difference and heat transfer irreversibility is dominated in total irreversibility. Moreover, the time evolution of dimensionless mass flow rate shows a damped oscillation behavior.

1. Introduction

Natural circulation based on density difference caused by temperature gradient and phase change has attracted many researcher's attentions due to no extra work consumption [1–5]. The natural circulation loop (NCL) has been widely used in many applications, such as nuclear plants, solar heaters, electronic components cooling, etc. It can transfer heat passively from the heat source to the heat sink, which is generally located above the heat source. Based on the phase process of the natural circulation, the NCL can be divided into the single-phase natural circulation loop (SPNCL) and the two-phase natural circulation loop (TPNCL).

Compared with the SPNCL, the TPNCL has an advantage of higher heat removal capacity duo to the latent heat of phase change. Rahmani et al. [6] carried out an experimental investigation for improving the performance of the solar still with the humid-air as the working fluid where the natural circulation was accomplished by the density difference caused by the effects of temperature and humidity. Goudarzi and Talebi [7] presented an optimal design of two-phase natural circulation loop to realize the entropy generation minimization of the TPNCL system, which consists of a steam separator, two horizontal sections, an adiabatic down-comer, a single-phase stand pipe, a heated section and a riser. An experimental investigation in an open TPNCL was conducted by Yan et al. [8] to analyze the fundamental phenomena in the two-phase flow. Flashing and geysering were observed during the experiment procedure due to a reduction of static pressure and violent expansion of the vapor, respectively. Meng et al. [9] experimentally investigated the effect of heating power on the thermal-hydraulic characteristics in a two-phase thermosyphon, where backflow and unidirectional clockwise flow were observed with the increase of heating power. Chehade et al. [10] carried out an experimental investigation of the thermal performance in a two-phase thermosyphon which was composed of an evaporator, a condenser and two connecting adiabatic pipes, and the optimal fill charge ratio about 7%–10%, the optimal water mass flow rate and temperature of 0.7 l/m and 5 °C, respectively, in the condenser were obtained.

* Corresponding author.
E-mail address: csdai@tju.edu.cn (C. Dai).

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However, it can be seen from the previous experimental studies that the design of an experiment setup of a TPNCL is relatively complex, and the instability of a TPNCL is relatively stronger when compared with a SPNCL, which may result in the system out of control. On the contrary, with the advantages of more reliability in operation and simplicity in construction, the SPNCL was widely used in many thermal systems [11–13]. Among the researches of this catalog, Misale et al. [11] presented an experiment investigation of a SPNCL with small dimensions and the effects of the heating power and inclination angle were studied. It was found that the thermos-hydraulic behavior always tended to be stable at a range of heating power. Meanwhile, the natural circulation was experimentally investigated by Garibaldi and Misale [12] in two kinds of mini-loops with the same widths and diameters but different heights. Two kinds of working fluids, water and FC43, were considered in this study and the velocity of FC43 in the SPNCL was twice than the water. An experimental analysis of a SPNCL with low and moderate heating power was carried out by Saha et al. [13], which showed that the steady flow could be achieved at lower power while the periodic oscillations was observed at moderate power. A 2-D and 3-D numerical simulation of the natural circulation in a toroidal loop were reported by Ridouane et al. [14,15]. The upper half of the loop was maintained at a constant low temperature while the lower half was maintained at a constant high temperature. In these works, different flow regimes such as conduction, steady flow, unsteady flow were presented at various Rayleigh numbers. By employing 3D CFD simulation, Kudariyawar et al. [16] investigated the both steady state and transient state characteristics of the rectangular SPNCLs with different configurations. In the configurations of horizontal heater and horizontal cooler, the generation of unidirectional and bi-directional pulsing was clarified with the temperature fields. A transient simulation of a SPNCL with two models, IAPWS-IF97 standards and Boussinesq approximation, was presented by Krishnani et al. [17], and it was concluded that the Boussinesq approximation was not valid for the SPNCL at higher power levels. In recent years, supercritical CO_2 has been also used as the working fluid in many industrial systems [18] for its heat transport capability and high volumetric expansion, which needs large operating pressure. A mathematical model for calculating the steady state performance of supercritical CO_2 in a SPNCL with end heat exchangers was developed by Kumar and Gopal [19]. The effects of operating pressures and heating fluid temperatures on the heat transfer characteristics of a supercritical SPNCL was numerically studied by Yadav et al. [20], and it was concluded that the operating condition should be near the pseudo-critical region in supercritical zone in order to obtain higher heat transfer rate. The flow instability of a SPNCL for supercritical CO_2 as the working fluid was presented by Chen et al. [21] in which constant wall temperature condition were used in both the heater and the cooler. It was found that the stability behavior in this study was different from that using water. The effect of pipe diameter on the thermal-hydraulic performance in a supercritical CO_2 SPNCL was also numerically investigated by Chen and Zhang [22] and stable flow could be achieved for larger dimeter. The trans-critical CO_2 natural circulation with unsteady heat input [23] was numerically studied and the slow increase of heat flux input can lead to lower system instabilities. Corresponding experimental investigation of trans-critical and supercritical CO_2 natural convection in a rectangular loop was conducted by Chen and Zhang [24] and three kinds of flow regimes was observed in the experimental runs. Besides, the influences of inclination angle and operation parameters [25] were numerically and experimentally investigated in a closed loop with supercritical CO_2. Misale et al. experimentally investigated the influences of pressure drop [26], heat sink temperature [27] and power steps [28] on the thermal-hydraulic behaviors of a SPNCL with a heating power input condition. Both semi-analytical and numerical models [29] were developed and assessed against experimental data to predict the dynamic behaviour of natural circulation. Rao et al. [30–33] investigated the effects of heat exchangers performance parameters, different excitations and core capacitance on the steady state, stability behavior and dynamics performance of a SPNCL with end heat exchangers.

In addition, the stability of the SPNCL with constant heat power supply in the horizontal heater has been both experimentally and numerically investigated based on non-linear stability analysis and linear stability analysis. Vijayan [2] et al. conducted an experimentally investigation of a large scale SPNCL with internal diameter of 26.9 mm and total length of about 7 m. Three kinds of unstable oscillating modes were observed through pressure difference in two ends of the heater. Meanwhile, the predicted stability maps for both laminar and turbulence flows were larger than that for experiments due to high conservatism. When considering an internal heat source in the natural circulation of a closed loop, Ruiz et al. [34] employed both stability analysis methods to investigate the effect of internal heat source on the stability of natural circulation with different loop configurations. The stability maps can be obtained with the use of linear stability analysis and the unstable region of the map increases with the increase of internal heat source. The loop configuration, vertical heater-vertical cooler, shows the best dynamic performance among all of the configurations. Misale et al. [35] presented the influence of heat sink temperature and heat power supply on the natural circulation in a loop. With linear stability analysis, it was found that all the experiment data were located on the unstable region since theoretical Stanton number was much higher than that for experiments. Besides, a novel method [36] based on the information entropy was proposed to evaluate the stability of a system by Misale.

Heat transfer process based on the second law of thermodynamics has been the fascinating topic [37]. The actual process is always an irreversible process and two kinds of important mechanisms, temperature difference and friction, cause the irreversibility of heat transfer process. Manjunath and Kaushik [38] summarized the entropy generation, exergy destruction and constructal theory in gas-to-gas, liquid-to-liquid and two-phase flow heat exchangers and reviewed various dimensionless forms of entropy generation and exergy destruction. Goudarzi and Talebi [39] presented the entropy analysis in the SPNCL with constant heating power and concluded that dimensionless entropy generation increases with the increase of modified Grashof number.

As a summary, it is noticed that the main thermal boundary condition of the heating section used in most previous studies for the SPNCL is limited to a constant heating power and the flow characteristic of the SPNCLs is primarily investigated. Although there are a few studies [30–33] about the SPNCL with end heat exchangers, the dimensionless parameter *Ntu* was used as a constant in their works which is actually a variable dependent on the driving temperature difference and there is no study aimed at the thermal-hydraulic performance and entropy generation of the SPNCL with end heat exchangers. Therefore, the conjugate heat transfer of the SPNCL is numerically presented in this study and a 3-D CFD model is developed. The second-law analysis and non-linear stability analysis are also conducted. The effects of driving temperature difference, heating or cooling fluid velocity on the heat transfer and flow characteristics are investigated. The temporal development of the mass flow rate and bulk mean temperature are obtained. The average heat transfer coefficient for natural convection at steady state and the heat transfer effectiveness and dimensionless entropy generation number of the SPNCL are also presented in this paper.

2. The configuration of a SPNCL

2.1. Physical model

The geometry structure of a single-phase natural circulation loop (SPNCL) is shown in Fig. 1, which consists of two heat exchangers and two vertical pipes with four elbows. The two heat exchangers are used as a heater and a cooler, respectively, for heating and cooling the loop fluid. Water is chosen as the working fluid in the SPNCL and the end heat exchangers. The tube thickness is not considered in this