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Theoretical and experimental studies of heat transfer characteristics of a single-phase natural circulation mini-loop with end heat exchangers

Haojie Cheng, Haiyan Lei, Long Zeng, Chuanshan Dai *

Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, School of Mechanical Engineering, Tianjin University, 92 Weijin Road, Nankai District, Tianjin 300072, China

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ABSTRACT

In the present work, the heat transfer and fluid flow characteristics of a single-phase natural circulation loop (SPNCL) with both the heating and the cooling ends are theoretically and experimentally studied. Distilled water is chosen as the working fluid circulating in a rectangular loop that the top and bottom sides are respectively cooled and heated by 245 mm tube-in-tube heat exchangers. The height and diameter of the mini-loop are 250 mm and 4 mm, respectively. Both analytical and experimental results are obtained by varying the heating fluid temperatures from 30 °C to 60 °C but fixing cooling fluid temperature of 10 °C. Based on the experimental data, a $Nu \sim Re$ correlation is obtained and applied into the one-dimensional mathematical model. A good agreement between the experimental and theoretical results with a new correlation can be observed. Experimental results show that stable flow can be reached for the cases with different T_h. The start-up time of natural circulation from quiescent state shortens with the increase of T_h. The Reynolds number and heat transfer rate at steady state are proportional to the heating fluid temperature T_h. Based on the proposed mathematical model, an optimal ratio of the heater length to the loop height can be reached when the total length and diameter of the mini-loop keep constants.

1. Introduction

Natural circulation loop (NCL) is commonly used as an energy transfer instrument in nuclear reactor [1], solar heater [2], computer cooling [3], etc., due to its simple construction, none power input from pump. Working fluid circulation in a single-phase natural circulation loop (SPNCL) is accomplished by the interaction between buoyancy force and frictional force. In a SPNCL, the buoyancy force is generated by the density difference due to temperature gradient. For the two-phase natural circulation in a loop (TPNCL), the circulation flow is based on the evaporation and condensation of working fluid. Normally, the NCL consists of a heating section (evaporator), a cooling section (condenser) and two adiabatic sections.

A great deal of experimental studies, theoretical analyses and numerical simulations on steady state, transient state and stability behavior of the SPNCL and TPNCL have been carried out. Different working fluids in the loops and thermal boundary conditions have been considered in these studies. The commonly used thermal boundary conditions are constant heat flux in the heater and convective heat transfer boundary used in the cooler. A generalized mathematical model of a SPNCL was presented by Thomas [4], and an agreement between their mathematical model and those experiment data had been confirmed. The steady state flow equation in a SPNCL with uniform or non-uniform diameter was derived by Vijayan [5], which could be expressed as $Re_{ss} = C[Gr_m/N_G]^r$. Meanwhile, a good agreement between dimensionless correlation and experimental data was verified. Misale et al. [6] reported an experimental investigation on a natural circulation mini-loop with different heating power and loop inclination angle. The loop inclination angle was considered in the modified Grashof number. Furthermore, Garibaldi and Misale [7] performed an experimental study with water and FC43 as the working fluids, respectively, in two kinds of mini-loops. It was found that the thermal-hydraulic behaviors for both the mini-loops are always stable. Meanwhile, an experimental investigation on thermal-hydraulic performance in a mini-loop with distilled water and Al_2O_3 nanofluid was presented by Miasle et al. [8]. It was observed that the thermal performances for the mini-loops between distilled water and Al_2O_3 nanofluid were similar. A three-dimensional CFD transient simulation on the natural circulation in a mini-loop was performed by Wang et al. [9]. The experimental data conducted by Misale et al. [6] was used to validate the proposed CFD model and an

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

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Nomenclature

A	cross sectional area (m^2)
Ar	ratio
C_p	specific heat capacity (J/kg·K)
D	diameter (m)
f	friction factor
g	gravitational acceleration (m/s^2)
Gr	Grashof number
h	heat transfer coefficient ($W/m^2 \cdot k$)
H	the loop height (m)
K	local resistance coefficient
L	length (m)
N_G	non-dimensional geometry parameter
Nu	Nusselt number
P	loop perimeter (m)
Pe	Pelect number
Q	heat transfer rate (W)
Re	Reynolds number
s	coordinate along the flow direction (m)
St	Stanton number
T	temperature (K)
t	time (s)
U	overall heat transfer coefficient ($W/m^2 \cdot K$)
V	velocity (m/s)
W	mass flow rate (kg/s)
Z	coordinate in the direction of gravity (m)

Greek symbols

θ	dimensional temperature
ρ	density (kg/m^3)
λ	heat conductivity coefficient (W/m·K)
μ	viscosity (Pa·s)
β	volumetric expansion coefficient (K^{-1})

Subscripts

c	cooler
cl	cold leg
h	heater
hl	hot leg
hy	hydraulic diameter
i	inner
o	outer
r	reference
ss	steady state

agreement between those experiment and simulation could be concluded. Compared with the mini-loop. the stability behavior for a SPNCL with a relatively large geometry scale was experimentally investigated by Nayak et al. by using water and Al_2O_3 nanofluids with various concentrations [10]. It was found that the use of nanofluids can suppress the flow instability and enhance the natural circulation flow rate. A unified model for a natural circulation loop with different geometries and boundary condition was proposed by Basu et al. [11]. An analytical study related to the entropy generation in a SPNCL was performed by Goudarzi and Talebi [12] where entropy generation formulas in each section were obtained. Saha et al. [13] experimentally and numerically investigated the thermal-hydraulic behavior of a SPNCL under low and moderate heating power with a variable ambient temperature. The periodic oscillations were observed at a moderate heating power. The stability behavior for the SPNCLs with four kinds of heater and cooler orientations was experimentally investigated by Vijayan et al. [14]. The maximum flow rate and the instability were observed for the orientation that both heater and cooler were horizontal. A three-dimensional CFD simulation for the instability in four different configurations of SPNCLs was performed by Kudariyawar et al. [15], which showed that for the configuration of horizontal heater and horizontal cooler, the steady state could not be achieved and uni-directional and bi-directional oscillation were observed at different heating powers. The validity for applying Boussinesq approximation to simulate a natural circulation loop was presented by Krishnani and Basu [16]. Compared with the complete variation of all relevant thermos-physical properties, Boussinesq model was only valid in transient simulation at low heating power. An experimental investigation of a SPNCL with molten salt as the working fluid in a wide range of input powers was presented by Srivastava et al. [17]. The start-up of natural circulation and heat loss in heat sink had been studied. The enhanced heat transfer performance of water-based nanocapsules in a SPNCL was experimentally studied by Ho et al. [18]. It was found that the heat transfer effectiveness increases with the increase of the heating power.

In addition, a single-phase natural circulation loop (SPNCL) can be found in many practical applications where a convective boundary condition was used in the heater of a SPNCL. Employing the number of heat transfer unit, Rao et al. [19–22] 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. A mathematic model for calculating the heat transfer performance of the natural circulation loop at steady state with CO_2 as the working fluid was developed by Kumar and Gopal [23]. By using the CFD code, FLUENT, Yadav et al. [24] numerically investigated the steady state performance of the CO_2 natural circulation loop with end heat exchangers at subcritical and supercritical states. It was found that the heat transfer rate in the supercritical region was higher than that in the subcritical region. A transient simulation of subcritical/supercritical CO_2 in a SPNCL with end heat exchangers was carried out by Yadav [25]. The effects of different operating pressures and temperatures, tilt angle and water mass flow rate on the thermal-hydraulic characteristics of a SPNCL were investigated. Cheng et al. [26] carried out a three-dimensional numerical simulation of a SPNCL with end heat exchangers and analyzed the entropy generation and stability of natural circulation.

Different from SPNCLs, TPNCLs have complex structure and stronger instability [27] due to the boiling and condensation, but higher heat transfer capacity. Pandey and Singh [28] used linear stability method to analyze the chaos behaviors of two-phase flow in a loop. A novel stability boundary, named Type A, was found in this study, which was different from the Ledinegg stability boundary. Chen et al. [29] presented an experimental investigation of a TPNCL and flow characteristics were observed through the monitoring the pressure variation. Flow reversal was found due to the onset of critical heat flux and the mechanism of flow reversal was compared between macro-channel and mirco-channel. Bodjona et al. [30] built a mathematical model of a TPNCL and used finite volume method to carry out a numerical simulation. Result showed that the density, temperature, pressure of loop fluid changed considerably with heating power. An experimental investigation of steady state performance in a TPNCL with multiple channels was performed by Bhusare [31] and it was found that two-phase pressure drop decreased with the increasing superficial gas velocity.

As a summary about the previous studies on the single-phase natural circulation loops, it can be concluded that the experimental studies are still limited and most of which had a heating section by