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A new idea of the flow model applied to a two-phase loop thermosyphon

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ABSTRACT

The two-phase loop thermosyphon (TPLT) is a high-efficiency heat transfer device which has been applied in many fields in recent years. The conventional flow models of a TPLT do not consider the particularity of the flow characteristics and cannot properly describe the refrigerant distribution under different working conditions. This paper tries to propose a new idea of the flow model which takes the variation of flow characteristics with the change of working conditions into consideration. A numerical simulation was conducted on a TPLT based on the proposed flow model. The change in heat transfer rate and the variation of refrigerant column height (driving force) in downcomer with increasing refrigerant charge were calculated to analyze the effect of filling ratio on the performance. The study in this paper could provide a reference for the design in practical application.

Keywords: two-phase loop thermosyphon; numerical simulation; flow model, operation stage;

NONMENCLATURE

Abbreviations	
TPLT	Two-phase loop thermosyphon
Symbols	
x	Vapor mass quality
μ	Dynamic viscosity, N·s m^{-2}
Re	Reynolds number
d	Pipe diameter, m
M	Mass flow rate, kg s^{-1}
α	Void fraction
ρ	Refrigerant density, kg m^{-3}
λ	Frictional factor
P	Pressure, Pa

1. INTRODUCTION

The two-phase loop thermosyphon (TPLT) is a highly efficient heat transfer device which has been applied in many fields, especially popular in the cooling of a data center in recent years [1-4]. A TPLT system consists of an evaporator, a condenser, a riser and a downcomer. The thermodynamic diagram of a TPLT is shown in Fig. 1. The refrigerant charged into the system boils in the evaporator. It becomes vapor and then travels along the riser to the condenser. The vapor releases its latent heat in the condenser and turns back to liquid phase. The TPLT is driven by the gravity and does not need an external energy source.

It is significant to build a proper flow model for the TPLT so that the operation state could be determined and the flow parameters could be calculated when the boundary condition is given. It might provide a reference when designing a TPLT system in practical application. In fact, some researchers have tried to build the flow model of a TPLT and evaluate the system performance under different working conditions. Zhang [5-6] analyzed

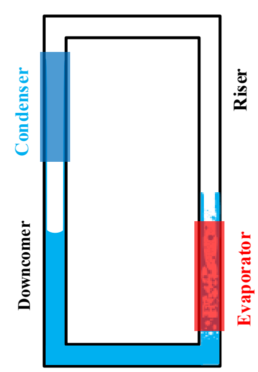

Fig. 1 Thermodynamic diagram of a TPLT.

several typical void fraction models and frictional pressure drop models, and investigated the TPLT system through a numerical simulation considering the partially-filled phenomenon in the downcomer. Tong [7] studied the flow characteristics of a TPLT system which used the R744 coolant. Cao [8] investigated the regulation of the refrigerant column height in downcomer through a numerical simulation.

The flow characteristics of the TPLT is special because it is deeply affected by the gravity. The flow states in each zone could be different. However, the traditional flow models in previous studies did not consider the multiple possibilities of the operation states and only regraded the flow state in most areas always as a two-phase flow state. Thus, the traditional flow models could not accurately describe the flow state of a TPLT and it is necessary to build the flow model from a new perspective.

the demand of evaporator. The redundant liquid refrigerant would appear in the riser and then form the two-phase flow. In addition, there is a liquid level in the downcomer in the first and second stage. The vapor condenses in the condenser and then travels along the inner wall of downcomer to the liquid pool.

Third stage: the immersion of liquid refrigerant in condenser; In this stage, the liquid level in the downcomer exceed the bottom of condenser and the liquid refrigerant fills the part of condenser. The condenser performance declines because of the decrease in the heat transfer area. The flow state in the downcomer is always the single-phase liquid flow in this situation.

The variations of flow state in different zones of the TPLT are shown in Fig. 2. When building the corresponding flow model for each zone, the operation stages should be determined in advance.

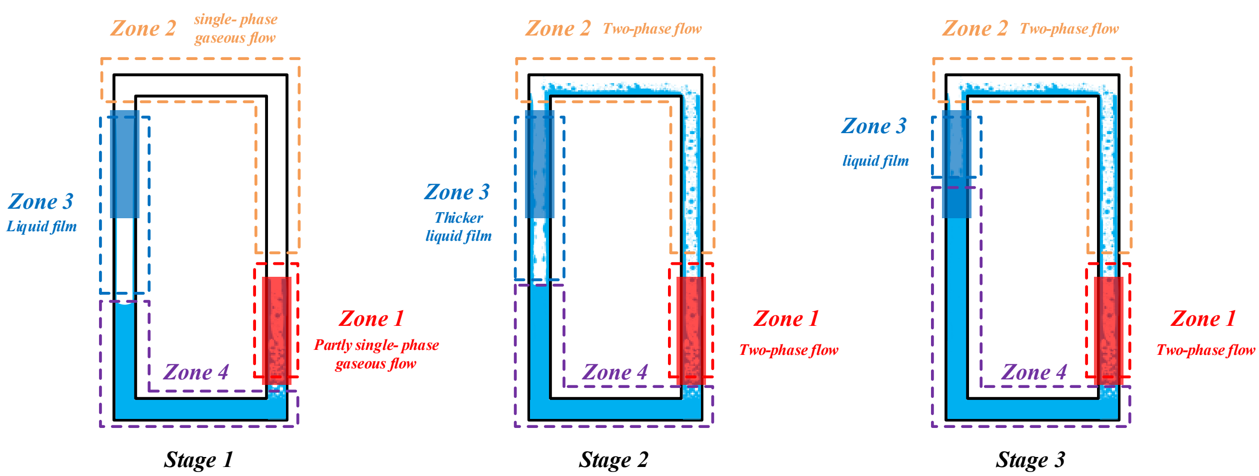

Fig.2 the different flow states in each zone under above three operation stages

2. THE METHOD OF NUMERCIAL SIMULATION

2.1 Operation stages of a TPLT system

When the working conditions (filling ratio and heating temperature) changes, the refrigerant distribution and flow patterns in the TPLT system could be different. According to the existing research [8,9], the operation state could be summarized as three stages.

First stage: the lack of liquid refrigerant in evaporator; In this situation, there is a lack of liquid refrigerant in the evaporator and part of flow in the evaporator is the single-phase gaseous flow. Thus, the evaporator is not fully utilized and the evaporator performance declines. Meanwhile, no liquid refrigerant exists in the riser and the flow state is the gaseous flow.

second stage: the appearance of liquid refrigerant in riser; In this stage, the amount of refrigerant has met

2.2 Simulation method

The simulation divided the cycle into an appropriate number of calculation cells. The parameters of the refrigerant were calculated for each calculation cell. The parameters of each calculation cell were calculated using the parameters of the preceding calculation cell. The simulation was conducted under the following assumptions.

(1) The model was one-dimensional along the axial direction of the tube.

(2) The heat transfer was uniform in each calculation cell in the evaporator and condenser.

The flow state in Zone 1 is two-phase flow in stage 2&3 and partly single-phase flow in stage 1. The simulation adopted the Thom model and Lockhart–Martinelli correlation, which are commonly used to calculate the void fraction and frictional pressure drop in two-phase flow, respectively.

The frictional pressure drop in a single-phase flow is calculated as follows:

$$\Delta P_f = \Delta P_l = \frac{1}{2}\lambda\frac{G^2}{\rho_l d}\Delta x \tag{1}$$

where λ is calculated as follows:

$$\lambda = \begin{cases} \dfrac{64}{\mathrm{Re}} & \text{laminar flow} \\ 0.3164\,\mathrm{Re}^{-0.25} & \text{turbulent flow} \end{cases} \tag{2}$$

Here, Re is the Reynolds number.

In the calculation of the frictional pressure drop in the two-phase flow, the Lockhart–Martinelli correlation was used.

$$\Delta P_f = \Delta P_l(\frac{1}{X^2}+\frac{C}{X}+1) \tag{3}$$

where the value of X is determined using formula (3), and the value of C is determined from the state of the two-phase flow.

$$X^2 = (\frac{\lambda_l}{\lambda_g})(\frac{1-x}{x})^2(\frac{\rho_g}{\rho_l}) \tag{4}$$

The Thom model for calculating the void fraction is as follows:

$$\alpha = (1+(\frac{1-x}{x})(\frac{\rho_g}{\rho_l})^{0.89}(\frac{\mu_l}{\mu_g})^{0.18})^{-1} \tag{5}$$

where x represents the vapor quality of the two-phase flow.

The flow state in Zone 2 is two-phase flow in stage 2&3 and single-phase flow in stage 1. The model adopted to calculate the void fraction and frictional pressure drop are the same to the Zone 1.

The liquid refrigerant in Zone 3 travels along the inner wall at a uniform speed and forms the liquid film. The thickness of the film s could be determined by the mass flow rate.

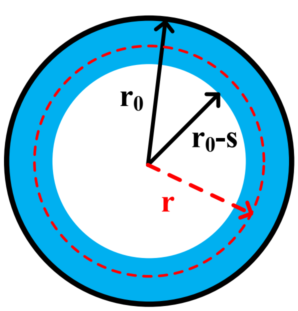

Fig. 3 the parameters of the liquid film in downcomer

On any circular interface with a radius of shown in the Fig. 3, the viscous force is equal to the gravity of the liquid inside.

$$\rho g[\pi r^2 - \pi(r_0-s)^2] = 2\pi r*(-\mu\frac{dv}{dr}) \tag{6}$$

Integrate both sides of the equation with respect to r.

$$v(r) = \frac{\rho g}{\mu}[\frac{(r_0-s)^2}{2}\ln r - \frac{r^2}{4}] + Const \tag{7}$$

And, we know that $v=0$ when $r=r_0$. Then, the $Const$ is solved.

$$v(r) = \frac{\rho g}{\mu}[\frac{(r_0-s)^2}{2}\ln\frac{r}{r_0} - \frac{r^2-r_0^{\,2}}{4}] \tag{8}$$

Thus, we have the equation (9) on the cross section in downcomer.

$$G = \iint \rho v(r)\square r dr d\theta = \int_0^{2\pi}\int_{r_0-s}^{r_0}\frac{\rho^2 g}{\mu}[\frac{(r_0-s)^2}{2}r\ln\frac{r}{r_0} - \frac{r^3-r_0^{\,2}r}{4}]dr d\theta \tag{9}$$

After simplification, we get equation (10).

$$G = \frac{2\pi\rho^2 g}{\mu}\left[\frac{r_0^{\,4}}{16} - \frac{r_0^{\,2}(r_0-s)^2}{4} + \frac{3}{16}(r_0-s)^4 - \frac{1}{4}(r_0-s)^4\ln\frac{r_0-s}{r_0}\right] \tag{10}$$

As a result, the thickness of the liquid film could be calculated based on the mass flow rate.

The Zone 4 is always the single-phase liquid flow. The frictional pressure drop can be solved by the formula (1).

In addition, the heat transfer model for boiling and condensation uses the empirical formulas.

The entire cycle was divided into N calculation cells, and the calculation began at the evaporator inlet. The simulation was conducted under different filling ratio and temperature boundaries. Before the calculation of the cycle, the operation stage of the TPLT should be judged. Then, the unknown parameters (evaporating pressure, liquid column height in the downcomer, heat transfer rate, pressure drop) were solved by iteration. The details of the calculation process are shown in the Fig. 4.

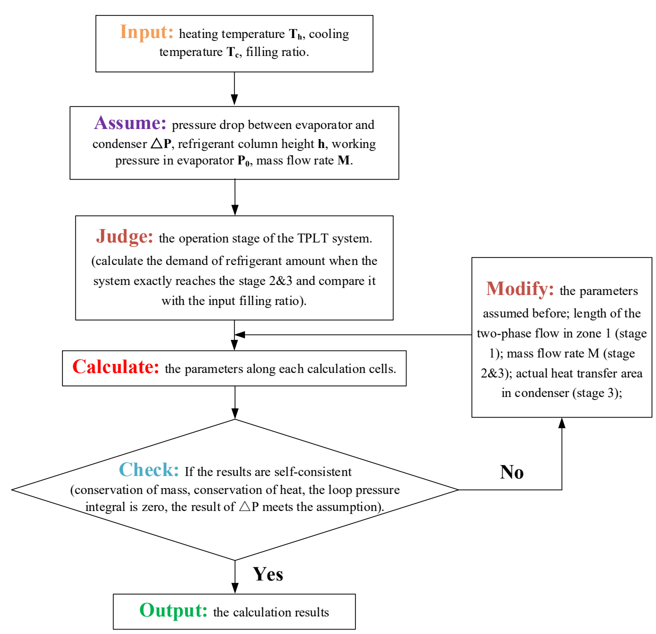

Fig.4 the flow chart of the calcualtion

Based on the method introduced above, the operation stage under given boundary conditions could be determined and the heat transfer or flow parameters of the cycle could be calculated.

3. THE RESULTS OF THE SIMULATION AND DISCUSSION

Before the simulation, the flow model was validated to evaluate the accuracy by using the data from previous experiment date [8]. The experiment results and the simulation results were shown in Fig. 5. The results show that the flow model could achieve acceptable accuracy.

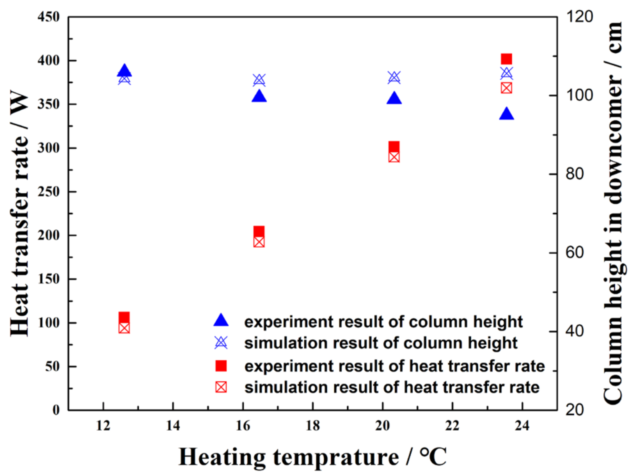

Fig. 5 the validation of the flow model

The simulation is conducted on a typical TPLT which has an inner diameter of 8 mm. The lengths of the evaporator, condenser, riser and downcomer were 1.44, 1.46, 1.70 and 1.90 m, respectively. R134a was chosen as the refrigerant. The heating temperature was set as 30℃ and the cooling temperature was 9℃.

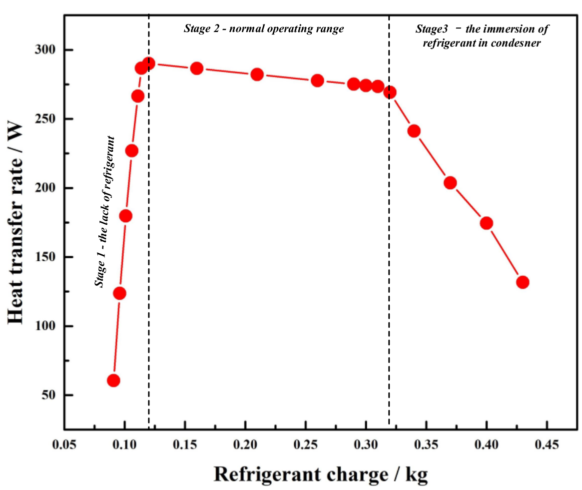

Fig. 6 the simulation resuslts of heat transfer rate

The Fig. 6 display the heat transfer results with increasing refrigerant charge while the variation of the refrigerant column in downcomer is shown in Fig. 6.

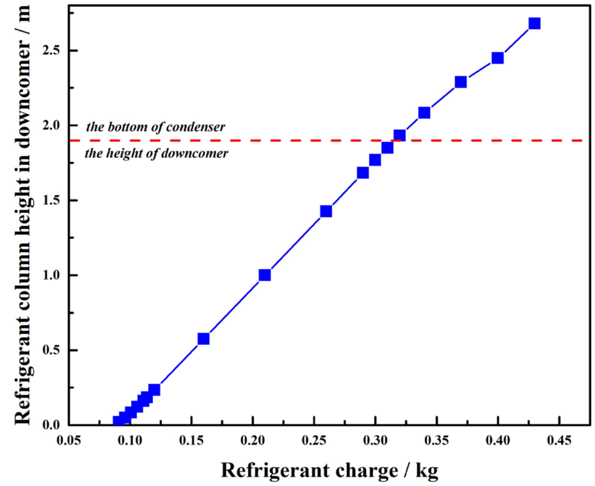

Fig. 7 the simulation resuslts of the refrigerant column height in downcomer

The results indicate that the flow model could finish the calculation in different operation stages. The heat transfer in evaporator was notably affected in stage 1 because there was a lack of refrigerant in evaporator. In stage 2, the heat transfer rate slowly decreased with increasing refrigerant charge. That is because the pressure drop between the evaporator and condenser increased. As shown in Fig. 7, the refrigerant column exceeded the bottom of condenser when the refrigerant charge was larger than 0.32 kg. It caused the immersion of refrigerant in condenser and the decrease of condensation heat transfer ability.

4. CONCLUSIONS

This paper proposes a new idea for the flow model applied to a two-phase loop thermosyphon. The flow model considers both of the difference of flow state in each zone and the change of operation stage. The model could properly describe the flow characteristic and be able to simulate the extreme condition. The simulation results indicate the effect of different operation stage. It might provide a reference for the design of a TPLT system.

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