Numerical simulation of phase transition and heat transfer in two-phase closed thermosyphon

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ABSTRACT: In this paper, a computational fluid dynamics model is developed to simulate the working state of a two-phase closed thermosyphon (TPCT). Two-phase volume model volume of fluid (VOF) and Lee model were used to simulate the heat transfer process of evaporation and condensation in the TPCT. The boiling and condensation heat transfer of TPCT were investigated numerically with water as working fluid. The internal local wall temperatures were measured at a filling rate of 0.5 to determine the heat transfer variations based on the transverse and longitudinal positions. The results show that the numerical model can simulate the phase transition process well. The temperature distribution in evaporating section is uniform. The temperature in condensing section and adiabatic section decreases with the increase of height in vertical direction. The temperature in horizontal direction is lower. The heat transfer mechanism of the TPCT was analysed under certain operating conditions.

1. Overview
TPCT is a gravity-assisted coreless thermosyphon, which uses evaporation and condensation mechanisms to transfer a large amount of heat with minimum temperature difference. TPCT has the advantages of low cost, simple geometry and high efficiency. It has been widely and successfully applied in many engineering applications, such as CPU cooling, solar hot water and geothermal energy recovery.

At present, the experimental research on the heat transfer performance of the TPCT is mature. The main factors that affect the heat pipe are inclination angle, liquid quantity, working medium, input and output power. The performance of the TPCT under different working conditions was analyzed by Mahbobe et Al. [1]. The results show that overcharge of heat pipe will decrease the performance of TPCT. The transient simulation model of TPCT was established by Limin Ma et al. [2]. They point that the heat transfer rate and the total heat transfer Coefficient increase with the increase of water bath temperature and the decrease of cooling water inlet temperature.

The predecessors have made some achievements in numerical simulation. Fadhl et al. [3] simulate two-phase flow and heat transfer during startup. The results show that the performance of R134a and R404a is better than that of R404A. Asghar Akhel et al. [4] investigated the effects of heat flux and packing ratio on the performance of TPCT. The results show that the performance of TPCT increases with the increase of heat flux density. Zhi Xu et al. [5] study the influence of filling ratio and wettability of evaporation section on thermal performance of water filled TPCT. The results show that the thermal resistance decreases by 59.5% with the filling rate increasing. The thermal resistance of the hydrophilic evaporation section is significantly lower than that of the hydrophobic evaporation section.

Compared with the experimental analysis, it is very difficult to simulate and predict the heat transfer process of the TPCT. The overall heat transfer mechanism is very complex. In the evaporation section,
phase transformation and heat transfer are carried out at the same time, so various states of heat transfer can be observed in the evaporation section, including natural convection, mixed convection and suppression of Nuclear Boiling, while there is no fixed reference value for the determination of heat transfer coefficient. It is often concluded from experimental experience that there is a large error compared with the true value.

2. Mathematical Models

2.1. VOF MODELS

Volume of fluid (VOF) model is widely used in numerical simulation of TPCT. The model can simulate the change of many physical parameters (such as density, velocity, etc.) of two or more discordant interfaces. The volume fraction of each new phase is added in the calculation. The total volume fraction of all the phases in the region is 1. We consider the volume fraction as a continuous function of space and time. In the simulation we use two-phase flow, formula is:

\[ \alpha_v + \alpha_l = 1 \]

where \( \alpha_v \) is the volume fraction of vapor and \( \alpha_l \) is the volume fraction of liquid. At this point, we have three scenarios:

- \( \alpha_v = 1 \): The grid is completely filled with liquid
- \( \alpha_l = 1 \): The grid is completely filled with vapor
- \( 0 < \alpha_v < 1 \): There is a two-phase interface in the grid

The equations of continuity equation, mass conservation, energy conservation and momentum conservation are used as governing equations to describe the motion of a working medium in a TPCT:

Continuity equation:

\[ \nabla \cdot \left( \alpha_v \rho_v \vec{V} \right) = -\frac{\partial}{\partial t} \left( \alpha_v \rho_v \right) + S_{MV} - S_{ML} \] (1)

Energy conservation:

\[ \frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\rho E \vec{V}) = \nabla \cdot (k \nabla T) + \nabla \cdot (\rho \vec{V}) + S_E \] (2)

Momentum conservation:

\[ \frac{\partial}{\partial t} (\rho \vec{V}) + \nabla \cdot (\rho \vec{V} \vec{V}) = \rho \vec{g} - \nabla p + \nabla \cdot \left[ \mu \left( \nabla \vec{V} + \nabla \vec{V}^T \right) - \frac{2}{3} \mu (\nabla \cdot \vec{V}) \vec{I} \right] + F_{CF3} \] (3)

2.2. Lee Model

The Lee model is currently the main phase transition model for TPCT simulation. The model assumes that mass and energy are transferred at constant pressure and quasi-thermal equilibrium. The model holds that the phase transition is mainly driven by the deviation between the interface temperature and the steady state temperature, and the phase transition rate is proportional to the deviation.

Condensation Section:

\[ S_V = -S_L = \frac{r \alpha \rho_v (T - T_{sat})}{T_{sat}} \] (4)

Evaporation Section:

\[ S_V = -S_L = \frac{r \alpha \rho_l (T - T_{sat})}{T_{sat}} \] (5)

the Empirical Coefficient \( r \), which is a mass transfer intensity factor, allowing researchers to adjust for different situations. Previous studies used a very wide range of values to achieve a minimum deviation.

3. Simulation Model

A two-dimensional model of TPCT is established. The closed copper pipe with a total length of 500 mm, an outer diameter of 22 mm and an inner diameter of 20.2 mm is used as the geometry of the TPCT. According to experience, the TPCT is divided into evaporating section and condensing section, which are separated by adiabatic section. The length of TPCT is 200, 200 and 100 mm, respectively. The coordinate origin is defined as the middle point at the bottom of the evaporation section of the heat pipe, where the \( x \) direction is horizontal and the \( y \) direction is vertical. The computational mesh contains 79971 cells. Near the right and left walls, the mesh is refined to capture the thin film of liquid that forms on the wall. Assume that there is no heat transfer between the top and bottom walls.
The water density $\rho$ and surface tension $\sigma$ are set as following:

$$\rho = 859.0083 + 1.252209T - 0.0026429T^2$$
$$\sigma = 0.09805856 - 1.845 \times 10^{-5}T - 2.3 \times 10^{-7}T^2$$

4. Boundary Conditions

We assume that the vapor is an incompressible ideal gas and that the bubbles are spherical when the liquid evaporates. The non-slip boundary condition is set at the inner wall of the TPCT. In order to simulate the evaporating process of the evaporating section with different input power, a constant heat flux is defined at the boundary of the evaporating section. Assuming that the adiabatic section is completely adiabatic. The zero heat flow is defined as the boundary condition on the adiabatic section. The condenser is partly cooled by the heat released when the vapor condenses. Suppose the condenser is cooled by water. Therefore, the convective heat transfer Coefficient is defined as the boundary condition on the wall of the condenser.

5. Simulation process and result

The TPCT is filled with 0.5 at the beginning of the simulation. Water vapor is defined as the prime phase and liquid water as the secondary phase. Fig. 2 shows the volume fraction of the pool boiling at 172.87 W at different time in the evaporation section, where the light color represents the vapor and the dark color represents the liquid. As shown in Fig. 3, a film of condensed liquid appears in the condensation section. The phase evolution process in the heat pipe can be found from Fig. 2. At first, the liquid fills half of the evaporating section and is heated by a constant heat flow applied to the outer wall. When the liquid reaches boiling temperature, the liquid begins to evaporate and change phase. The continuous evaporation leads to the decrease of liquid volume fraction. As the volume fraction of vapor increases, small bubbles are produced in some places, and the small bubbles continuously form and aggregate into large bubbles and are transported to the top of the liquid pool. After the above process, the saturated vapor is transported through the adiabatic section to the condensing section. When the vapor reaches the wall of condensing section, the vapor condenses along the wall and forms a liquid film gradually. Then, under the action of gravity, these liquid films will flow back along the wall to the liquid pool in the evaporation section for replenishment. The above cycle describes the heat transfer process of the TPCT during operation.
The temperature distribution on the outer wall of the TPCT with a heating power of 172.87 W is shown in Fig. 4(b). The wall temperature of evaporation section and condensation section is relatively stable. The wall temperature of the upper end of the evaporation section and the adiabatic section decreased with the increase of the height, mainly because the wall temperature decreased due to the falling of the liquid film. By calculating the average temperature of eight different monitoring points, it is found that the thermal resistance of the heat pipe system is about 0.33 K/W.
Fig. 4 Horizontal (a) and Vertical (b) temperature distribution at different positions of heat pipe

As shown in Fig. 4(a), the horizontal temperature distribution at different locations during the operation of the TPCT is recorded. As shown in the Fig. 4(a), there is little change in the horizontal temperature in the evaporation section. Under the condensation of the Tube Wall, the temperature of both sides of the condensing section presents the shape of high middle and low at both ends. The vapor in the adiabatic section flows in the pipe and the wall is adiabatic, so the intermediate temperature is higher than that in the condensation section.

Fig. 4(b) shows the vertical temperature distribution at different locations of the 3.5 s heat pipe. It can be found from the diagram that the temperature changes little in the evaporating section and decreases with the increase of the height in the adiabatic section and the condensing section. Near the top of the condensing section, the temperature is significantly increased due to the return of vapor. The abnormal temperature point in the evaporation section is due to the intense evaporation of the liquid surface, which may be caused by large air bubbles. At the same time, the temperature variation in the middle of the heat pipe is stable, and the temperature fluctuation in the heat pipe is larger the closer to the wall.

To sum up, when the heating power is 172.87 W, the temperature of the evaporation section rises with the input of the heating power, and when the temperature of the evaporation section reaches the boiling temperature, the phase transition begins. The high-temperature region of the evaporation section expands due to the upward movement of steam, and a high-temperature region appears. Then, as the steam reaches the condensing stage and the temperature begins to drop, it condenses into small droplets on the wall, which gather to form a liquid film and flow downward under the action of gravity. And as there is no heat loss in the adiabatic section, the temperature of the section increases due to the axial heat conduction of the heat pipe. After several cycles, the temperature distribution in the TPCT becomes uniform.

6. Conclusion
In this paper, the volume fraction of vapor phase and the temperature distribution inside and on the wall of the TPCT are studied by numerical simulation. It can be concluded that the VOF and Lee models can be used to simulate the phase transition mechanism in the TPCT. The simulation results show that:

- When the temperature of evaporation reaches boiling temperature the phase transition begins. When the vapor reaches the condensing section the temperature begins to drop. After several cycles, the temperature distribution in the TPCT becomes uniform.

- The temperature distribution of evaporation section is uniform, the temperature of condensing section and adiabatic section decreases with the increase of height in vertical direction, and the temperature in Horizontal Direction is higher and lower in the middle.

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