Numerical Simulation on Flow and Heat Transfer in Oscillating Heat Pipes

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ABSTRACT

In order to predict the heat transport capability of oscillating heat pipes (OHPs), a mathematical and physical model of OHP was built to simulate the process of flow and heat transfer in vertical bottom heating mode. Water was used as working fluid. Mixture model in FLUENT was used for two-phase flow numerical simulation. The result showed that the numerical simulation was successful to reproduce the behavior of the internal flow of OHP, including vapor generation in evaporation section, oscillation phenomena caused by the pressure difference and heat transfer due to oscillation. The quasi periodic thermal oscillation with the same characteristic frequency for both evaporation section and condensation section, indicated that heat transfer due to oscillation. Comparing with the experimental tests, the simulation results agreed with the experimental records fairly well. It was found the simulation could predict the heat transport capability of OHPs successfully.

Keywords: oscillating heat pipes (OHPs), numerical simulation, heat transfer, flow, predicting correlation

1. INTRODUCTION

An oscillating heat pipe (OHP) is a two-phase flow device used for transferring heat without any moving mechanical parts [1,2]. It consists of tubes/channels of capillary dimensions arranged in a serpentine manner and joined end to end as shown in Fig.1. It is predicted as one of the most promising solution for higher heat dissipation compact cooling. The heat transfer characteristics of OHPs have become a hot research. However, most studies focused on the experimental investigations. Only a few researches paid attention on the numerical simulations. Zuo and North [3] simulated the operation of vapor and liquid slugs in OHP by the single spring-mass-damper system, which far away from the experimental results. Wong [4] predicted the direction of vapor and liquid slugs by the multiple spring-mass-damper system, but without considering the effect of heat exchange. Dobson [5] and Faghri [6-7] established the mass, momentum and energy conservation equation of OHP by the control volume method. Khandekar [8] proposed the artificial neutral network to predict the thermal performance of OHP, which based on an amount of experimental data. In fact, there was still no an effective numerical simulation to predict the thermal performance of OHPs successfully.

With the aim of exploring potential applications of OHP technology, it is very important to predict the thermal performance of OHP by the numerical simulation, rather than by a large number of experiments. In this work, a mathematical and physical model of OHP was built to simulate the process of flow and heat transfer. The simulation results were compared with the experimental results.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

In the experiments, an experimental apparatus of OHPs were established for thermal performance test to study the flow and heat transfer. The four-turn OHP was selected as a typical shape.
Pure water was used as working fluid. The operational orientation was vertical bottom heating mode.

In the thermal performance test, the copper tubes with outer diameter \((D_o)\) of 2.5 and 3mm, inner diameter \((D_i)\) of 1.3 and 1.8 mm were used as manufacturing material to be bent into the OHPs separately. The heat transfer length \((L)\) of 200 mm were adopted for comparative experiments. In the liquid filling process, internal channels of copper tubes were first exhausted and the working fluid was filled fully into the tube under the pressure difference. Liquid filling ratio was controlled around 50±5% by the second vacuum, which discharged the excess liquid. The experimental apparatus of OHPs was shown in Fig.2. The nickel chrome electric wires were wound around the copper tube, which was wrapped in thermal insulation adhesive plaster, as evaporation section. They were connected to the transformer, which supplied heating power by adjusting the current and voltage. The length of evaporation section was 20 mm, the same as the condensation section; and the condensation section was cooled by water \((25±0.05\,^\circ C)\). The OMEGA K-type thermocouples were installed to measure the wall temperature at different positions of OHPs. The detailed location of thermocouples was shown in Fig.2.The pulse of temperature was measured to reflect the internal working fluid oscillation indirectly.

All tests were conducted at an ambient temperature of 25±1\(^\circ\)C. Base on the application requirements, when the average temperature of evaporation section was over 100 \(^\circ\)C, the experiment would be stopped. The thermal resistance of OHPs was equal to temperature difference between condensation section and evaporation section divided by heating power. 

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R_{\text{OHP}} = \frac{(T_e - T_c)}{Q_h} \quad (R_{\text{OHP}}: \text{thermal resistance of OHP}; \quad T_e: \text{average temperature of } T_1, T_2, T_3 \text{ and } T_4 \text{ approximately instead of evaporation section}; \quad T_c: \text{average temperature of } T_{13}, T_{14}, T_{15} \text{ and } T_{16} \text{ approximately instead of condensation section}; \quad Q_h: \text{heating power}).
\]

3. DESCRIPTION OF SIMULATION

3.1 Physical model

The 2D physical model is built to simulate the internal flow and heat transfer in OHPs, shown in Fig.3. Pure water is used as working fluid. The internal flow of OHP is mainly vapor-liquid two phase flow, assuming the density of liquid phase is incompressible, and the vapor phase is compressible. The phase and density change with the temperature changes. The geometric model and mesh diagram are shown in Fig.3. The design length of evaporation section is 20mm, and the length of condensation section is 20mm.

3.2 Definite conditions

As the OHP running in a negative pressure, we assumed that the water vaporization temperature is 303K. When liquid phase temperature is greater than 303K, it begins evaporation. When gas phase temperature is less than 303 K, it begins condensation. The heat flux in evaporation section depends on the power input. The heat transfer coefficient in condensation section is set according to the actual situation. The insulation section is set to insulation boundary condition.

Although the mixture model can be used in FLUENT, it can not directly calculate mass and energy transfer, therefore it need user defined function to achieve mass and energy transport, in order to achieve heat transfer process of evaporation and condensation.
4. SIMULATION ON START-UP PROCESS

In the simulation case, the four-turn OHP with inner diameter \((D_i)\) of 1.3 and heat transfer length of 200 mm was selected as 2D model for comparison. The heating power was 24W. As shown in Fig.4, the start-up of OHP had been recorded, which went through the process of heat transfer. From 1s to 5s, the temperature in evaporation section increased due to power input. When the time up to 7s, the evaporation section reached a certain temperature, the generation of bubbles began. The region of high temperature in evaporation section was expanding from 7s to 9s. As the temperature increased, the bubbles jetted across the evaporation section to the condensation section. High temperature appeared in the condensation section, while the evaporation section was cooled down in 10s. After that, the vapor slugs (bubbles) and liquid slugs (the liquid region between bubbles) oscillation occurred and made the heat transfer from evaporation section to condensation section. The temperature distribution of OHP became uniform. In 13s, vapor slugs (bubbles) condensed into liquid in the condensation section. With the help of gravity and capillary forces, the condensed liquid returned back to the evaporation section. At the same time, the temperature in evaporation section increased from 10s to 17s, which reserved energy for the next oscillation cycle. In 18s to 20s, the new cycle began. The evaporation section received the energy and reached a certain temperature. The condensed liquid evaporated and generated the bubbles again. As a result, the heat transfer process of OHP mainly depended on this vapor and liquid slug oscillation, which occurred due to pressure difference between evaporation and condensation.

Therefore, the numerical simulation was successful to reproduce the startup process of OHP, including vapor generation in evaporation section, oscillation phenomena caused by the pressure difference and heat transfer due to oscillation process. They matched with the experimental observation. As shown in Fig.5, the temperature change in OHP startup process (the total time is 35 seconds) was recorded. It was found that when the hotwall (marked in Fig.3) reaches a certain temperature (about 345K), the temperature oscillation began. The oscillation amplitude and temperature difference between evaporation and condensation section was decreasing with the startup of OHP. The quasi periodic thermal oscillation with the same characteristic frequency appeared in both evaporation section and condensation section, which indicated heat transfer due to oscillation process. Comparing to the experimental records in Fig.6, the trend of temperature change in simulation was consistent with experimental results.
5. NUMERICAL SIMULATION COMPARED WITH EXPERIMENTAL RESULTS

5.1 Comparison of temperature curves

In the case, the OHP with inner diameter of 1.3mm and heat transfer length of 200mm was selected for comparison between simulations and experimental results. Fig.7 was the temperature record for OHP performance test in 24W; while Fig. 8 was the temperature record for OHP 2D simulations in 24W. As can be seen in Fig.8, the oscillation range in temperature was consistent.
with the experimental record. The average temperature of the experimental record in evaporation section was about 57 °C; while condensation section’s was about 32 °C. The average temperature of 2D simulation record in evaporation section was about 63 °C; while condensation section’s was about 28 °C.

![Fig.7 Temperature record for OHP performance test in 24W](image1)

The simulation temperature difference was slightly higher than the experimental record, but it represented the simulation model was successful to predict the OHP performance and operation. Furthermore, it was noticed that the simulation record needed some time to develop into the stable oscillation state after the startup process. In contrast, the experimental record reached the stable oscillation state earlier. Therefore, the longer simulation, the more accurate results can be obtained, closer to the real operation.

5.2 Comparison of thermal resistance

![Fig.8 Temperature record for OHP 2D simulation in 24W](image2)

![Fig.9 Comparison of thermal resistance among 2D simulation and performance test](image3)

After the section discussed above, it proved that 2D mathematical model could successfully simulate the internal flow of an OHP. In this section, several cases with different parameters were selected for comparison in different operating conditions. As can be seen in Fig.9, the thermal resistance of 2D model simulation was higher than the test data. From the comparison of fitting equations between 2D simulation and performance tests, the gap kept stable. It was also noticed that the 2D simulation results were closer to the performance test in the lower heating powers. The gap would enlarge with the increase of heating power. This may be due to the defects in the mixture model itself. As flow visualization and temperature oscillation record [9], the flow pattern changed with the change of heating power. When the bubble and slug flow transferred into the annular flow or the oscillation frequency increased, the mixture model can not fit for the flow pattern change. In conclusion, it was believed that 2D model was considered as the good solution for OHP simulation.
6. CONCLUSIONS

In order to predict the heat transport capability of OHPs, a mathematical and physical model of OHP was built to simulate the internal flow and heat transfer in vertical bottom heating mode. Water was used as working fluid. Mixture model in FLUENT was used for the two-phase flow numerical simulation. Conclusions of the studies can be summarized as follows:

(1) The numerical simulation was successful to reproduce the startup process of OHP, including vapor generation in evaporation section, oscillation phenomena caused by the pressure difference and heat transfer due to oscillation. The quasi periodic thermal oscillation with the same characteristic frequency for both evaporation section and condensation section, indicated that heat transfer due to oscillation. Comparing with the experimental observations, the simulation results agreed with the experimental results fairly well.

(2) According to the comparison of temperature curves record in 2D model and performance tests, it was found that 2D model was successful to simulate the OHP operation, which more consistent with the experimental data.

(3) According to the comparison of thermal resistance in 2D model and performance tests, it was found that the simulation thermal resistance was higher than the test data, but also reflected the decreasing trend with the increase of heating power. The 2D model was considered as the good solution for OHP simulation.

ACKNOWLEDGEMENT

Acknowledge the financial support of Guangdong provincial Science and Technology Project (2010A080802003) and Guangzhou Panyu District Science and Technology project (2010-Z-41-01)

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