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Numerical Simulation of Heat Transfer Performance of Micro-heat Pipe Array based on FLUENT

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Abstract：The structure and basic principle of heat pipe and plate micro heat pipe array are introduced in detail, and the application of FLUENT grid technology and numerical technique is introduced. The thermal conductivity, the phase change and the effect of the liquid filling rate on the heat transfer performance of the heat pipe were simulated by using FLUENT of CFD software. The results show that when the liquid filling rate is 20% ~ 30%, the thermal conductivity of the micro heat pipe starts to rise, reaching $6.11 \times 10\text{-}5$ W • m-2 at the highest level. When the liquid filling rate of 30% to 40%, the thermal conductivity of the micro-heat pipe began to decline, which indicates that the best filling rate is when the liquid filling rate is 20 ~ 30. When the temperature of the outer wall of the condensation section is 67.5 ℃, the maximum heat flux can reach 8.1×105 W • m-2.

1. Introduction

Microheat pipes can carry large amounts of heat over long distances through very small cross-sectional areas without any power. The first "heat transfer device" [1] was studied by R.S.Gaugler of Ohio General Generator Company in the world, and the patent of No.2350348 was applied. Firstly, the principle of standard heat pipe with absorbent core or modern heat pipe was put forward. B.R.Bin and G.P.Peterson [3-5] have carried out theoretical analysis and experimental research on single micro heat pipe, established a two-dimensional steady-state flow and heat transfer model, and obtained the formula to calculate the maximum heat transfer capacity [4].D.Khrustalev and A.Faghri[6] established a mathematical model for the maximum heat transfer capacity and thermal resistance of a single micro-heat pipe for further study. M. Murakami [7] studied the heat transfer coefficient of the micro-heat pipe cluster. After that, Sartre et al. studied the micro-heat pipe array with parallel groove made of aluminum plate, and established the theoretical model of the micro-heat pipe array.Kim[8] et al. established the mathematical model of heat and mass transfer of micro heat pipe, and optimized the design.Zhao Yaohua et al. [9] have made an experimental study on the heat transfer of microheat pipe arrays. The results show that the heat transfer capacity is the best and the maximum heat flux is 200Wcm-2 when the liquid filling ratio of methanol is about 0.3, and the heat transfer efficiency is 85% higher than that of the traditional heat pipe.

2.Flat microheat pipe array

Micro heat pipe array (as shown in figure 1) is a kind of aluminum alloy material, with a certain number of flat thin plates with diameters of 1~2mm independent of each other arranged in parallel.It is mainly made up of metal sealing package, capillary structure and working medium, which is divided into evaporation section and condensation end. When one end is heated, the working medium achieves

efficient heat transfer through evaporation and condensation phase transition without any external power. Due to the high efficiency of heat transfer in micro heat pipe, widely used in various fields of heat dissipation, it has become the focus of heat pipe research, and continuously analyzed and simulated the factors that affect the heat transfer performance.
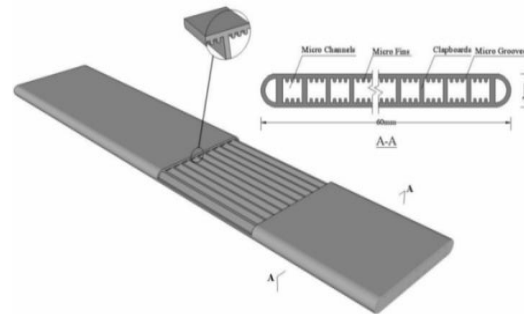

FIG.1 Plate microheat tube array.

FIG.2 Micro-wing structure inside microthermal tube array.

Multiple heat pipes in the micro heat pipe array operate independently, which can avoid the influence of single heat pipe rupture on the heat transfer effect.In addition, each internal micro heat pipe adopts a microfin structure that can enhance heat transfer. As shown in FIG. 2, the heating surface of the micro heat pipe can be increased, thus improving the heat transfer performance. In addition, the micro heat pipe array can be designed in different sizes according to actual demands, which is easier to meet the design requirements of various industries. It has a flat appearance and can be closely combined with the surface of most heating components. The raw material of the micro heat pipe array is aluminum with micro groove shaped by one-time extrusion, and the cost is much lower than that of traditional copper.

3. working principle
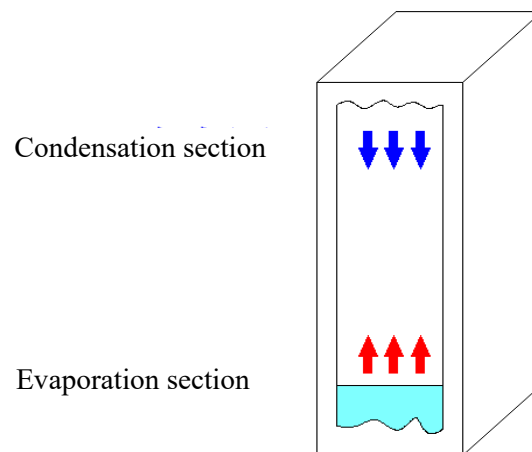

Condensation section

Evaporation section

FIG.3 Schematic diagram of microheat tube array working principle.

The principle of microtube array is shown in Fig. 3. In the closed vacuum tube, the hot end liquid-steam phase transition process is used rapidly, and the heat is condensed and exothermic at the cold end after endothermic evaporation at the hot end. In general, the negative pressure of $1.3 \times (10-1 \sim (-4)$ Pa is pumped into the tube before the working fluid is rushed into the tube [11], which makes the liquid filled porous material close to the inner wall of the pipe to be sealed. From the bottom up, the microheat pipe is the evaporation section, the adiabatic section and the condensation section. When there is a temperature difference between the two ends of the micro-heat pipe, the liquid working fluid in the absorption core of the evaporation section will vaporize and steam flow will occur. Condensation to the

condensing end and releasing heat to form a liquid, and the liquid flows back to the evaporation section along the porous material by capillary force. As long as there is a temperature difference or even a small temperature difference, the cycle will continue. In heat transfer, micro heat pipes must go through six main interrelated processes

4. Grid Technology of FLUENT
ENT can import modules built by Gambit and other software for unit calculation and storage of solving variables, as follows.

Two-dimensional quadrilateral and triangular elements
Three dimensional tetrahedron core element
Hexahedron core unit
Prism and polyhedron element

In the application of FLUENT software, two numerical methods can be selected: pressure based solver and density based solver. The pressure solver is applied to the conventional projection algorithm. In the projection method, the velocity field is first solved on the basis of the momentum equation, and then the velocity field which can satisfy the continuity condition is obtained by the correction of the pressure equation. There are two kinds of pressure - based separation solver and coupling solver in FLUENT software.

5. Establishment of Heat transfer Model

5.1 Modeling and mesh division of aluminium tube-methanol gravity heat pipe
The physical model adopted in this paper is aluminum tube-methanol gravity heat pipe, which is circular in shape, and the single heat pipe is simplified as two-dimensional simulation. First, the heat pipe model was established. The heat pipe was successively divided into evaporation section, adiabatic section and condensation section from the bottom to the top, and the length was successively 300 mm, 400 mm and 300 mm. The outer diameter of the heat pipe is 24 mm, the inner diameter is 20 mm, and the liquid filling rate in the pipe is 20%~40%. ICEM-CFD was used to divide the heat pipe model into two dimensional (Shell Mesh), the mesh elements in the computational region are all quadrilateral. The method of generating mesh (Patch Dependent) based on the contour line of the surface is adopted to capture geometric features and improve the calculation accuracy.
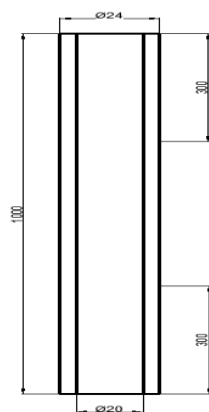

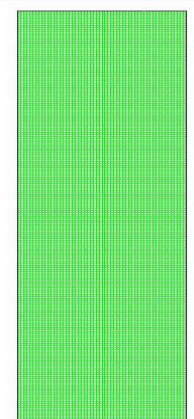FIG.4 Lv tube a methanol gravity heat pipe model.

FIG.5 A two-dimensional surface mesh with a heat pipe.

5.2 Numerical simulation of heat conduction problem of heat pipe with internal heat source
In this paper, the heat conduction problem of the heat pipe can be regarded as a super heat conduction body without considering the phase transition in the heat pipe. Because the evaporation section needs heat input, the outer wall can be defined as the boundary condition of the constant heat flux wall, so the outer wall will naturally transfer heat to the inner wall through heat conduction. The inner surface is the interface between solid and liquid, which belongs to the coupling interface. The adiabatic section can be set to a wall boundary condition with a constant heat flux of 0. The outer wall of the condensing section is facing to the outside world. Because the convection heat transfer coefficient between the object and the surrounding fluid on the boundary of the condensing section and the surrounding temperature are specified, the outward heat dissipation can be set as the third kind of boundary condition. The upper and lower boundaries are by default adiabatic boundaries.

5.3 Numerical simulation of gas-liquid phase problem in heat pipe
In this paper, the volume function model (VOF) of the fluid is selected for the calculation of gas-liquid phase in the heat pipe, the sum of the volume fraction of each control unit is equal to 1, and the n-s control equation is adopted to simulate the evaporation and condensation phenomena in the heat pipe. SIMPLE algorithm is adopted in the whole process.[12]
equation of continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

The momentum equation

$$u\frac{\partial U_i}{\partial x} + v\frac{\partial U_i}{\partial y} + w\frac{\partial U_i}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\left(\frac{\partial^2 U_i}{\partial x^2} + \frac{\partial^2 U_i}{\partial y^2} + \frac{\partial^2 U_i}{\partial z^2}\right) \tag{2}$$

Energy conservation equation

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{3}$$

RNG k - epsilon model

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k U_i)}{\partial x} = \frac{\partial}{\partial x}\left(\alpha_k \mu_{eff}\frac{\partial k}{\partial x}\right) + G_k - \rho\varepsilon \tag{4}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon U_i)}{\partial x} = \frac{\partial}{\partial x}\left(\alpha_\varepsilon \mu_{eff}\frac{\partial\varepsilon}{\partial x}\right) + \frac{C_{1\varepsilon}^*}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{5}$$

6.Results and analysis
There are many factors affecting the heat transfer performance of heat pipe, such as capillary limit of heat pipe, geometry of microgroove, inclination angle, liquid filling rate, working fluid, working temperature and so on. In this paper, FLUENT software is used to simulate the effect of liquid filling rate and different working fluids on the heat transfer performance of heat pipe.

6.1Effect of different working fluids on Heat transfer performance of Heat Pipe
The effects of water, methanol and ethanol on heat pipe heat transfer performance were simulated by FLUENT transient calculation. It can be seen from FIG. 6 that when the external wall temperature of the evaporation section increases, the heat flux also increases.Water as working medium, in the cooling section of the outer wall temperature is 71 ℃, the increase of heat flux leveled off gradually, the maximum is 3.86 x 105 w. m - 2, ethanol as the working medium, in the cooling section of the outer wall temperature of 69.9 ℃, the maximum heat flux of 4.91 x 105 W m. - 2, methanol as working medium, in the cooling section of the outer wall temperature of 67.5 ℃, the maximum heat flux can reach 8.1 x 105 W m. - 2.This shows that the heat transfer effect of methanol as working medium is good, and the heat transfer performance of the heat pipe can be improved.
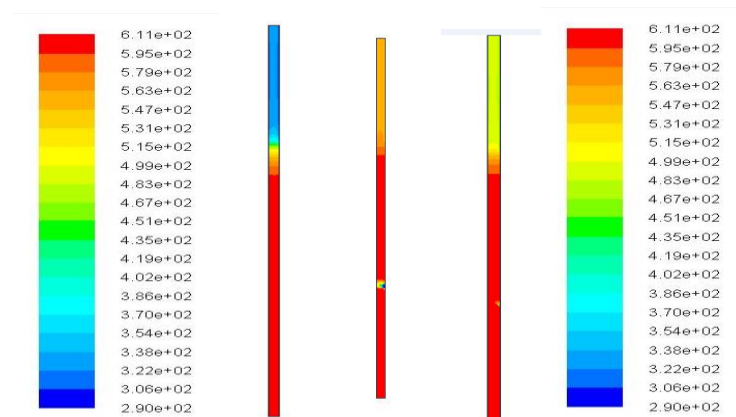
FIG.6 The temperature field of microheat pip   FIG.7 The temperature field of microthermal
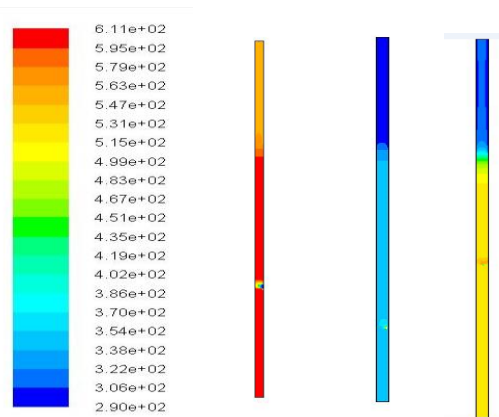   under different working conditions.   tube at different filling rate.

6.2Effect of different liquid filling rate on Heat transfer performance of Heat Pipe
The liquid filling rate is another important parameter affecting the working performance of heat pipe. If the liquid filling rate of heat pipe is too high or too small, it will not only cause unstable heat transfer, but also affect the heat transfer effect. Therefore, a lot of experimental studies have been conducted to obtain the range of the best liquid filling rate.In order to obtain the relationship between the liquid filling amount of the thermosyphon and the heat flow [13], Streltsov obtained the following formula by referring to the classical Nusselt vertical wall membranous condensation theory:

$$G = \left(\frac{4}{5}l_c + l_a + \frac{4}{5}l_e\right)\left[\frac{3\mu_l\rho_l\pi^2 d_i^2}{h_{fg}g}\right]^{1/3}\sqrt[3]{Q} \qquad （6）$$

However, the theoretical results calculated by the formula will be greatly different from the actual situation, because the shear force between the steam and liquid film inside the heat pipe is not fully considered, which is the main factor affecting the heat transfer performance.Moreover, the heat transfer coefficient in the heat pipe is related to the state of the liquid pool. The heat transfer coefficient will be higher when the liquid is boiling in the nuclear state, so the liquid filling rate calculated by equation (6) is low.

It can be seen from figure 7 that when the liquid filling rate is 20%~30%, the thermal conductivity of the micro heat pipe starts to rise, reaching 6.11 times 10-5 W·m-2 at the highest.When the liquid filling rate is 30%~40%, the thermal conductivity of the whole micro heat pipe starts to decline, which indicates that the optimal liquid filling rate is 20%~30%, which indirectly verifies that the optimal liquid filling rate proposed by Harada et al. is basically coupled

7. Conclusion
 An idealized numerical analysis of the micro-heat pipe array was carried out by software FLUENT, and the theoretical calculation results and experimental data were compared and analyzed.The results show that the methanol working medium has greater heat flux for the surface temperature of the same evaporation section under the optimal liquid filling rate.Due to the thermal properties of methanol itself, the most obvious factor affecting the heat transfer capacity of the micro-heat pipe when the core of the heat pipe is boiling is the shear stress on the gas-liquid interface caused by methanol vapor-liquid interaction friction.However, due to the limitations of the model itself, the structure of the microgroove inside the microheat pipe suction core was not taken into account, and it could not be concluded whether the shear stress formed by the contact between the working medium and the microchannel bending liquid surface affected the heat transfer capacity of the microheat pipe.

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