EXPERIMENTAL STUDY ON EVAPORATION-CAPILLARY PUMPING FLOW IN CAPILLARY WICK AND WORKING FLUID SYSTEM

by

Jinwang LI[a,b*], ***Ningxiang LU***[a], ***and Tianshu CONG***[a]

[a] College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing, China
[b] Key Laboratory of Low-Grade Energy Utilization Technologies and Systems, Ministry of Education of China, Chongqing University, Chongqing, China

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The evaporation-capillary pumping flow of the capillary wick and the working fluid system was experimentally studied in this paper. The capillary wick used in the experiment was fiber, and the working fluid contained water, ethanol and ethanol aqueous solution with water content of 25, 50, and 75 wt.%. The results show that the capillary pumping rate with ethanol as working fluid is in range 210.0-1812.5 kg/m²s when there is no heat load added. When the heating flux is 10616, 15924, 21231, and 26539 W/m², the evaporation-capillary pumping rate is 102.5, 247.5, 390.0, and 530.0 kg/m²s, respectively. The higher the heat load power, the greater the evaporation-capillary pumping rate and the higher the final stable temperature. With the increase of heat load power, the time required to reach temperature balance becomes shorter and the temperature fluctuations after reaching temperature equilibrium become larger. The obvious temperature fluctuation has occurred when the heat flux is 26539 W/m². The evaporation capillary pumping rate corresponding to the four different concentrations of ethanol solution in the experiment gradually decreases with the increase of water content. The temperature change processes and the final equilibrium temperatures of the four working fluids are nearly the same. The differences in boiling point of the working fluids do not have much influence here.

Key words: *evaporation, capillary pumping flow, capillary wick, working fluid*

Introduction

Heat pipe is a heat transfer device which uses the principle of phase transformation to transfer heat efficiently. It is the most efficient heat transfer element known at present. Its thermal conductivity exceeds the thermal conductivity of any known metal. Therefore, it is known as the *superconductor* of heat conduction.

In recent years, heat pipe theory and technology have been more and more widely used in spacecraft thermal control, electronic and electrical equipment heat dissipation, *etc.* New heat pipes like micro heat pipe, miniature heat pipe, loop heat pipe, capillary pumped loop heat pipe, pulsating heat pipe, oscillating heat pipe, flat plate heat pipe/vapors chamber, *etc.* are the hot developing directions in the field of heat pipe. For the wicked heat pipes, the capillary wick is the key component. It provides the driving force for the circulation of working fluid

* Corresponding author, e-mail: ljw@nuaa.edu.cn

inside the heat pipe. The capillary pumping force produced by the pores in the capillary wick and the flow of the working fluid in the capillary wick determine the heat transfer performance of the whole heat pipe [1-3].

Owning to the importance and complexity of the capillary wick, a lot of studies have been focused on it in recent years. Giraudon *et al.* [4] proposed a test bench in order to investigate the effect of porous samples hydrodynamic characteristics, for which the manufacturing process and the characterization were well controlled, on the evaporator heat transfer coefficient and operating limits. Several porous structures were also manufactured following a specific design of experiment and characterized in terms of thickness, porosity, permeability, pore radius and static contact angle. Yeh *et al.* [5] have investigated on the effects of various bimodal pore size distributions of biporous wicks for a loop heat pipe by using a statistical method. Iverson *et al.* [6] have developed a novel experimental approach for characterizing the performance of heat pipe wick structures by simulating the actual operation of wick structures in a heat pipe. Diamantis *et al.* [7] have developed an experimental set-up to investigate the performance of heat pipes for pumping the working fluid of the system using external waste heat. Kaya and Goldak [8] investigated the heat and mass transfer as well as the boiling limit in the capillary porous structure of a loop heat pipe by numerical studies. Huang and Liu [9] carried out a numerical simulation of heat and mass transfer in the evaporator capillary wick with a new three-layer model. Ren *et al.* [10] have analysed heat and mass transfer characteristics of the capillary wick using numerical simulation by setting up the mathematical model of the wick.

Heat pipe can be working at a certain temperature. However, temperature oscillation can also be found in some case and it has attracted a lot of studies focused on it in the recent years. Ku *et al.* [11] found out that the temperature oscillation is caused by the thermal and hydrodynamic interactions between the evaporator, the compensation chamber and the condenser. The temperature oscillation is characterized by the vapor front moving inside and outside the condenser periodically. It is postulated that the rise and fall of the temperature of the liquid returning causes the compensation chamber temperature and the void fraction inside the evaporator core to increase and decrease. Vershinin and Maydanik [12] found out that during the operation of miniature loop heat pipes one can observe pulsations of the operating temperature, which depend on the amount of the working fluid, the device orientation in the gravity field and the conditions of the condenser cooling. Intense pulsations, whose amplitude may exceed tens of degrees, arise from the lack of working fluid in a loop heat pipe when hot condensate or vapor bubbles periodically penetrate into the compensation chamber and act on the vapor phase in it, increasing its temperature and volume. Li *et al.* [13] found out that temperature oscillations can occur in loop heat pipes, during both start-up and normal operation, especially at comparatively low heat loads. It is hypothesized here that these operational oscillations result principally from three factors: original liquid blocking along the vapor flow passage, alternative turn-out of menisci and flooding in the wick, and two-phase flow instability in the condenser and the connecting pipelines. Singh *et al.* [14] found that the thermal response presented by the loop to achieve steady state was very short during the testing of micro loop heat pipe under step and random power cycles. At low heat loads, thermal and hydraulic oscillations were observed throughout the loop. The amplitudes of these fluctuations were very high at condenser inlet and liquid line exit. Celata *et al.* [15] found out that the thermal and hydraulic oscillations were observed throughout the loop heat pipe with the evaporator above the compensation chamber. The effect of these oscillations on the thermal performance of the loop heat pipe was not very significant.

The evaporator or the heat pipe can be studied as a whole system, while the capillary wick can also be studied separately. When the evaporator or even the whole heat pipe are processed, and then the external heat source and other related equipment are attached to inferring indirectly the performance of the capillary wick by studying the external parameters, because the whole evaporator or heat pipe system is quite complex, the parameters obtained from the final external measurement are influenced by many internal and external factors. The porous structure, the porosity, the effective pore radius, the permeability, and the effective thermal conductivity are interactive parameters. Although it is attractive for researchers and engineers to understand the effect of each parameter on a capillary wick's working state and performances, it is difficult to adjust each parameter in experiments [16-18].

When the capillary wick is investigated separately, the traditional method is to measure capillary pumping force, permeability and thermal conductivity. However, the relationship between capillary pumping force and permeability is contradictory. The larger the capillary pumping force, the smaller the permeability. There is no uniform criterion on how to balance this pair of contradictory parameters in design period. When measuring the capillary pumping force provided by the capillary wick, the traditional method only investigates the maximum rising height of the working fluid in the capillary wick, neglecting the changing process of the working fluid in the capillary wick. In addition, it is difficult to distinguish and measure the rising height of the working fluid clearly, because the capillary wick is usually not transparent, the common working fluids are colorless or light-colored and the internal pore structure of capillary wick is quite complex [19-22]. Therefore, the rising height of the working fluid in the capillary wick is rather fuzzy, and it is difficult to distinguish accurately. Especially when the pore diameter of the capillary wick is very small, the rising height of the working fluid in the capillary wick will be very large, which is even more difficult to measure.

For the measurement of the permeability of capillary wick, the traditional method needs to measure the mass-flow rate of the working fluid under certain pressure through the capillary wick. Because the pore diameter of the capillary wick is generally very small, the sealing requirement on the periphery of the sample is very high. Besides, the traditional permeability is proposed by hydrogeology, and the experimental measurements are often obtained under the condition of external pressure, which is different from that in the heat pipe where the capillary wick drives the circulation of the working fluid by capillary force. For the heat pipe, the interrelation between the capillary wick and the working fluid is very important, so the measurement of the maximum capillary pumping height and permeability of the capillary wick cannot completely reflect the interrelation between the capillary wick and the working fluid.

The performance of heat pipe is affected by many factors when testing by traditional method, and it is not conducive to reflecting the disadvantages of the actual performance of capillary wick. A new testing method is developed to study the evaporation capillary pumping flow in the capillary wick and working fluid system in this paper. It is not affected by condenser, steam pipeline and condensing pipe, so it can reflect the actual performance of the capillary wick and working fluid system more veritably when this method was used.

Test method

Heat pipe uses the phase transition of the internal working fluid to transfer heat. The heat is input at the evaporator and then it will transfer to the condenser.

When the heat pipe is working, the capillary wick pumps the working fluid, meanwhile evaporates the working fluid. When the evaporation rate is small, the evaporation surface is on the outer surface (near the surface of the steam side), and the capillary wick is maintained in the state of nearly saturation. As the increases of the evaporation rate, the evaporation surface will move toward the liquid side, then the pumping rate will increase, and the evaporation rate will decrease until the two are equal, thus achieving a new equilibrium. It can be seen that when the heat pipe works normally, the evaporation rate of the working fluid is equal to the pumping rate of the capillary wick.

During the actual operation of the heat pipe, there is a steady pumping rate of the working fluid, and it is equal to the evaporation rate of the working fluid. Based on this, a new testing method was developed in this paper, the schematic diagram of which is shown in fig. 1.

In the test, one end of the test section is immerged into the working fluid in the container, the other end of the test section is heated by a heating system. When it is heated to the phase change point the working fluid at the heating surface will evaporate and emit to the outside environment. Through the capillary action, the capillary wick continuously pumps the working fluid from the working fluid container to the heating (evaporating) surface. The pumping rate can be measured by the weight measurement system (including precision electronic balance and data acquisition system). The temperature of the capillary wick at the heated point is measured by the thermocouple prepared.

In this experiment, the working fluids used include water, anhydrous ethanol and ethanol aqueous solution with water content of 25, 50, and 75 wt.%, respectively. The capillary wick is made of the fiber felt with thickness of 2 mm, length of 100 mm, and width of 120 mm, and it is set on the internal face of the pipe which is 19 mm in diameter, 1 mm in thickness and 100 mm in length. The heat load is produced by heating resistance band. The detail structure and size of the test section and heating system is shown in fig. 2. Three temperature measuring points are equidistantly arrangement in the heating part as shown in fig. 2.

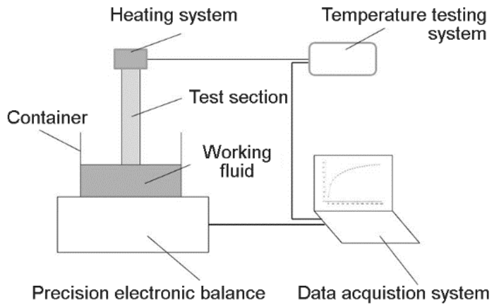

Figure 1. Experiment schematic

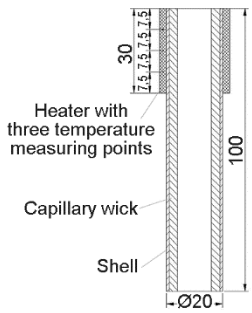

Figure 2. Test section and heating system schematic

Results and discussion

Effect of different working fluids on capillary pumping flow

In this paper, water and ethanol were used as working fluids to study the capillary pumping flow. The results are shown in fig. 3. It can be seen from fig. 3 that no matter which working fluid is used, the pumping rate is first fast and then slow, and finally tends to balance. The capillary pumping rate (mass-flow) of water is higher than that of ethanol. Because the density of water is greater than that of ethanol, in order to eliminate the influence of density, the mass-flow rate is converted into volume flow rate, and the result is shown in fig. 4. As can be seen from fig. 4, the capillary pumping rates (volume flow) of water and ethanol are generally very similar, mainly determined by the total pore volume of the capillary structure; in the middle stage of capillary pumping flow, the capillary pumping rate (volume flow) of water is slightly larger, which is caused by the difference of the surface tension between the two working fluids (the surface tension of water is greater than that of ethanol), which is also consistent with the previous research results [23, 24].

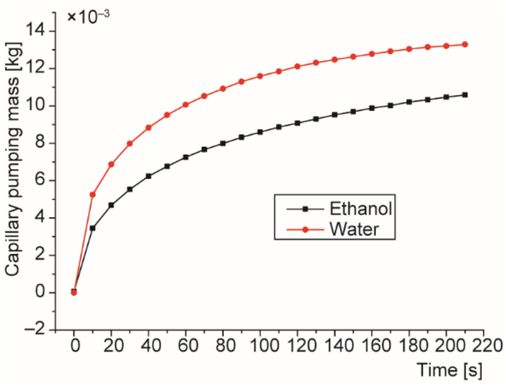

Figure 3. Capillary pumping flow curve

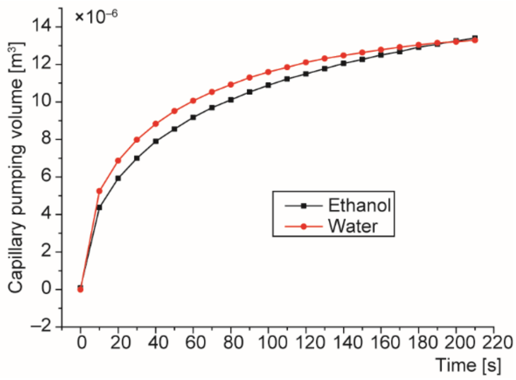

Figure 4. Capillary pumping flow curve (volume change)

Effect of heating power on evaporation-capillary pumping flow

On the basis of the above study of capillary pumping flow, the evaporation-capillary pumping flow behavior under different power is further studied by applying different heating power at the evaporation end. The heating powers of 10, 20, 30, and 40 W are studied, and the heating fluxes are 10616, 15924, 21231, and 26539 W/m^2, respectively. The results are shown in fig. 5. As can be seen from fig. 5, the higher the heating power is, the greater the evaporation-capillary pumping rate is, and the greater the final stable temperature is. And with the increase of power, the time required to reach temperature balance becomes shorter and the temperature fluctuations after reaching temperature equilibrium become larger. This is very consistent with the operation condition of conventional heat pipes.

When the temperature reaches equilibrium, the evaporation-capillary pumping rate reaches equilibrium. The evaporation-capillary pumping rate corresponding to various conditions is shown in fig. 6. It can be seen from fig. 6 that when the heating power is 10, 20, 30, and 40 W, the corresponding evaporation-capillary pumping rate (mass-flow rate) after reaching equilibrium is 0.0246, 0.0594, 0.0936, and 0.1272, respectively. When the cross-section area of the wick is taken into consideration, the corresponding evaporation-capillary pumping rate (mass-flow rate) of these four different heating power are 102.5, 247.5, 390.0, and 530.0 kg/m^{2}s, respectively. Besides, it can be seen from fig. 3 that the capillary pumping rate (mass-flow) is between 210.0 kg/m^{2}s and 1812.5 kg/m^{2}s before adding heat load. Therefore, it can be seen from the above results that when the heat flux is less than 26539 W/m^2, the evaporation-capillary pumping flow rate has not reached the max limit of the capillary wick and working fluid system, but a certain temperature fluctuation has appeared at this case.

Effect of working fluids concentration on evaporation-capillary pumping flow

As we all know, water is one of the best heat pipe working fluids, but it will freeze and expand when the temperature is below 0 °C, which will lead to physical destruction of heat

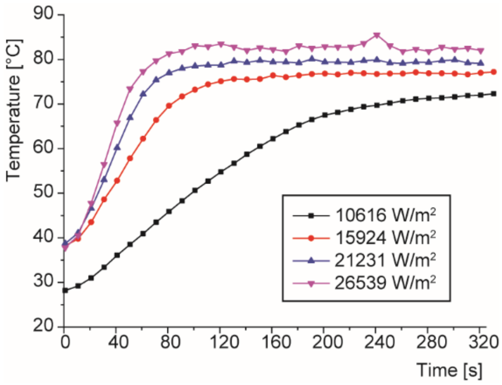

Figure 5. Evaporation-capillary pumping flow temperature curve

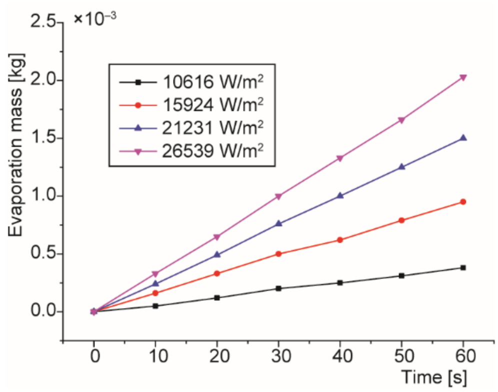

Figure 6. Evaporation rate with different heat load

pipe equipment. This limits the application of water as heat pipe working fluid in aerospace, military industry and other fields, where the equipment often needs to be stored/operated for a long time at –40 °C or even lower temperatures. When ethanol is added in the water with a certain mass fraction, the freezing point of the ethanol aqueous solution can be as low as –40 °C, so that it can meet the environmental adaptability requirements of some special applications, such as aerospace, military industry, *etc*.. In addition to freezing point, the surface tension, viscosity, density and other physical parameters of ethanol aqueous solution also change greatly compared with pure water and pure ethanol, and these parameters also vary with the change of concentration and temperature. Because the boiling point of each component of the ethanol aqueous solution is different, when it is applied in heat pipe, the volatile component first boils, thus causing the change of component concentration gradient at the gas-liquid interface, which leads to the change of surface tension gradient. At the same time, the temperature gradient at the gas-liquid interface also caused the change of the surface tension gradient through thermo-capillary action. Under the influence of the double surface tension gradient, the solution produces a large pumping force between the high temperature region and the low temperature region, which makes the liquid flow spontaneously to the high temperature region, thus enhancing the boiling heat transfer. So, this kind of binary working fluid shows some properties better than pure water on some cases.

In this paper, the evaporation-capillary pumping flow of four different concentrations of ethanol aqueous solution with water content of 0, 25, 50, and 75 wt.%, respectively, has been studied experimentally. The results are shown in fig. 7. Although the boiling point of the aforementioned four different concentrations of ethanol aqueous solution increases with the increase of water content (78.0, 79.8, 81.9, and 85.7 °C, respectively), the corresponding temperature variation process and the final equilibrium temperatures of these four working fluids are basically the same.

After the temperature reaches equilibrium, the evaporation-capillary pumping flow rate (mass-flow) of the aforementioned four different concentrations of ethanol aqueous solution is shown in fig. 8. Among the four different concentrations of working fluids, the evaporation-capillary pumping rate corresponding to anhydrous ethanol was the highest, followed by the ethanol aqueous solution with water content of 75 wt.%. With the decrease of water content, the corresponding evaporation-capillary pumping rate also gradually decreased. The corresponding evaporation-capillary pumping rate (mass-flow) of these four different concentrations of working fluids is 0.057, 0.0486, 0.0336, and 0.0156 kg/s, respectively. When the cross-section area of the wick is taken into consideration, the corresponding evaporation-capillary pumping rate (mass-flow) of these four different concentrations of working fluids are 237.5, 202.5, 140.0, and 65.0 kgm/m^{2}s, respectively.

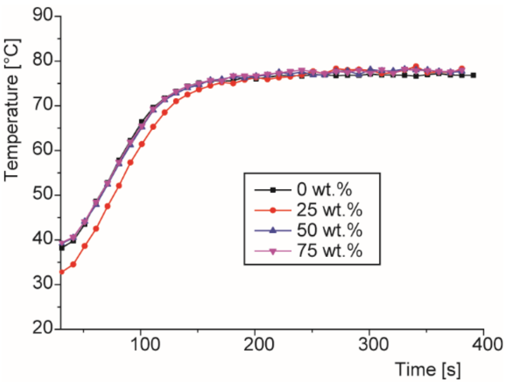

Figure 7. Evaporation-capillary pumping flow temperature curve with different concentration working fluid

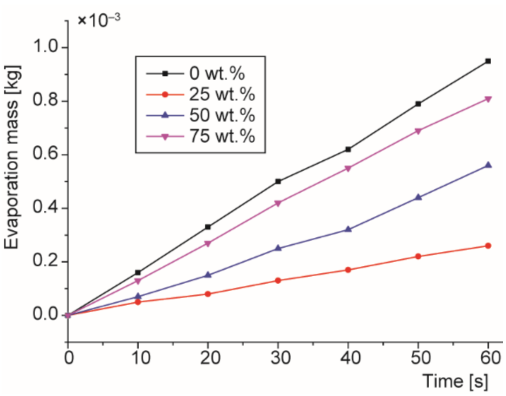

Figure 8. Evaporation rate with different concentration working fluid

The presented studies prove that although the boiling point of the four different concentrations of ethanol aqueous solution increases with the increase of water content, the evaporation-capillary pumping rate gradually decreases. The combination of the two effects results in the similar temperature change process and the final equilibrium temperature of the four working fluids.

Conclusions

In this paper, the evaporation-capillary pumping flow of the capillary wick system was experimentally studied. The capillary wick used in the experiment was fiber felt, and the working fluid contained water, anhydrous ethanol and ethanol aqueous solution with water content of 25, 50, and 75 wt.%, respectively. The main conclusions are listed as follows.

- The capillary pumping rate with ethanol as working fluid is between 210.0 kg/m^{2}s and 1812.5 kg/m^{2}s under the condition of no heat load. When the heating flux is 10616, 15924, 21231, and 26539 W/m^2, the evaporation-capillary pumping rate is 102.5, 247.5, 390.0, and 530.0 kg/m^{2}s respectively.
- The higher the heat load power, the greater the evaporation-capillary pumping rate and the higher the final stable temperature. Also, with the increase of heat load power, the time required to reach temperature balance becomes shorter and the temperature fluctuations after reaching temperature equilibrium become larger. (Obvious temperature fluctuation has occurred when the heat flux is 26539 W/m^2).
- The evaporation capillary pumping rate corresponding to the four different concentrations of ethanol solution in the experiment gradually decreases with the increase of water content (237.5, 202.5, 140.0, and 65.0 kg/m^{2}s, respectively). The temperature change processes and

the final equilibrium temperatures of the four working fluid are basically the same. The difference in boiling point does not have much influence here.

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