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Temperature Oscillation and Frequency of a Capillary Driven Heat Pipe with Reservoir

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Abstract*—Capillary driven heat pipe is a two-phase closed system and the attached reservoir can effectively control the operating temperature. How to restrain the temperature oscillation of evaporator and reservoir is important for the operation of a heat pipe and thermal design. The experiments and analyses are carried out for the influences on the temperature oscillation and frequency of a capillary driven heat pipe. The experimented frequency of temperature oscillation decreases from 0.018 to 0.012 Hz, then to zero with the sub cooling value of return liquid increased. The temperature oscillation is guessed due to the two-phase in the evaporator and reservoir, their oscillation frequency are analyzed. When the reservoir tubing has a smaller damping value, there will be a self-oscillation of the reservoir, the frequency is normally one or two quantities bigger than that of the evaporator inherent. The results show that the temperature oscillations can be effectively restrained by, one is that the structure of evaporator must be designed to make the continuous generated vapor flow out the wick easily during operation, the other is the return liquid ought to be sub cooling enough to the reservoir temperature set value.

***Index Terms*—Capillary driven heat pipe, temperature oscillation, frequency, sub cooling value.**

I. INTRODUCTION

The capillary driven heat pipe as a thermal control system in space techniques has many advantages [1]. When it works, the working fluid is drawn through the wick into the evaporator where it vaporizes. The special wicking material in the evaporators provides the ability to transfer large heat loads over long distance without the need of a pump to circulate the working fluid. The liquid is transported from the condenser to the evaporator via the liquid piping under the capillary pressure developed in the evaporators. Heat is removed from the working fluid in the condenser where the vapor is condensed back to liquid. The unique feature of it, in contrast to conventional heat pipes, is that the wick structure is isolated in the evaporator section permitting greater distances between the condenser and the evaporator.

The reservoir can be applied to a capillary driven heat pipe. The main function of the reservoir is to control the operating temperature of the capillary driven heat pipe by a small temperature controller [2]. If the operating temperature is needed to be increased, the heating system of the reservoir wall is opened, and the inner saturation pressure is increased to drive some liquid in the reservoir flowing into the condenser, then in the condenser, part of the heat transfer surface of phase change is closed. The condensing area decreases and the operating temperature is increased up to a higher level. Otherwise, the cooling system of reservoir wall is opened by temperature controller, the lowing inner saturation pressure decreases to draw part liquid back in the reservoir, then more heat transfer surface of phase change is increased to make the operating temperature of the system reach a lower level.

Despite the theoretical ability of capillary driven heat pipe, in some experiments, the evaporator was deprimed during rapid power reduction, and pressure oscillations during pressure oscillations during steady operation have been observed. For space applications, they may not have been successfully operated in low gravity. The pressure oscillations and radial liquid motions belong to characteristics associated with unstable system operation [3].

Many experimental results of capillary driven heat pipes indicate that some monitoring points behave temperature oscillation, those shows that the corresponding inner unsteady flow of working fluid reaches a certain extent [4]. The unsteady flow usually leads to much lower heat transfer capacity [5]. So, making unsteady characteristics clear is the prerequisite of normal operation to further application of thermal control.

For the evaporator of capillary driven heat pipe, the direction of heat flux is opposite to that of the vapor-out-wick, that is, the evaporator is the inverse evaporator. The heat transfer processes in the evaporator may make vapor-liquid two-phase flow become the pressure oscillation source in the capillary driven heat pipe.

For the reservoir, the design demands that during operation, there must be one-third to two-third vapor-space. That is, there exists two phase working fluid during operation. The reservoir space has compressibility. If the pressure of loop system oscillates, the reservoir functions as a pressure spring and this may exert influences on system operation.

The purpose of studying the operating characteristics is obtaining the factors that can induce unsteady characteristics harmful to system operation, and then, further effective measures can be taken to control and remove its influences. This is of great significance to the design and normal operation of the capillary driven heat pipe.

It is tentative to suppose that if the oscillation frequency of evaporator is the same as or similar to that of the reservoir, the working fluid will flow resonantly to make the evaporator fail.

In this paper, the inherent frequencies of evaporator and reservoir are focused. Firstly, some experimental results of temperature oscillations are shown, the oscillation frequencies are read and discussed under some operating conditions. Then some frequencies of the evaporator and reservoir are obtained by some analytical methods, some influential factors are discussed. Finally, further measures can be recommended to take to remove the unfavorable effects, this has an important significance to normal operation of capillary driven heat pipe.

II. EXPERIMENTAL CAPILLARY DRIVEN HEAT PIPE AND RESULTS

The experimented capillary driven heat pipe, as shown in Fig.1, consists of two cylindrical inverse evaporators, three condensers, one reservoir, valves and connecting tubes. The evaporator is the inverse evaporator. The three parallel condensers adopt the double-hole tube. The double-hole tube has an inner groove surface and this can enlarge the heat transfer area of inner surface. Vapor condenses and flows through one hole and cooling liquid flows through another, the condensing heat transfer across the wall between the two holes to the cooling liquid. Also, the double-hole structure of the condenser is convenient for thermocouple layout.

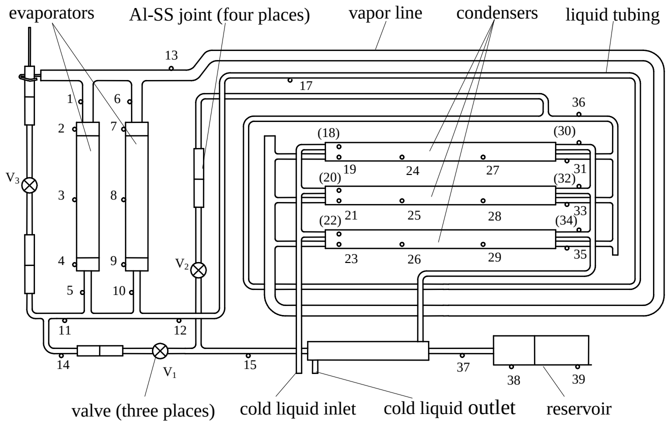

Fig. 1 Set-up schematic of the layout and thermocouples of a capillary driven heat pipe

The tubings of liquid and vapor of the capillary driven heat pipe in Fig.1 are mainly made of pure aluminum. The working fluid is ammonia; its inner pressure is higher at ambient or operating temperatures. For the charging and controlling of ammonia, some valves are necessary, aluminum is not strong and suitable to resist, so the technique of connecting Aluminum and Stainless Steel (Al-SS) is used. Three places need valves; correspondingly six Al-SS joints are used. Valve V_1 and V_2 can control the joint position between the reservoir and the capillary driven heat pipe. While through valve V_3, working fluid can be added or released conveniently. The tubing between the reservoir and V_1, V_2 are made of stainless steel, and its sub cooler is joined to the main loop by SS tube. During operating of capillary driven heat pipe, when the liquid flows out of the condenser, the volume design can make it be sub cooled enough.

All the thermal couples are adjusted before they are installed to the capillary driven heat pipe, the accuracy can reach ±0.15℃. The data-collection unit is used to collect each channel of thermal couple signal. One small intelligent controller is used to control the reservoir temperature.

The temperature measurement points of the capillary driven heat pipe are also shown in Fig.1. T_2 and T_3 indicate the head and middle wall temperature of the first evaporator respectively. T_{18} and T_{19} are separately double-hole tube wall temperatures of cooling liquid and working fluid of the first condenser inlet. T_{31} and T_{36} correspondingly indicate the tube wall temperatures near the condenser outlet. T_{39} is the wall temperature of the reservoir. T_{11} and T_{12} are wall temperatures of the liquid tube near the evaporator inlet. T_{13} indicates the wall temperature of the vapor tube at the evaporator outlet. T_{14} and T_{37} are the wall temperatures at the tube near the sub cooler.

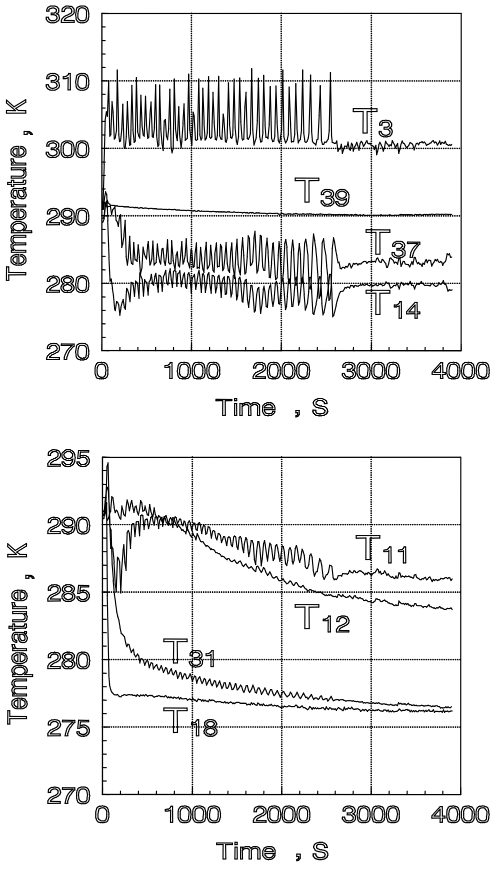

Fig. 2 Effect of subcooling value of return liquid on capillary driven heat pipe operating, $Q_1 = 600W$ and $Q_2 = 150W$

The experimental results are demonstrated in above Fig.2, the effect of sub cooling value of return liquid on the operation of the capillary driven heat pipe is shown at Q_1=600W, Q_2=150W and T_{39}=290K. During the time interval 0~2600 s, the temperatures of T_3, T_{14}, T_{37}, T_{11} and T_{31} all oscillate obviously, and the oscillation frequency decreases from 0.018 to 0.012Hz. During this time period, the temperature level of T_{11}, T_{12} and T_{31} all drop continually. That is, the sub cooling value of return liquid in the capillary driven heat pipe increases continually. From time 2600 s, each monitoring temperature does not oscillate obviously. The experimental results show that with the increment of sub cooling value of return liquid, the stability of system operation in increased.

III. ANALYSIS ON EVAPORATOR

The capillary driven heat pipe is a two-phase closed system; there will always be many small perturbations due to various factors, especially due to the vapor reason in the evaporator. For the higher power operating of inverse evaporator, it can be supposed that there is a vapor film existing at top of the inner evaporator grooves, as shown in Fig.3. Hear the interface between the case top and the wick, the elastic control volume of vapor film is caused by three reasons. Firstly, applying the heat of flow to the evaporator, the liquid evaporates and small part of them stagnates in the film. Secondly, very small part of vapor condenses at the surface of liquid side to provide the sensible heat of sub cooling to make the working fluid be saturated. Thirdly, compression and expansion of the vapor film occurs.

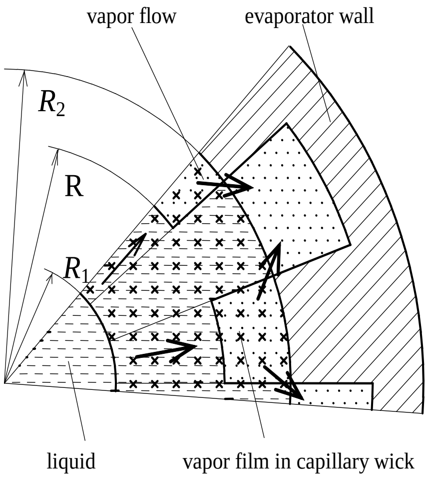

Fig. 3 Vapor film vibration of evaporator

In the previous analysis [6], on the basis of energy and mass balance equation to the equilibrium state of controlling volume, the linearization way of small perturbation is adopted to study the elastic regulation of pressure perturbation in the evaporator, and the frequency of pressure oscillation is obtained as follows.

$$f = \frac{\alpha_c}{2\pi h_{fg}\rho_v}\sqrt{\frac{2\Delta T_0 T_{s0}(k-1)}{R_2^2 - R_0^2}} \qquad (1)$$

Where ΔT_0 is the sub cooling value of the return liquid, k is the adiabatic exponent, T_{s0} is the steady saturation temperature, h_{fg} is the latent heat of working fluid vaporization, ρ_v is the density of the working fluid vapor, α_c is the condensing heat transfer coefficient.

In Fig.4, the experimental frequencies of temperature oscillation are compared with the theoretical values of the corresponding working conditions. The relative errors shown are defined as the percent rate of the absolute values of frequency difference to the arithmetic mean value. The frequency difference is between the experimental frequency of temperature oscillation and the theoretical value. The results indicate that the errors are basically less 20%.

Also shown in Fig.4, when the frequencies are smaller, the errors are bigger, and the biggest is nearly 50%. This may be due to that the other perturbations in the capillary driven heat pipe also exist. When the oscillation frequencies are smaller, those perturbations can moderate the pressure oscillation greater in the evaporator, and it makes the analytical model of the pressure oscillation deviate from real situation more essentially. However, it is shown clearly that the frequencies of the experimental temperature oscillation can presumably reflect those of the relative pressure oscillations qualitatively.

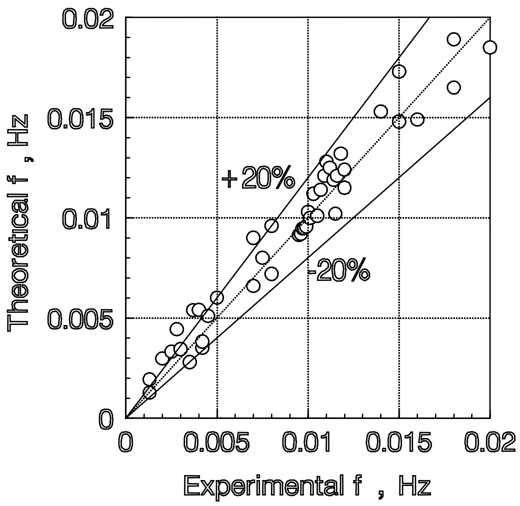

Fig.4 Frequency comparison between those experimental temperature oscillation with those from theoretical values at the same corresponding conditions

IV. ANALYSIS ON RESERVOIR

Under the perturbation outside the reservoir, it is assumed that the vapor in the reservoir proceeds a multi-change process. The multi-change exponent is n, and the subscript "*0*" indicates the parameters of equilibrium state, then,

$$(P_0 + \Delta P)(V_0 + \Delta V)^n = P_0 V_0^n \quad (2)$$

Expanding the above equation using *Taylor* series and omitting the higher minor quantities,

$$-\frac{\Delta V}{\Delta P} = \frac{1}{n}\frac{V_0}{P_0}, \quad -dV = \frac{1}{n}\frac{V_0}{P_0}dP \quad (3)$$

Then, the velocity of the working liquid in the reservoir line is,

$$v_3 = -\frac{1}{A_r}\frac{dV}{dt} = \frac{V_0}{nA_r P_0}\frac{dP}{dt} \quad (4)$$

Neglecting the effect of gravity, the force balance equation of the liquid flow in the reservoir line is,

$$P_l A_r - PA_r - T = \rho_l A_r L_r \frac{dv_3}{dt} \quad (5)$$

In (5), T indicates the wall friction force of the liquid in the reservoir line. If the flow is laminar, then,

$$T = 8\pi\mu L_r v_3 \quad (6)$$

Considering (4), (5), (6), the differential equation of two-order free vibration with damping is obtained, added the boundary conditions,

$$\frac{d^2(P - P_l)}{dt^2} + 2m\frac{d(P - P_l)}{dt} + k^2(P - P_l) = 0 \quad (7)$$

Where, $(P - P_l)\big|_{t=0} = \Delta P_0$, $\frac{d(P - P_l)}{dt}\Big|_{t=0} = \Delta P_{0v}$, $m = \frac{4\pi\mu}{\rho_l A_r}$, $k = \sqrt{\frac{nA_r P_0}{\rho_l L_r V_0}}$

The differential Equation (7) is very similar to the vibration equation of the mass-spring-dashpot system as shown in Fig.5.

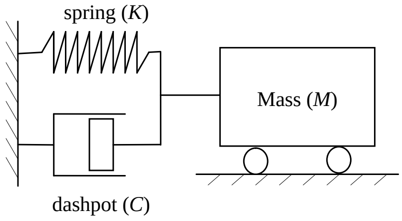

Fig.5 Schematic diagram of mass-spring-dashpot

When the damping value of the reservoir line is small, the vapor in the reservoir functions as pressure spring. The liquid in the reservoir tubing has a certain mass, and when it flows, the tube has a damping function. The general solution of (7) can be divided into three kinds of situation according to the m and k values. Firstly, big damping situation $m>k$. Secondly, critical damping situation, $m=k$. thirdly, small damping situation, $m<k$. For the most operating cases of capillary driven heat pipe, the reservoir and its tubes belong to the third situation, and then the general solution is,

$$P - P_l = B\exp(-mt)\sin(\omega t + \phi) \quad (8)$$

In (8), $B = \sqrt{\Delta P_0^2 + \dfrac{(\Delta P_{0v} + m\Delta P_0)^2}{k^2 - m^2}}$, $\omega = \sqrt{k^2 - m^2}$,

$$\phi = \arctan\frac{\Delta P_0\sqrt{k^2 - m^2}}{\Delta P_{0v} + m\Delta P_0},\ (\Delta P_{0v} + m\Delta P_0 > 0),\ \phi = \arctan\frac{\Delta P_0\sqrt{k^2 - m^2}}{\Delta P_{0v} + m\Delta P_0} + \pi,\ (\Delta P_{0v} + m\Delta P_0 < 0)$$

The period of pressure oscillation is $2\pi/\sqrt{k^2 - m^2}$, but it is different from the simple harmonic vibration. The amplitude of pressure oscillation is $B\exp(-mt)$, and it decreases with time. So, the pressure in reservoir tends to be its set value P_l. The inherent frequency of oscillation is,

$$f = \frac{\omega}{2\pi} \quad (9)$$

The results are shown in Fig. 6. The inherent frequencies of pressure oscillation in the reservoir will change by step regulation with the relative parameter R_r. There three factors to affect the frequency, those are the damping value of reservoir line, the vapor space size in reservoir and the temperature set value of reservoir wall. Among them, the temperature influence is smaller. While the damping value of reservoir line is the most influential factor. With the increment of the radius of reservoir line, the inherent frequency increases in accordance with step case regulation. The vapor space of the reservoir is designed from one third of the whole reservoir space to two third. With the increasing of vapor space in reservoir, the inherent frequency decreases in accordance with step case regulation. Some steps are longer, for one step, the inherent frequencies keep constant within some certain scope.

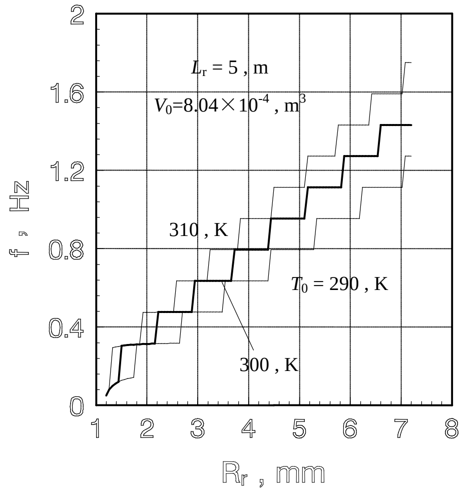

Fig.6 Intrinsic frequencies change with tube radii at smaller damping values with three reservoir temperature values set

Theoretically, if the frequency of pressure oscillation in the reservoir is the near the same as or similar to that of a certain place, then the resonance of liquid occurs. The calculation results indicate that the inherent frequencies of pressure oscillation in reservoir are one or two quantities bigger than the inherent frequencies of the evaporator, so it is less possible to resonate.

It is worth to mention that for the experiments of the capillary driven heat pipe with reservoir, when the wall temperature of evaporator oscillates, the wall temperature of the reservoir may not display its oscillation. This may be because the pressure oscillations in the reservoir are modulated to different extents by those in the evaporator.

The greater modulation to the reservoir can lead to temperature oscillation of reservoir wall, while smaller modulation may not be enough to make the temperature of reservoir wall oscillate.

V. CONCLUSIONS

For the capillary driven heat pipe with reservoir, the results indicate that there are pressure oscillations both in the evaporator and in the reservoir. The calculated inherent frequencies of pressure oscillation in the evaporator are at the quantities of 0.001Hz to 0.02 Hz. The calculated inherent frequencies of pressure oscillation in the reservoir are at the quantities of 0.1Hz to 2 Hz. The inherent frequencies of the reservoir are one or two quantities bigger than those of the evaporator, so, it is less possible to resonate. By the optimization of the evaporator and reservoir, the temperature oscillation can be restrained to some extents. In the evaporator, the structure should make the generated vapor flow out the wick easily. For the reservoir, the damping value of the reservoir tubing of the experimental set-up should be smaller. Importantly, the return liquid ought to be sub cooling enough.

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