The Droplets Condensate Centering in the Vapour Channel of Short Low Temperature Heat Pipes at High Heat Loads

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Abstract. The results of experimental studies of the process of condensate microdroplets centering contained in the moving moist vapour in the vapour channel of short heat pipes (HPs) for large thermal loads are presented. A vapour channel formed by capillary-porous insert in the form of the inner Laval-liked nozzle along the entire length of the HP. In the upper cover forming a condensation surface in the HP, on the diametrical line are installed capacitive sensors, forming three capacitors located at different distances from the longitudinal axis of the vapour channel. With increasing heat load and the boil beginning in the evaporator a large amount of moist vapour in the vapour channel of HP occur the pressure pulsation with frequency of 400-500 Hz and amplitude up to $1 \times 10^4$ Pa. These pulsations affect the moving of the inertial droplets subsystem of the vapour and due to the heterogeneity of the velocity profile around the particle flow in the vapour channel at the diameter of microdroplets occurs transverse force, called the Saffman force and shear microdroplets to the center of vapour channel. Using installed in the top cover capacitors we can record the radial displacement of the condensable microdroplets.

1. Introduction

Intense advancement and practical use of short low-temperature range HPs initiates a thorough study of characteristics of the inner flow inside vapour channel at high heat loads [1-3]. Formation of complex three-dimensional flows of moist vapour in the Laval-liked vapour channel of short low temperature range HPs, presence of a relative motion of phases during movement and condensation cause a generation of fluctuations, an occurrence of additional shearing and normal stresses at the condensation film and vapour border, and an instability of the film thickness. At high thermal power, received by the HPs, and boiling in the grid evaporator, excessive vapour occurs in the convergent part of the nozzle, thus leads to pressure increase up to the value, at which the average temperature of layers of the flat grid evaporator becomes lower than the boiling temperature of working fluid, and boiling in the evaporator stops. Excessive vapour spreads through the divergent part of the vapour channel to the cooled area of the HPs and is partially condensed. Due to the condensation effect, the pressure in the vapour channel decreases and the boiling process in the flat evaporator proceeds. Pressure increase period, vapour wave spreading in the condensation area of the HPs and return expansion wave define the pulsation period in the vapour channel [4-7].

Converging movement of vapour jets in the converging part of the Laval-liked vapour channel lead to a coagulation of primary droplets at the critical section of the vapour channel and increasing the size and weight of drops. The main mechanism of coagulation is thermal movement of microdrops in a pair, the volume and mass of each formed drops by coagulation, respectively, equal to the sum of the volumes and masses of fused droplets, velocity and internal energy of each new drops are deter-
mined from the momentum conservation law and the conditions of an absolute inelasticity in shock at the confluence. The main mechanism of formation of droplet size spectrum in one-component moist vapour in the limited volume of the HPs vapour channel are coagulation and growth of primary droplets at the critical section to the size of 100-500 nm and further condensation increase in the diffuser part of the vapour channel to sub-micron and larger dimensions.

The occurrence of pressure pulsations in the moist vapour flow inside the vapour channel in short HPs is a complex phenomenon having a strong impact on the movement of the inertial drip subsystem of the two-phase vapour.

The thermal power $E$, $W$, entering to the flat grid evaporator of the short HPs, when the evaporator’s temperature $T_{ev}$, K, exceeds the boiling temperature $T_B(p)$, K of the working fluid, is defined according to the next equation:

$$ E = \frac{\pi_{ev} - T_B(p) \rho(p)}{R_{eq}(T)} $$

where $F(z)$ — surface area of the evaporator inside the vapour channel of the HP, m$^2$; $R_{eq}(T)$ — heat resistance of the flat evaporator, K/W/m$^2$.

It is considered that moist vapour is formed of two subsystems: microdrops system and dry vapour system. Rate of vaporization of the moist droplet vapour flow is defined in the standard way:

$$ \dot{M} = G_{mix} = G_{vp} + G_{dr} $$

where $\dot{M}$ — the amount of the dry vapour, generated over the evaporator per unit time, kg/s; $G_{mix}$ — mass flow of moist saturated vapour over the evaporator, kg/s; $G_{vp}$ — mass flow of dry saturated vapour over the evaporator, kg/s; $G_{dr}$ — mass flow of microdrops over the evaporator, kg/s.

For the purpose of simplification of the analytical model construction, the real droplet vapour flow over the evaporator - having microdrops dimensioned by complicated double-humped distribution function, Lee, Reges, Almenas, [8], is reported in terms of a mono-dispersal system of spherical microdrops with arithmetic middling radius $r_{a}$, m, which is frequently used while analyzing two-phase droplet vapour flows:

$$ r_{a} = \frac{1}{n_{dr}} \sum_{i=1}^{n_{dr}} r_{dr} n_{dr} $$

where $r_{a}$ — radius of the i microdrops in the unit volume of the droplet vapour flow over the evaporator, m; $n_{dr}$ — number of microdrops of the working fluid with radius $r_{dr}$ per unit volume of the droplet vapour medium, 1/m$^3$.

Considering the accepted assumption over spherical shape of microdrops, the expression for absolute moisture $\gamma$ of the droplet vapour flow:

$$ \gamma = \frac{M_{dr}}{M_{dr} + M_{vp}} = \left[ 1 + \frac{\rho_{vp}}{\rho_{dr}} \left( \frac{2}{\pi} \frac{1}{r_{dr}^3} - 1 \right) \right]^{-1} $$

where $M_{dr}$ — total mass of microdrops per unit volume of the droplet vapour flow over the evaporator, kg; $M_{vp}$ — vapour mass per unit volume over the evaporator, kg; $\rho_{vp}$ — density of the dry vapour, kg/m$^3$; $\rho_{dr}$ — density of microdrops of the working fluid, kg/m$^3$; $n_{dr}$ — total number of microdrops of all sizes per unit volume over the evaporator, 1/m$^3$.

The density of moisture vapour without taking into account the relative motion phases:

$$ \rho_{vp}^{min} = \frac{\rho_{vp}^{min} \gamma_{vp}}{\gamma_{vp} + \gamma_{dr} \gamma_{vp}} $$

Synergies between consumable and absolute mass concentrations of microdrops or consumable and absolute moisture are defined according to the following relation:

$$ \psi = \frac{U_{dr}}{U_{vp}} : \gamma_{c} = \frac{\gamma_{c}}{(1-\gamma_{c})+\gamma_{c}} = \left[ 1 + \frac{\rho_{vp}}{\rho_{dr}} \left( \frac{2}{\pi} \frac{1}{r_{dr}^3} - 1 \right) \right]^{-1} = \frac{G_{dr}}{G_{mix}} $$
where \( U_{dr} \) — average velocity of the microdrops movement in the vapour flow, m/s; \( U_{vp} \) — average velocity of the vapour phase, m/s. The value \( \gamma \) represents the relation between quantity of the condensed droplet phase and total quantity of the two-phase droplet vapour.

Mass flow rate of microdrops on the evaporator’s surface are considered to be proportional to vaporization velocity and mass flow rate of the vapour:

\[
G_{dr} \approx B \left( \frac{E}{r(T_b)} \right)^a \left( \frac{c_{vp}}{F} \right)^b
\]

where \( a \approx 0.25 \) and \( b \approx 0.17 \) — numerical coefficients; \( B \approx 0.11 \) — coefficient with account for thermophysical properties of the working fluid and structural parameters of the evaporator (porosity, typical dimension of channels and pores); \( r(T_b) \) — specific vaporization heat of the working fluid in the HP, J/kg.

To evaluate the vapour quantity transported from the evaporator to the condensation zone of the HPs, equation (7) is used, where the microdrops subsystem contribution to the generation of overpressure of the two-phase droplet mixture over the evaporator \( P(T_e) \) in the vapour channel is neglected:

\[
G_{mix} = G_{vp} + G_{dr} \approx A \left( \frac{\rho_{vp} U_{vp}}{\eta_{mix}} \right) L
\]

where \( A \) — a numerical coefficient of unity order; \( \eta_{mix} \) — coefficient of dynamic viscosity of the moist vapour with microdrops, Pa·s; \( L \) — the length of the vapour channel of the HPs, m.

The Reynolds number of the streamlined ferry drops in the vapour channel can be written in the following form:

\[
Re_{dr} = \frac{|U_{vp} - U_{dr}| r_a}{\nu_{vp}}
\]

where \( \nu_{vp} \) is the kinematic viscosity of the vapour; \( r_a \) - the arithmetic mean radius of the drops; \( U_{vp} \) and \( U_{dr} \) are the velocities of the vapour and drops along the longitudinal axis in the z-direction.

For the motion analysis of the drops in HPs vapour channel, we introduce the following notation. Let the longitudinal component of two-phase vapour velocity \( U_{vp} \) (projection on the longitudinal axis Oz) varies along the transverse axis Oy. Then vapour velocity as the carrier medium on the opposite sides of the moving also along the axis Oz drops will be different. According to the Bernoulli equation, the static pressure in the vapour flow will be greater where velocity less, in addition energy loss in the first approximation can be neglected. The pressures difference leads to occurrence of the transverse shear force acting on microdroplets, and which is called the Saffman force. The expression for shear Saffman force \( f_{sa} \) on a little solid sphere at small values Reynolds number to be [9-10]:

\[
f_{sa} = 6.46 \rho_{vp} \sqrt{\nu_{vp} r_a^2 (U_{vp} - U_{dr})} \left| \frac{dU_{vp}}{dy} \right| s_{mix} \left( \frac{dU_{vp}}{dy} \right).
\]

where \( \rho_{vp} \) is the density of the vapour; \( r_a \) — the arithmetic mean radius of the drops; \( dU_{vp}/dy \) is the shear rate of the mean vapour flow. This model describes plane-parallel shear flow, the direction of shear is perpendicular to the direction of flow. It is noted that the shear lift force is proportional to the square root of the shear rate. In deriving equation 10, it was assumed that:

\[
Re_{dr} = \frac{|U_{vp} - U_{dr}| r_a}{\nu_{vp}} \ll 1 ; \quad Re_{C} = \frac{|dU_{vp}|}{\nu_{vp}} \ll 1 ; \quad Re_{fl} = \frac{\Omega r_a^2}{\nu_{vp}} \ll 1 ; \quad Re_{sa} \ll \sqrt{Re_{C}}.
\]

where \( \Omega \) is the rotational speed of the drops and \( Re_{C} \) is associated with noncentral drops interactions.

On the results of the work [11], the expression for Saffman force for the liquid drops can be obtained by considering the vapour and the working fluid viscosity as follows:

\[
f_{sa} = C \left( \frac{\nu_{vp}}{\nu_{dr}} \right) \rho_{vp} \sqrt{\nu_{vp} r_a^2 (U_{vp} - U_{dr})} \left| \frac{dU_{vp}}{dy} \right| s_{mix} \left( \frac{dU_{vp}}{dy} \right).
\]

where \( \mu_{vp} \) and \( \mu_{dr} \) are the dynamic viscosities of the vapour and working fluid, respectively. \( C \) — a numerical coefficient of unity order. The effect of inertial focusing of solid and liquid particulates and
droplets under the Saffman force in stationary and oscillating shear flows was noted earlier in several papers [12-15]. In [16] theoretically and experimentally demonstrated the focusing effect of submicron aerosol particles, moving in tapering capillary of diameter $10^{-3}$ m with a speed of 100 m/s. Analysis of real two-phase vapour flow with a complex type of heterogeneity around the inertial condensate microdroplets in the vapour channels of heat and mass transfer devices, including HPs, is a much more difficult task and currently cannot be adequately completed with obtaining analytical expressions for the shear Saffman force. Upon the occurrence of longitudinal pressure pulsations with a frequency of 400-500 Hz in Laval-liked vapour channel of short HPs when moving moist vapour starts coagulation of droplets at the critical section and further condensation growth in the diffuser part of the HPs vapour channel. This leads to the inertial drops lag relative to the flowing vapour and the occurrence of Saffman transverse shear forces.

2. Materials and method

To measure the droplets condensate centering, short HPs were used whose vapour channel was made in the form of a Laval-liked nozzle [1-4]. Figure 1 shows the HP circuit with flat evaporator, convergent-divergent vapour channel, turbulator and capacitive condensation sensors.

Figure 1. layout of HPs equipped with capacitance sensors: 1 – flat upper lid with a smooth surface; 2 – cylinder body of HP; 3 – cone-shaped turbulence agitator; 4 – capillary-porous insert defining the vapour channel’s form; 5 – flat bottom lid; 6 – injector channels; 7 – capillary-porous evaporator; 8, 9 – three capacitance sensors, two of which are intended for a condensate film thickness pulsations measurement, while the third one has a sensing element of CT3-19 thermistor mounted on its electrodes to measure the film temperature. All the details of the manufacture of the HPs is given in [7,17].

The diethyl ether $\text{C}_4\text{H}_{10}\text{O}$ is selected as the main working fluid, which has the boiling temperature under the atmospheric pressure of $T_B = 308.55$K (35.4°C), freezing temperature $T_F = 156.95$K (−116.2°C) and critical parameters $T_C = 466.55$K (193.4°C), $P_C = 3.61$MPa. The volume of the working fluid in the capillary-porous insert and the evaporator in such a short HPs is not less than 18 cm$^3$. For the experimental investigation of radial shear in the condensate microdroplets in the moving moist vapour in the Laval-liked vapour channel of short HPs in the occurrence of longitudinal pulsations, on the condensation surface were installed measuring system. Three capacitive sensors installed in the top lid of the HPs at the same distance from the center, as shown in Figure 2, the first two of them on a diametrical line, and a third with microtermistor 8 on the perpendicular line.

Figure 2. Diagram of the setup of three capacitance sensors in the HPs top lid A-A: 1 – HPs top lid with a smooth surface made of stainless steel 1X18H9T; 2 – the actual capacitance sensors that are laser welded to the lid 1 along their perimeter, herewith the polished gauging surface of sensors is flush-lined with the lid’s inner surface; 3 – glass insulators (glass-to-metal junctions); 4 – measuring electrodes of the sensors; 5 – fastening nut filling node HPs, which is welded to the inner surface of the lid 1; 6 - locking screw HPs filling node; 7 - the grounding electrode of the capacitance sensors; 8 - micro-thermistor CT3-19.
The outer electrodes of the two diametrically installed sensors constitute the external capacitor $C_1$ with a capacity of $C_1 = 0.21\pm0.005$ pF; the internal electrodes of the two diametrically installed sensors constitute the inner capacitor $C_3$ with the capacitance $C_3 = 0.26\pm0.005$ pF; one of the diametrically installed sensors as a whole represents the average capacitor $C_2$ with a capacitance $C_2 = 1.55\pm0.005$ pF. The radii of installing the electrodes of capacitors $C_1 : R_1 = 6$ mm, $C_2 : R_2 = 5$ mm and $C_3 : R_3 = 4$ mm from the longitudinal axis of the HPs.

3. Measurement of film thickness

To perform measurements of the radial pulsating of the film thickness due to droplets condensate centering inside the HPs vapour channel we used the method of detection of electrical capacity $\Delta C$ changes of open capacitive sensor as the thickness of the liquid condensate on its surface changes. Variating capacity of the open capacitance sensor, in the event of film condensation of the vapour inside of the main HP, is included in the oscillating counter of the measuring generator $\sim 33$ MHz of the capacitance transducer [7,17], and changes its frequency. Identical capacitive sensor of the reference HP, filled with noncondensable air, is included in the oscillating counter of the reference generator of the capacitance transducer. The main HP, called measuring, is filled with diethyl ether and the reference one, which is completely identical to the main HP, is filled with dehumidified air with dew point temperature lower than 233.15K ($-40^\circ$C).

Switchboards, connecting the installed in the measuring HP the capacitors $C_1, C_2, C_3$ and installed in the reference HP capacitors $C_{10}, C_{20}, C_{30}$ are made on the basis of chip ADG1411 and controlled by a computer. The duration of the measurement of difference frequencies for each pair of capacitors $C_1 — C_{10}, C_2 — C_{20}$ and $C_3 — C_{30}$ at least 7-10 min to achieve a steady state. The resulting oscillogram reflect the steady state flow of the moist vapour inside the HPs vapour channel. All the details of the measurement procedures is given in [7, 17].

Figure 3 shows oscillograms of the appeared radial pulsations with frequency $f_{\text{radial}} = 85 \pm 6$ Hz of the condensate film thickness on the capacitive sensors $C_1, C_2, C_3$ surfaces at longitudinal excitatory pressure pulsation $f_R = (473\pm5)$ Hz.

Figure 3. Oscillograms of the appeared radial pulsations with frequency $f_{\text{radial}} = 85 \pm 6$ Hz of the film thickness of diethyl ether on the surface of the capacitors $C_1, C_2, C_3$ at longitudinal excitatory pressure pulsation $f_R = (473\pm5)$ Hz.

The amplitude of the pulsation film thickness systematically increases from the external to the internal capacitor $C_1$ to the capacitor $C_3$, but the increase is small and within the error of measurement of the thickness of the capacitive transducer $\pm 2\cdot10^{-3}$ mm. This means a decrease in the concentration of inertial microdroplets in a condensing moist vapour near the HPs side walls and the increase in the
microdroplets concentration in the axial zone of the HPs vapour channel. Overheating of the HPs evaporators relative to the boiling point of diethyl ether \( \delta T = Tev - TB = 15.03 \text{ K} \), the frequency of the longitudinal pressure pulsations \( f_P = (473 \pm 5) \text{ Hz} \). By increasing the thermal power \( E \), entering to the HPs evaporators, the frequency of the radial pulsations of the condensate film thickness increases and reaches the value of \( 96 \pm 6 \text{ Hz} \), moreover, the ripple amplitude also increases up to \( 1.25 \times 10^{-3} \text{ mm} \), \( 1.38 \times 10^{-3} \text{ mm} \) and \( 1.52 \times 10^{-3} \text{ mm} \), see figure 3. In this case the overheating of the HPs evaporators relative to the boiling point of diethyl ether is \( \delta T = Tev - TB = 20.1 \text{ K} \), the frequency of the pressure pulsations (longitudinal excitation pulsations) \( f_P = (502 \pm 5) \text{ Hz} \).

The ratio of the frequency of radial pulsations \( f_{\text{radial}} \) of the film thickness on the HPs condensation surface to the pressure pulsation frequency \( f_P \) in the vapour channel (longitudinal excitation pulsations) appears to be proportional to the vapour moisture coefficient [18-19] above the evaporator with boiling working fluid \( f_{\text{radial}} / f_P \sim (85-96) \text{Hz} / (400-500) \text{Hz} \sim 0.17-0.24 \).

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