Numerical Simulation of Pulsation Flow in the Vapour Channel of Short Low Temperature Heat Pipes at High Heat Loads

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Abstract. The results of the numerical simulation of pulsations in the Laval-liked vapour channel of short low-temperature range heat pipes (HPs) are presented. The numerical results confirmed the experimentally obtained increase of the frequency of pulsations in the vapour channel of short HPs with increasing overheat of the porous evaporator relative to the boiling point of the working fluid. The occurrence of pressure pulsations inside the vapour channel in a short HPs is a complex phenomenon associated with the boiling beginning in the capillary-porous evaporator at high heat loads, and appearance the excess amount of vapour above it, leading to the increase in pressure $P$ to a value at which the boiling point $T_B$ of the working fluid becomes higher than the evaporator temperature $T_{ev}$. Vapour clot spreads through the vapour channel and condense, and then a rarefaction wave return from condenser in the evaporator, the boiling in which is resumed and the next cycle of the pulsations is repeated. Numerical simulation was performed using finite element method implemented in the commercial program ANSYS Multiphysics 14.5 in the two-dimensional setting of axis symmetric moist vapour flow with third kind boundary conditions.

1. Introduction

Intensive development and implementation of short low-temperature range HPs with increased heat transfer characteristics raise problems of detailed research of internal flow processes and condensation in vapour channels. In the case when the vapour channel is made in the form of the Laval-liked nozzle, and surrounded by the capillary-porous insert along the full length of the short HPs, leads to increase the velocity and frequency of pulsations of moist vapor flow [1-3], and heat transfer coefficient in compared with the HPs with standard cylindrical vapour channel and equal overall dimensions. Occurrence of pulsations of the moist vapour flows inside the vapour channel made in the Laval-liked form of the nozzle in short HPs is a complex phenomenon, connected with the beginning of the boiling process in the capillary-porous evaporator and excess of vapour over it. Pulsation research is discussed in details in [4-5]. The present paper comprises the results of numerical simulation of the moist vapour flow in the vapour channel, similar to the Laval nozzle, with the experimental results of measuring the frequency of the pulsations, which were obtained in the following way. Specially designed HPs for measuring the frequency of the pulsations is shown in figure 1.

2. Materials and methods

The HP’s length is 100 mm, its diameter is 20 mm, the max. diameter of the vapour nozzle in the convergent and divergent regions is 16 mm, the critical nozzle diameter is 4 mm, the length of the nozzle convergent region is 13 mm, the total angle of the convergent region is 41°, the length of the nozzle divergent region is 81 mm, the total angle of the divergent region is 8.5°, and the length of the cylindrical region in the nozzle throat section is 1 mm.
Porosity of the insert and evaporator is 72% and together they form one hydraulic system designed to deliver the working fluid to the evaporator when the HP’s is operating. Diethyl ether C₄H₁₀O is used as a working fluid, which has boiling temperature under atmospheric pressure of Tₜ₅₅ =308.55K (35.4°C), and dielectric constant ε =4.3 (298K).

The top cover 1 with installed sensors as shown in figure 2:

Condensation zones of the HP’s with insulated thermocouples are set into the vortex continuous-flow calorimeter, shown in figure 3, with stabilized water flow. The HP’s evaporator, also equipped with thermocouples, is heated using a resistance heater, and the temperature is maintained at δT₉₅₅ higher than the diethyl ether boiling temperature of Tₜ₅₅ = 308.55K (35.4°C) under atmospheric pressure. The heater temperature is stabilized and HP’s evaporators overheat value is set in the range of δT = T−Tₜ₅₅ = 0÷20K.
3. Experimental results

Pulsation characteristics of HPs measured in the following way. Overheating of the evaporator $\delta T$ relatively of the boiling point of diethyl ether at atmospheric pressure $\delta T = T - T_B$ with the aid of resistive heater 6 and high-precision temperature controller increased in discrete steps on size of 1K. Electrical pulses of 100 kHz and amplitude 5V are applied to the electrodes of the capacitive sensors 10, figure 3. The modulation rate is measured via a gain and filtering circuit 13, whereupon the signal goes to measuring input of digital oscilloscope 14. The oscilloscope is connected to the computer 15 via USB-interface. Started from specific overheating $\delta T_S = (T - T_B)$ of HP’s evaporator, electrical pulses become modulated. The modulation rate is measured using gain and filtering circuit 13, digital oscilloscope 14 and computer 15. Measuring inaccuracy of modulation rate does not exceed 3-5 Hz.

Figure 3. 1-vortical continuous-flow calorimeter; 2- HP’s bolting flange; 3-glass cover; 4-cover fastening; 5-heat pipes; 6-resistance heater; 7-outlet stub tube for water flow; 8-inlet stub tube for water flow; 9-silicone sealant of the sensing wire; 10-capacitive sensors for measuring the thickness of the condensed layer of the working fluid; 11-small printed circuit board with the measuring (first HP) and reference (second additional HP) generators; 12-external digital generator; 13- phase detector; 14- low-frequency filter; 15—computer; 16—commutation switch; 17—digital voltmeter; 18—container for constant water head; 19—source of air bubble; 20—water flow meter; 21—vacuum-jacketed container for zero point temperature 273.15 K (0°C).

Figure 4. Oscillograms of increase of modulation frequency depending on thermal load on HP.
Initial pulsed flows occur in HP’s with the nozzle, similar to the Laval nozzle, in event of overheating of the evaporator $\delta T$=9K, frequency (modulation frequency of electromagnetic pulsation) is $f_1 \sim$386 Hz, lower oscillogram; $\delta T$=20K, $f_1 \sim$502Hz, upper oscillogram. The oscillograms without pulsations in the vapour channel of HP does not have a low-frequency (400 -500 Hz) modulating features.

The insensitivity zone of the capacity sensors in the cylindrical channel, defined by the initial convective nature of the vapour flow, is greater than in the vapour channel of Laval-liked HPs. Dynamic range of pulsations in the Laval-liked HPs vapour channel, is a little greater in frequency, in comparison to dynamic range of pulsations 406 Hz – 474 Hz in cylindrical vapour channel, and equals to 386 Hz – 502 Hz.

Table 1 shows pulsation rate values (modulation rate), obtained in the HP’s with the vapour channel in the Laval-liked form, $f_1$, Hz, and in the HP’s with standard cylindrical vapor channel, $f_2$, Hz, depending on overheating $\delta T$, K, of evaporators.

| Overheating of the evaporator, $\delta T$, K | Pulsation frequency $f_1$, Hz | Pulsation frequency $f_2$, Hz |
|------------------------------------------|-------------------------------|-------------------------------|
| 9.05                                     | 386±5                         | -                             |
| 10.1                                     | 396±5                         | -                             |
| 11.03                                    | 426±5                         | 406±5                         |
| 12.15                                    | 450±5                         | 420±5                         |
| 13.0                                     | 456±5                         | 437±5                         |
| 14.07                                    | 474±5                         | 440±5                         |
| 15.03                                    | 474±5                         | 454±5                         |
| 16.0                                     | 478±5                         | 453±5                         |
| 17.1                                     | 490±5                         | 460±5                         |
| 18.06                                    | 491±5                         | 472±5                         |
| 19.02                                    | 495±5                         | 473±5                         |
| 20.12                                    | 502±5                         | 474±5                         |

Both HPs have equal outer diameters 20 mm and equal sectional areas of capillary-porous inserts near the condensation region. As the overheating of the evaporator $\delta T$= 20K increases, pulsation frequency in the Laval-liked nozzle goes up to $f_1 \sim$ 502 Hz, derivative of the relationship between pulsation frequency and temperature is approximately 10.5 Hz/K.

While investigating HP’s with standard cylindrical vapour channel and equal outer diameter 20 mm, length 100 mm and thickness of the evaporator and capillary-porous insert 3 mm, initial pulsed flows occur in event of overheating of the evaporator $\delta T$=11K, frequency (modulation frequency of electromagnetic pulsation) $f_2 \sim$406 Hz. As the overheating of the evaporator $\delta T$=20K increases, pulsation frequency in the cylindrical vapour channel goes up to 474 Hz, derivative of the relationship between pulsation frequency and temperature is approximately 7.5 Hz/K.

4. Numerical results

Numerical simulations of the vortex pulsation flows inside a vapour channel of the Laval-liked HP’s have been performed in finite element modeling in CFD 10.0 code Fluent 6.3.26 under 2D, double precision axisymmetric conditions. Navier-Stokes equations with measured boundary conditions were solved, i.e. using fixed temperature values of heat source and heat outlet. The model was studied as a longitudinal section along the axes of the two injector channels, which helps to preserve all the specific features of whirling instability under the conditions of continuous circulation motion of the working fluid during liquid and vapour phases. In the construction of the design model about 457233 finite elements were used, with increased meshing at injection capillary channels sections, nozzle throat section and turbulence element. The model size is a compromise between available computer resources and computational investigation error.

It is clearly visible transition from stationary convective flow regime in the vapour channel to pulsatile flow regime, figure 5. At high temperature overheating, received by the HP’s, 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 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 HP’s 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 HP’s and return expansion wave define the pulsation period in the vapour channel.

Figure 5. The results of flow simulation of compressible supersaturated vapour environment inside a vapour channel. The figure presents test values of the vapour flow pulsation in the vapour channel in the Laval–liked form of a HP’s, as overheating of HP’s evaporator is increased in reference to boiling temperature of diethyl ether 308.55K by 2K; 5K; 8K; and 13K, from left to the right.

5. Validation of numerical scheme

Evident conversion from convection mode to convection-vortex mode and then to pulsation mode of the vapour flow inside of the HP’s, is recorded at evaporator overheating value $\delta T \approx 9K$.

Maximum value of velocity of diethyl ether moist vapour flow, obtained using calculation method in the throat section of the vapour channel using by the colour indication of the software CFD Design 10.0, reaches 100 -110 m/s when pulsation occurs. This fact gives the opportunity to evaluate the Reynolds number $Re$ of the vapour channel during pulsation, which is defined by the formula:

$$Re = \frac{\rho_{mix} u_{vp} D_c}{\eta_{mix}}.$$  

We substitute moist vapour density (vapour and drops) $[6-7]$ $\rho_{mix} \approx 3 \text{ kg/m}^3$, dynamic coefficient of viscosity of the moist vapour $\eta_{mix} \approx 8 \cdot 10^{-6} \text{ Pa s}$; maximum value of the vapour flow velocity (colour indication) near the throat section of the vapour channel $u_{vp} \sim (100 -110) \text{ m/s}$; critical diameter of the vapour channel $D_c \sim 4 \cdot 10^{-3} \text{ m}$, and obtain the value $Re \sim (1.5-1.65) \cdot 10^5$, the Prandtl number $Pr = 0.77$.

Duration of the pulsation period inside the divergent part of the HP’s vapour channel can be estimated using the formula:

$$\Delta \tau_0 \sim \frac{\Delta L}{u_{vp}}.$$  

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Then substitute values of distance between pulsation crests (maximums) obtained in figure 5 \( \Delta l \sim (2-3) \cdot 10^{-2} \) m, moist vapour flow velocity in divergent part of the vapour channel obtained using colour indication by the software CFD Design 10.0 \( u_{vp} \sim (20 – 30) \) m/s, and you will obtain numerical value of duration of the pulsation \( \Delta t_0 \sim (0.75 – 1.5) \cdot 10^{-3} \) s, close to experimental values.

![Figure 6](image)

**Figure 6.** The results of calculation of the axial flow velocity module in successive steps through time. When boiling in the capillary-porous insert and the initial velocity of the flow of the two-phase vapour directly over the surface of the evaporator 0.5-1 m/s in the throat section of the nozzle the axial flow velocity reaches 5 m/s and more. Five steps of calculation of the moist vapour flow velocity, from up to down. Obvious occurrence of pulsations, pulsation frequency rises, what consistent with the experimental results [4-5].

**References**

[1] Seryakov A V 2013 *Int. J. Eng. Res. & Tech* Velocity measurements in the vapour channel of low temperature range heat pipes 2 1595

[2] Seryakov A V, Konkin A V and Belousov V K 2011 *Proc. 8 Minsk Int. Sem. Heat Pipes, Heat Pumps, Refr., Power Sour.* The intensification of heat-transfer characteristic of heat pipes (Minsk, Belarus) 2 59

[3] Seryakov A V, Konkin A V and Belousov V K 2012 *Russian Vestnik SibSAU* Application of jet vapour nozzle in heat pipes of medium temperature range 1(41) 142

[4] Seryakov A V 2014 *Int. J. Heat Mass Tran. Theory Appl.* Pulsation flow in the vapour channel of short low temperature range heat pipes 2 40

[5] Seryakov A V 2016 *Russian J. Appl. Mech. Tech. Phys.* Characteristics of low temperature short heat pipes with a nozzle-shaped vapour channel 57 69

[6] *Tables of physical values* 1976 Guide under the editorship of Kikoin I.K., the member of Academy of Science (Moscow: Atomizdat) 1008p

[7] Vargaftic N 1963 *Spravochnick po teplophizicheskim svoistvam gasov i zhidkostey* (Moscow: Publishing house of Physico-Mathematical literature) 708p