Extreme vibration increase of the heat transfer coefficient of short heat pipes

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Abstract. The results of the heat transfer coefficient studies of the short linear heat pipes (HP's) with a formed by the capillary-porous insert vapour channel in the Laval nozzle-liked form under high thermal loads and external vibrations are presented. Under high heat power loads the vaporization process in the capillary-porous evaporator and vapour propagation in the vapour channel acquires a pulsating character with a frequency of 400-500 Hz and the amplitude up to 10³ Pa. For the first time it was experimentally detected that under external longitudinal vibration, attached to the HP’s body with an limited amplitude of 0.15 mm and frequency equal to the frequency of arising internal vapour pulsations, the HP’s heat transfer coefficient shows the resonance nature and increases by up to 20%. The increase in the heat transfer coefficient is due to the boiling process intensification in the grid HP’s capillary-porous evaporator.

1. Introduction
The problem of the heat transfer coefficient increasing of the short linear HP’s is an important technological task in the development of the spacecraft with strict takeoff mass regulation. The use of the short linear HP’s is justified in the case of constructive impossibility of the closed loop HP’s placing, as well as to improve the long-term reliability and stability of passive cooling systems without any distributed supply and discharge lines of loop HP [1-3].

It is well-known that in the linear HP under high heat power loads (high temperature head at the evaporator) in the vapour channel arise pressure and velocity pulsations [4-5]. These pulsating phenomena lead to the complication of vapour flows in the Laval-liked vapour channel and to the intensification of evaporation and condensation and increase the heat transfer coefficient in such HP [5].

The problem of the external vibrations influence on the heat transfer systems, especially on the short linear HP, is of great interest in terms of controlling inhomogeneous hydrodynamic flows of two-phase working fluid in the capillary-porous structure, and in the analysis of vapour flows in the HP vapour channel.

Alaei et al. [6-7] published the results of studies of the low-frequency longitudinal vibrations influence with amplitude up to 2 mm on the heat transfer parameters of vertically oriented HP. Authors measured the HP’s thermal resistance under various heat power loads, the coefficients of the working fluid filling and the vibration frequencies, they recorded a decrease in the thermal resistance of HP’s up to 0.064 K/W at the external longitudinal vibrations frequency of 30 Hz.

Chen et al. [8] investigated the horizontal vibrations influence and variable condensation temperature on the heat transfer coefficient in a cylindrical copper HP with longitudinal risks on the inner surface for the working fluid return to the evaporator. Longitudinal horizontal vibrations with frequencies of 3-9 Hz and amplitudes of 2-25 mm, which caused vibration acceleration within the range of (0.1-1) g, were applied in the HP’s experimental study. It is shown that when longitudinal vibrations are applied to a horizontally oriented HP, the heat transfer coefficient increases in the direct ratio to the vibrational energy in the interval up to the value of 500 mm² Hz². When this limit is exceeded, the simple proportional relationship between the vibration energy and the HP’s heat transfer coefficient is broken, the coefficient value sharply reduced. In addition, the influence of the HP condensation surface temperature on the heat transfer coefficient value is significantly greater, than the influence of vibrations.
In Asia'sa, Shusser'a et al. [9] detailed study of the heat transfer coefficient of linear HP's at high axial accelerations up to 12g very interesting results were obtained. Under such mechanical loads, the HP's accelerating effect exceeds the capillary pressure developed by the porous system of the HP's insert, and a result of such accelerating is the drainage of the evaporator, when the external acceleration acts opposite to the working fluid flow direction through the insert. The effect of acceleration on the working fluid flow direction is complex phenomenon. However, already at the acceleration of 6 g, the HP's instability operation begins, manifested in the occurrence and development of high-amplitude temperatures oscillations of the evaporator and heater, associated with the onset of fragmented film boiling, drying and overheating of the evaporator due to insufficient working fluid flow. Instability increases at high accelerations, the average heater and evaporator temperatures systematically increase along with the growth of temperature oscillations. After switching off the mechanical accelerations, the HP's normal functioning is restored.

In the short linear HP's with a Laval-liked vapour channel and with large amount of the working fluid in the insert (wick) pores and at high temperature head on the evaporator and the internal pulsations arisen, the influence of longitudinal external vibrations is particularly significant. To study this effect of longitudinal external vibrations on the HP's heat transfer coefficient, previously manufactured short stainless steel HP's were used, the vapour channel in which is formed along the entire length of the heat transfer by means of a grid capillary-porous insert connected to a grid flat evaporator. The internal vapour channel is made in the form of Laval-like nozzle [4-5], measuring capacitive sensors [10] are flush mounted with the flat top cover, and for the actual heat transfer coefficient measurements, stationary and vibrating calorimetric measuring stands designed and manufactured, a brief description of which is given below.

2. Experimental setup
A schematic diagram of the experimental test setup is shown in Figure 1. In this study was applied stainless steel HP's with shaped vapour channel in the converging-diverging Laval-liked nozzle form with nonlinear varying diameter and with flat top and bottom covers.

Figure 1. HP's diagram: 1 – top cover; 2 – cylinder body of the HP’s; 3 – cone-shaped turbulator; 4 – capillary-porous insert; 5 – bottom cover; 6 – capillary injector channels, 7– bottom flat capillary-porous insert-evaporator. There are capacitance sensors 8, 9, installed inside the top cover [4 – 5], one of which is intended for a condensate film thickness measurement, while another one has a sensing element of CT3-19 thermistor mounted on its electrodes to measure the film temperature.

The diethyl ether C₄H₁₀O is used as the working fluid, which has the boiling temperature under the atmospheric pressure of Tᵦ =308.65 K (35.5°C), freezing temperature Tᵦ = 156.95 K (~116.2°C) and critical parameters Tₑ = 466.55K (193.4°C), Pₑ =3.61MPa. The diethyl ether mass in the pore system of a metal mesh capillary-porous insert and evaporator is not less than 12.28·10⁻³kg. The developed sensors enables us to perform measurements of local characteristics of the film thickness and temperature, without making any major disturbances in the flow. The HP’s dimensions are chosen in such a way that it is possible to establish capacitive sensors [10] for film thickness and temperature measuring.
All heat transfer coefficient measurements in stationary mode were carried out using two HP’s, measuring one and reference one [10]. 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 at a pressure of 1 bar with dew point temperature lower than 233.15K (-40°C). The heat transfer coefficient $K_{HP2}$ of the second HP does not exceed 0.15% from the first one (measuring one) $K_{HP1}$ and is not taken into account. The second HP, completely identical to the first one, performing the reference function in measurements with the help of high-frequency generators the condensate film thickness in the first HP.

The pulsation characteristics of HP’s in stationary mode have been investigated previously [4–5] and the experimental values of the pulsation frequencies are shown in table 1. Measuring inaccuracy does not exceed 3-5 Hz.

| Overheating of the evaporator, $\delta T_e$, K | Pulsation frequency $f_{puls}$, Hz |
|---------------------------------------------|---------------------------------|
| 9.05                                        | 386±5                           |
| 10.1                                        | 396±5                           |
| 11.03                                       | 426±5                           |
| 12.15                                       | 450±5                           |
| 13.0                                        | 456±5                           |
| 14.07                                       | 474±5                           |
| 15.03                                       | 474±5                           |
| 16.0                                        | 478±5                           |
| 17.1                                        | 490±5                           |
| 18.06                                       | 491±5                           |
| 19.02                                       | 495±5                           |
| 20.12                                       | 502±5                           |

3. Vibration heat transfer coefficient measurements

To measure the HP’s heat transfer coefficient with external longitudinal vibration exposure, an experimental stand was created, including the previous measuring HP’s and a specially designed flow microcalorimeter. The whole experimental stand, including a flat resistive heater with polished heating surfaces, HP and a vortex flow microcalorimeter 1, shown in Figure 2, was installed on a movable paper diffuser of a high power sound electrodynamics loudspeaker type 100 GDN-3-8, the operating frequency range of which lies within 31.5 Hz–1000 Hz. The average vibration diffuser amplitude at low frequencies (up to 50 Hz) in the free state reaches $\xi = 7$ mm, and decreases sharply with an increase in frequency above 300 Hz. When HP together with a water-filled flow microcalorimeter and a resistive heater installing, the vibration amplitude at a frequency of 500 Hz does not exceed $\xi_0 \leq 0.1–0.15$ mm, $\xi = \xi_0 \sin(2\pi f_{vibr})$. The rate of HP movement in the vertical direction at such vibrations is equal to $\xi = f_{vibr} \xi_0 \cos(2\pi f_{vibr}) = 0.15$ mm $\cdot 500$ Hz $\cdot 7.5 \cdot 10^{-6}$ m/s, the magnitude of the overload arising in the capillary-porous structure (CPS) due to vibration acceleration reaches of $0.15$ mm $(500$ s$^{-1})^2 \sim 37.5$ m$^2$/s$ \sim 3.8$ g, which is less than the available pressure developed by the HP’s capillary-porous insert structure $\sim 5.5$ g.

The flow microcalorimeter design for the HP’s heat transfer coefficient $K_{HP}$ measuring under vibrations is a difficult task associated with the small size and weight of the microcalorimeter when it is necessary to achieve a heat exchange conditions that is not inferior to $\alpha_{cal}$ in a large stationary vortexial flow calorimeter. The general layout of the measuring vibration microcalorimetric stand is shown in Figure 2.
Figure 2. Scheme of vibration measurements of the HP’s heat transfer coefficient: 1–microcalorimeter; 2 – HP; 3–flange; 4 – generator; 5 – capacitive sensor; 6–channels for wires; 7 –inlet fitting; 8 – pressure hose; 9–constant pressure vessel of flowing water; 10–outlet fitting; 11 – drain hose; 12–flowmeter; 13 – cover; 14–bubble generator; 15 – heater; 16–support disk; 17 – loudspeaker diffuser; 18 –sound loudspeaker; 19 –generator; 20 –amplifier; 21 – diffuser holder; 22 – centering springs; 23 –generator; 24 –amplifier; 25 – oscilloscope; 26 – computer; 27 – small permanent magnet; 28 – measuring coil; 29 –vibration control device; 30 –frequency meter; 31 –switch; 32 –voltmeter; 33 –Dewar vessel with zero point 0 °C.

Figure 3 shows the resonance curves of the HP’s heat transfer coefficient $K_{HP}$ dependence on the longitudinal external vibrations frequency at three different evaporator temperature head $\delta T_{ev}$ and pressure pulsations fixed in the Laval-liked vapour channel.

1: Evaporator temperature head $\delta T_{ev} = T_{ev} - T_B = 20.1K$, the frequency of internal pulsations $f_{puls} = 502 \pm 5Hz$, stationary vapour flow inside the HP channel $G_{mix} \approx 3.147 \cdot 10^{-4}$ kg/s, the average vapour channel pressure is $6.13 \cdot 10^5$ Pa, the increase in the $K_{HP}$ coefficient at resonance with superimposed external longitudinal vibrations with amplitude $\xi_{vibr} = 0.15$ mm reaches 20 %;

2: Evaporator temperature head $\delta T_{ev} = T_{ev} - T_B = 15.02 K$, the frequency of internal pulsations $f_{puls} = 474 \pm 5Hz$, stationary vapour flow inside the HP channel $G_{mix} \approx 2.56 \cdot 10^{-4}$ kg/s, the average vapour channel pressure is $5.25 \cdot 10^5$ Pa, the increase in the $K_{HP}$ coefficient at resonance with superimposed external longitudinal vibrations with amplitude $\xi_{vibr} = 0.15$ mm reaches 18 %;

3: Evaporator temperature head $\delta T_{ev} = T_{ev} - T_B = 10.1K$, the frequency of internal pulsations $f_{puls} = 396 \pm 5Hz$, stationary vapour flow inside the HP channel $G_{mix} \approx 1.71 \cdot 10^{-4}$ kg/s, the average vapour channel pressure is $4.53 \cdot 10^5$ Pa, the increase in the $K_{HP}$ coefficient at resonance with superimposed external longitudinal vibrations with amplitude $\xi_{vibr} = 0.15$ mm reaches 14 %.

Presented in Figure 3 the values of the HP’s heat transfer coefficients depending on the temperature head on the evaporator at three different values of the vibration parameters show extreme resonant vibration behavior. Deviations of experimental points from approximating curves do not exceed 3.5 %.

At different frequencies of external vibrations, when $f_{vibr} < f_{puls}$ or $f_{vibr} > f_{puls}$ begins to occur misalignment and partial oscillations damping, there are slowing antiphase movements of the liquid layer, leading to a decrease in the oscillations amplitude of the vapour bubbles and to a decrease in the resonance contribution to the HP’s heat transfer coefficient.
Figure 3. The results of the Laval-liked nozzle vapour channel HP’s heat transfer coefficient $K_{HP}$ measurements with a depending on the longitudinal external vibrations frequency.

The obtained results mean the vaporization intensity increase in the capillary-porous evaporator and the growth rate increase of the vapour bubbles, compared to the known results of the stationary growth rate of the vapour bubbles in a large volume of superheated liquid [11-13]:

$$r_{\text{bub}} = r_{\text{min}} + \frac{4g\Delta T_s}{(T_P)^{0.5}} \sqrt{\lambda_C p_1^2} \cdot \sqrt{\tau}.$$  \hspace{1cm} (1)

The exponent 0.5 for the time parameter $\tau$, s, in equation (1) reflects the stationary growth of vapour bubbles over time in a large volume of superheated liquid without taking into account the relative motion of the phases. However, in reality, due to the difference in densities, there is a convective movement—the bubbles pop up in the gravitational force field $1g$, and in the experimental data obtained on the dependence of the bubble growth rate on time, the degree index is somewhat large, reaching a value of ~ (0.6 – 0.7) [13].

During the vapour bubble movement along the grid layers with a constant temperature $T_{ev}$ ($z=\text{const}$) to the injection channels in the capillary-porous HP’s evaporator $\tau = R / u_{\text{bub}} \approx 1 \cdot 10^{-2} \text{m} / 5 \cdot 10^{-3} \text{m}/\text{s} \approx 2 \text{s}$, the total length of the perpendicular oscillatory bubble displacements at the harmonic oscillations with frequency $f_{\text{vibr}} = 500 \text{ Hz}$ and amplitude $2\xi L = 3 \cdot 10^{-4} \text{ m}$ reaches $\tau = f_{\text{vibr}} \cdot 2\xi L \cdot 2s \approx 0.3 \text{ m}$, while the growth rate of its radius $r_{\text{bub}}$ can be considered close to constant. As a result, an additional contribution appears in the functional dependence of the bubble radius on time, as shown in equation (2):

$$r_{\text{bub}} = r_{\text{min}} + \frac{2g\Delta T_s}{(T_P)^{0.5}} \sqrt{\lambda_C p_1^2 \xi^2} \cdot \sqrt{\tau} + b f_{\text{vibr}}^2 \xi^2 \cdot \tau^n.$$  \hspace{1cm} (2)

where the exponent of $n$ can be tried to estimate from the experimental results, and the coefficient $b$ does not exceed two.

The exponent $n$ can be estimated from the assumption that the resonant increase in the heat transfer coefficient $K_{HP}$ is due to a vapour bubbles faster growth at harmonic vibrations in a capillary-porous evaporator as follows:

$$b f_{\text{puls}}^2 \xi^2 \cdot \tau^n = 1.2 \cdot \frac{2g\Delta T_s}{(T_P)^{0.5}} \sqrt{\lambda_C p_1^2} \cdot \tau^{0.5}.$$  \hspace{1cm} (3)
And after the transformation of the equation (3) we obtain:

$$\tau^{n-0.5} = 1.2 \cdot \frac{2 \Delta T_{\text{ev}}}{r(T,P)\Delta p_{\text{vap}}} \sqrt{\frac{\lambda L}{C_{P} \rho_{L}}} \; b_{\text{puls}} \xi_{\Sigma}^{-1} ; \quad n = 0.5 = \ln \left(1.2 \cdot \frac{2 \Delta T_{\text{ev}}}{r(T,P)\Delta p_{\text{vap}}} \sqrt{\frac{\lambda L}{C_{P} \rho_{L}}} \; b_{\text{puls}} \xi_{\Sigma}^{-1}\right).$$

(4)

We substitute in equation (4) all the necessary parameters [14-15], including the thermophysical properties of diethyl ether $r(T,P) = 345 \text{kJ/kg}$ at evaporator temperature $T_{\text{ev}} =328.75 \text{K}(55.6^\circ \text{C})$ and pressure $P = 6.13 \times 10^5 \text{Pa}$ ; $\rho_{\text{vap}} = 3.3 \text{kg/m}^3$ ; $\lambda_i = 0.13 \text{W/m} \cdot \text{K}$; $C_{P_i} = 2.33 \text{kJ/kg}^\circ \text{C}$ ; $p_l = 703 \text{kg/m}^3$; $\Delta T_{\text{ev}} =20 \text{K}$; $b = 2$ ; $\xi_{\text{puls}} = 5 \times 10^5 \text{I/s}$; $\xi_{\Sigma}^{-1} = 3 \times 10^{-4} \text{m}$ and after calculations obtain the following value of the exponent n:

$$n = 0.5 = \ln(2.050757) = 0.718 ; \quad n = 1.2 \pm 0.1 .$$

(5)

The exponent n is greater than one in equation (2), $n > 1$ for the rate of vapour bubbles growth as a function of time $t$, $s$, and this means the manifestation of a strong influence of the relative motion of vapour bubbles in the diethyl ether boiling layer under external influence.

The faster vapour bubbles growth due to their forced relative motion in the perpendicular direction to the main flow with constant conditions of the grid evaporator with periodic cell structure leads to more intensive vaporization at a constant temperature head value on the evaporator $\delta T_{\text{ev}}$, thereby increasing the heat transfer coefficient $\alpha_{\text{ev}}$ in the evaporator.

In addition, with a small thickness of the liquid layer on the HP’s lower cover surface, the introduced change by the vibration effect in the initial growth rate of a vapour bubbles is relatively large and the vibration further contributes to the liquid redistribution over the heating surface into the superheated injector capillary channels. This increases the flow rate of liquid and vapour in the injection channels and thus the heat transfer coefficient of the evaporator.

4. Conclusion

The resulting resonant increase in the heat transfer coefficient $\alpha_{\text{HP}}$ at the coincidence of the frequencies of internal pulsations in the vapour channel and the HP’s evaporator and longitudinal external vibrations of the HP’s body, indicating an accelerated growth of vapor bubbles in the boiling layer of diethyl ether on the surface of the bottom cover, depends on the value of the temperature head on the evaporator $\delta T_{\text{ev}} = T_{\text{ev}} - T_B$ and increases with its increase, but it is limited by the evaporator drying.

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