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VIBRATIONS IN SPACE-ROCKET SYSTEMS

The outcomes of researches of thermal regimes of heat pipes and thermosi-phons in conditions of vibration effects of different frequencies and amplitudes are presented. The vibrations influence on thermal resistance of thermal pipes and the maximal transferred ability was experimen-tally investigated. It is found, that thermal resistance of a thermal pipe can decrease and rise at action of vibration. The boundary frequency bands and amplitude are determined, at which one heat and mass transfer is improved or is worse. For an investigated heat pipes of boundary magnitudes of frequencies are equal 60 Hz, and amplitudes are equal approximately 3 or 5 mm. The data of other authors are affirmed for another type heat pipes (they received for boundary frequencies 60 and 120-140 Hz). The outcomes of research of influencing of orientation of a heat pipes and thermosi-phons on operating of vibrations are submitted. The idealised substantiation's of vibration actions on heat and mass transfer of all three zones of thermal tubes (zone of vaporization, condensation and transport) are given. On the basis of experimentally established dependences the new concept of influence of vibrations on processes in thermal pipes is offered. The necessity task of the wide theoretical and experimental researches of influence of vibrations on heat and mass transfer intensity in the porous systems is submitted.

vibration, space-rocket systems

Introduction

Heat pipes are used as highly efficient heat pipelines. Being parts of construction elements they enable to level off the their temperature. Thermal pipes may solve the important problem for space-rocket thechnology as to rational management by thermal streams and the general temperature regime of spacecrafts. The advantages of heat pipes do them irreplaceable for space thechnology in some cases. The analysis of numerous constructive variants of the heat pipes, developed to the present time for the various airborne equipment, allows to select such main fields of use of the heat pipes in aircraft and space-rocket engineering.

– *Systems of support of a thermal regime,* in particular, systems of thermoregulator and support of life-support system, of thermal stability of tanks of rockets, of inhabited module of spacecrafts, of instrument compartments of artificial satellites, space suits, performance of heat-shielding functions.

– *Systems of cooling of the radio-electronic equipment.* Heat pipes solve a problem of cooling of radio-electronic equipment, in conditions of its miniaturization and reduction of its weight or the sizes, in conditions of weightlessness or overloads.

– *Power systems*. First of all the application of a nuclear energy in space systems assumes to use heat pipes as effective means of heat removal from a nuclear reactor, means thermal stability, maintenance of isothermality, protection against radioactive radiation

Now the various designs with heat pipes are applied in the manufacturing plants [1, 2]. Hundreds ideas on use of heat pipes in various high calorific intensity units are known in space-rocket engineering - from *rocket engines to radiators of space power systems.* One of the important problems of designing *spacecrafts* of various functions is to maintain the necessary temperature inside them. Besides everything it is necessary to equalize the temperature on the surfaces of various spacecraft elements for preventing their deformation. The most promising direction when solving the aforementioned problems is the application of heat pipes as an element of the design. As a result of the experiments, it was possible to prove the possibility of using heat pipes as the

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means for thermal heat stability process of the space vehicle [1].

The specificity of operation of space-rocket thechnology is those, that the vibrating processes of different intensity accompany of working processes practically in all aggregates of rockets, spacecrafts and stations, of satellites (Fig. 1, [3]). Longitudinal self-oscillations of a missile body as outcome of interplay of elastic vibrations of a design with processes which are flowing past in Liquid Rocket Propulsion (LRP) and its fuel-delivery tubes are well-known. Activity of rocket engines - liquid, solid-propellant, electrical, air -jet, - is always accompanied by oscillations of working aggregates of different frequency and amplitude. These oscillations are those disturbing forces, which one calls the different forms of mechanical oscillations of configuration items of a rocket as elastic mechanical system. To take into account in such complex to a system, what is the rocket, appearance and effect of vibrations on components and on working processes in different aggregates is difficult extremely. Moreover, the definition of reasons of their appearance and identification of their characteristics is impossible till now. Therefore obtaining of a maximum of information quantity about vibrations determines reliability of a missile first of all. The vibrations of mechanical components of inadmissible intensity can result in a structural failure of separate aggregates rocket - space systems in a consequent of loss of strength. On the other hand, the interplay of mechanical members with liquid and frequently by hyperthermal gaseous propulsive masses results in a breakdown.

The intensification of processes of heat and mass transfer by own oscillations generated by the installation quantitatively is different, and its mechanism in many respects depends on a condition of working fluid (one or two phase). It is necessary to partition mechanism of effect of vibrations on heat and mass transfer in relation both phase of working fluid and from the mechanism of creation of oscillations in a system.. The main problem thus is the definition of optimum regimes of processes in conditions of effects of vibrations. The appearance of maximum or minimum of performance parameters is depending on magnitudes of frequencies and amplitudes of oscillations. This optimum can play both positive and negative role.

We examine the phenomena, related with effect of vibrations on activity of systems with heat pipes. At once we shall mark, that these effects are not always negative. Sometimes they play the positive role, since intensify heat and mass transfer processes and can, for example to facilitate cooling of the combustion chamber LRP. Moreover, now there is a large activity on usage of vibrations for increase of efficiency of heat and mass transfer equipments generally and systems with heat pipes specifically. The presence of gas liquid flows in aggregates of rocket-space systems (RSS) with heat pipes creates also reasons for appearance of vibrations. It is determined by that any turbulent' flows are accompanied by velocity pulsation's, causing vibrations of configuration items, which one in turn influence intensity heat and mass transfer of processes.

The functioning in conditions of vibration effect limits the extension of the areas of application of heat pipes and thermosiphons. The reason is that the vibrations are inherent in some installations by its nature. Such installations are the space structures, space station, rockets, air and rocket engines, vessels, other transportation facilities. It is assumed that the vibrations improve the heat and mass transfer processes. Therefore common neglect of vibration actions can put the thermal systems in margin of safety of action. Actually, in accordance with experiences, the vibrations not only improve the heat change, but also degrade it. Therefore knowledge of the impact of vibrations, intrinsic to the installation, on operational modes of used heat pipes and thermosiphons is necessary for preventing breakdown first of all. One way to intensification of heat and mass transfer of processes with phase transitions of working fluid is connected with synthetically created vibration actions. In this case also it is necessary to know frequency bands

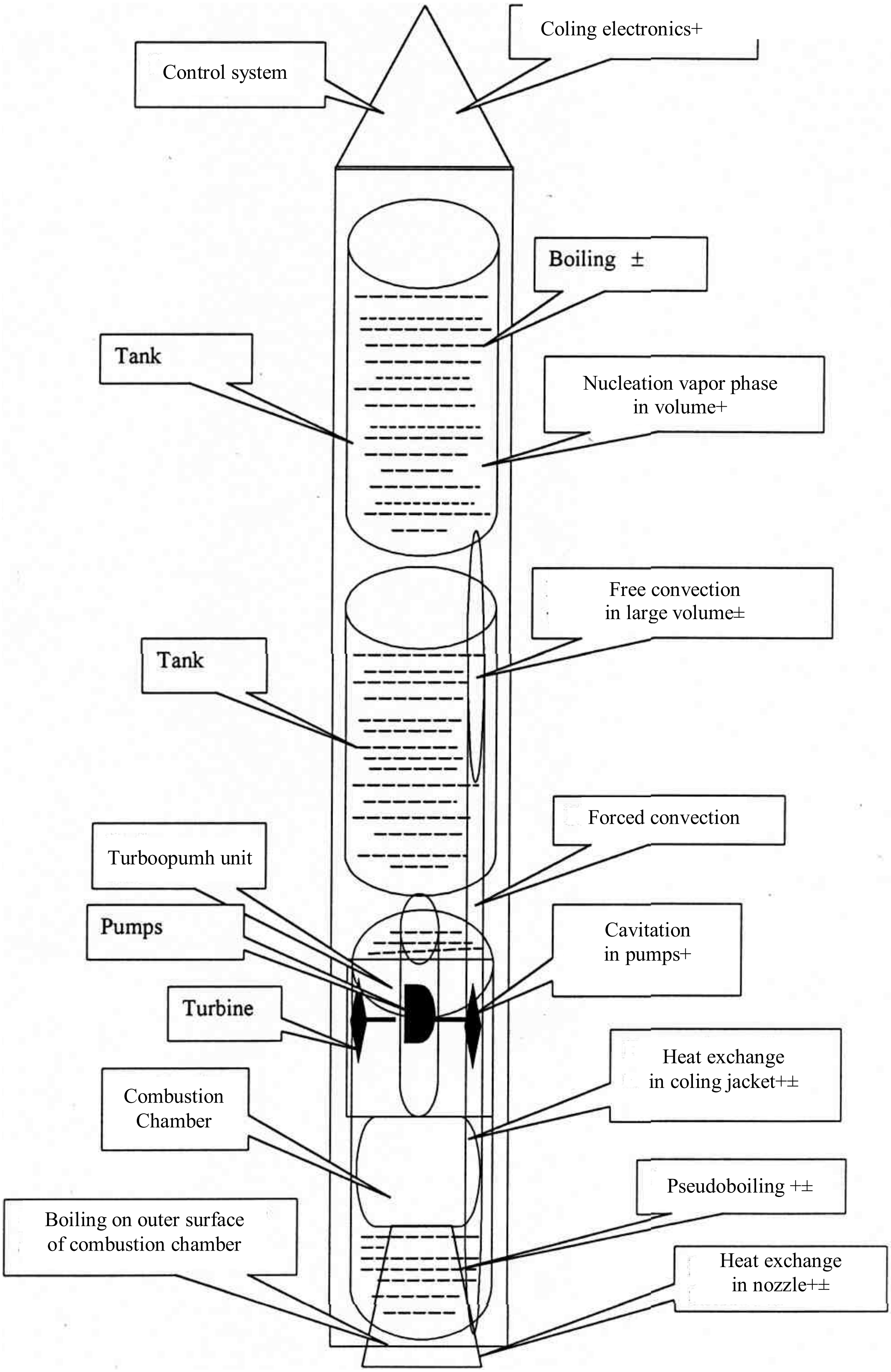

Fig. 1. Vibration action on head and mass exchange on rocket

and amplitudes, which one improve or degrade heat and mass transfer. The research of influencing of vibrations to the thermal processes with phase changes of working fluids with reference to heat pipes and thermosiphons goes by two ways. One way is the research of operational models of heat pipes or thermosiphons for a different variation of frequencies and amplitudes, designs, heat power, working fluid, types of capillary porous structure and so on. Another way is analysis of influencing of vibrations on the processes of vaporization, boiling, condensation, on the two-phase flows in a general formulation regardless to the particular type of a heat pipes.

The experimental date about vibration impact on processes in heat pipes

For realization of experimental researches of the heat pipes [2, 4, 5, 7] with the gas channel diameter from 1 up to 20 mm, supplied with wick made from metal grid were selected. Working mediums of the heat pipes are water, acetone and spirit at the various degree of filling. The heat pipe was settled on the vibrating stand. For a heat supply and heat removal from a heat pipe external heat-carriers - the hot and cold water, directed in the heating and cooling chambers were used accordingly.

Some results of experimental researches are submitted on Fig. 1 – 3 and table 1 – 6.

On Fig. 2 the continuous curve shows dependence of thermal resistance of a heat pipe with diameter of 6 mm from the transmitted thermal capacity, taken at absence of vibrations. Points show some characteristic modes of a vibrating heat pipe.

The kind of dependence of thermal resistance from transmitted capacity and character of vibrations effect for a pipe with diameter of 6 mm is a differs from the results received for heat pipes of the greater size not to a great extent. However for more small pipes this dependence differs from usual (Fig. 2). The positive inclination of diagram $R = f(W)$ in a range of small magnitudes of transmitted capacity first of all is evident. Character of effects of vibration of different frequencies on this

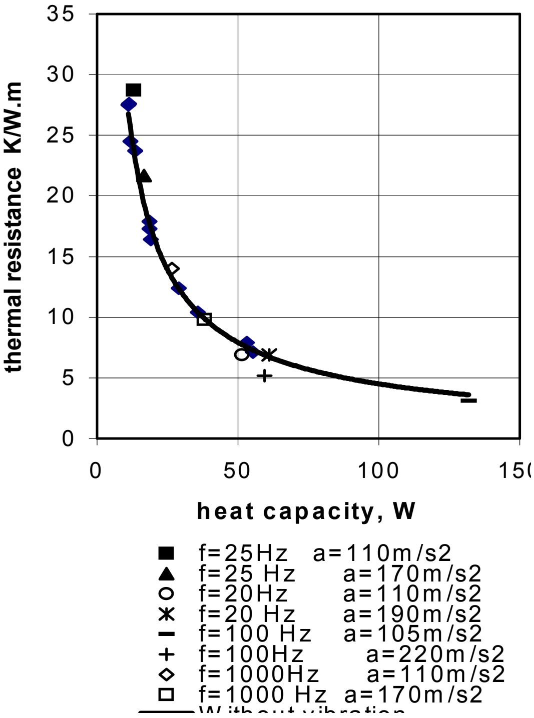

Fig. 2. Dependence of thermal pipe resistance on transmitted capacity

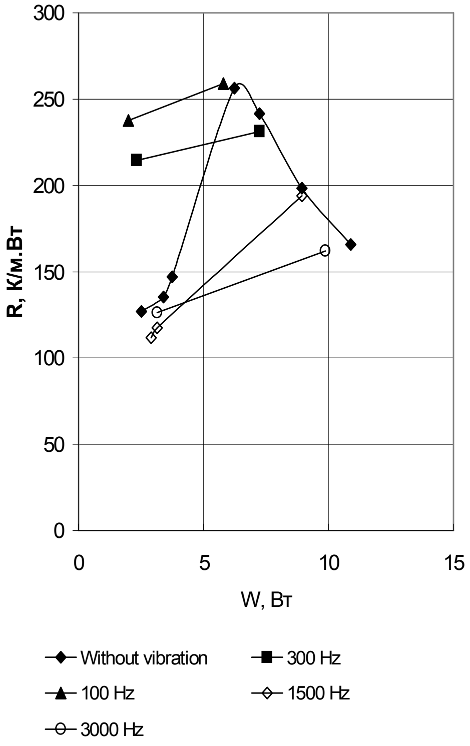

Fig. 3. Dependence of heat pipe resistance on transmitted capacity at various frequencies of vibration

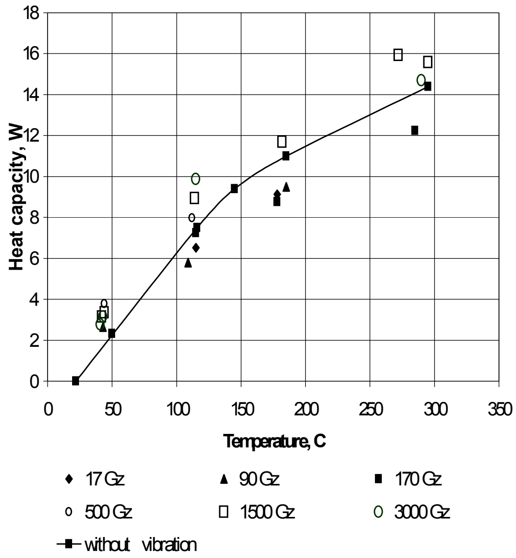

Fig. 4. Dependence of transmitted capacity of a heat pipe on temperature of a heated up site under various frequency of vibration

dependence is determined, basically frequency. Rather low frequencies of vibration (100 – 300 Hz) sharply worsen efficiency of a heat pipe in the field of small magnitudes of transmitted thermal capacity. Vibrations of higher frequencies (1500 – 3000 Hz), on the contrary, reduce thermal resistance in the field of average and high magnitudes of transmitted capacity. Obviously, qualitative distinctions of characteristics of pipes in diameter of 6 and 4 mm shows strong influence of edge effects on a stream parameters in the thermal pipes of small diameter.

The characteristic of a heat pipe is submitted as dependence of transmitted capacity from temperature of the hot end on Fig. 4.. These data qualitatively correlate with the data Fig. 3: The high-frequency vibrations are increasing transmitted capacity at the fixed temperature gradient, and low-frequency vibrations, on the contrary, reduce it.

Thus, vibrations of various frequencies have differently an effect for efficiency of heat pipes of the different characteristic size. The greatest effect (positive) is rendered vibrations with frequency about 100 Hz for a thermal pipe with diameter of 6 mm, this characteristic frequency grew up to several thousand Hz for a pipe in diameter of 4 mm.

The given experimental results here have not by universal character unfortunately. The strong experimental dependence from the characteristic frequencies causing abnormal changes of characteristics of a thermal pipe was detected not only for its characteristic size, but also for orientation of a pipe concerning a direction of vibrations, for type of wick and for other parameters. The correlation analysis on the limited volume of experimental data has not allowed determining types of this dependence. For example, in Fig. 5 dependence of thermal resistance of a heat pipe on parameters of vibrating influence are given.

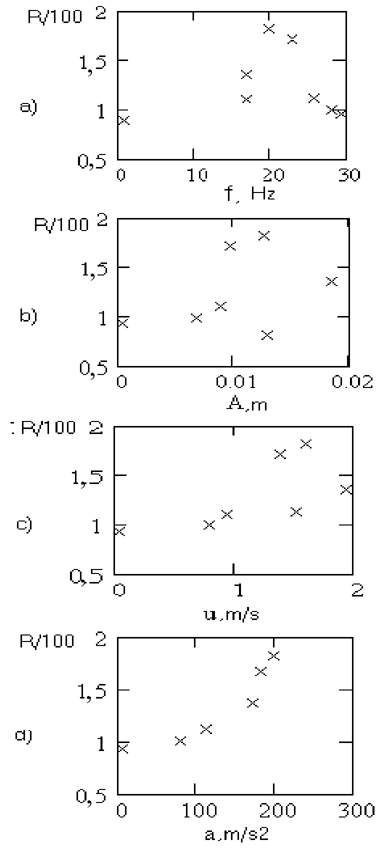

Fig. 5. Thermal resistance of a heat pipe as function of parameters of vibration

The data in Fig. 5 are received for a heat pipe with diameter 20 mm. In this series of experiments the fluctuations with frequency 0 – 30 Hz and acceleration of 0-300 m/s^2 were used. On fig. 5 (a) influence of vibration of various frequencies on the thermal resistance is shown at the fixed vibrating acceleration equal of 100 m/s^2.

Appreciable influence on a mode of operation of this heat pipes the vibrations of a narrow frequency range - about 17 – 25 Hz is showing (see Fig. 5). On Fig. 5 (b – d) dependence of thermal resistance from the amplitude of fluctuations, vibrating speed and vibrating acceleration for this frequency range are represented. Analyzing these data, it is possible to conclude, that the independent parameters determining a mode of operation of a vibrating heat pipe are frequency and vibrating acceleration. Thus, influence of vibrating acceleration is shown only in some narrow enough range of frequencies, which is various for pipes of a different design. So for a similar heat pipe with diameter 6 mm the characteristic frequency has made 110 Hz, and for a pipe with diameter 3 mm has made near 800 – 1000 Hz.

Such type of dependence of a mode of operation of a heat pipe causes the assumption of the resonant phenomena. The nature of this resonance cannot be connected to mechanical fluctuations of a design of a thermal pipe or acoustic waves in a steam phase of the heat-carrier. A liquid phase of the heat-carrier in capillaries is a unique probable element for which such own frequencies can be characteristic.

Dependence of thermal resistance from vibration acceleration appeared rather complex and ambiguous. At small-transmitted capacities the increase of vibrating acceleration resulted in growth of thermal resistance of a thermal pipe. On the contrary, at the big heat demands, amplification of vibration reduced thermal resistance. Value of thermal resistance generally grew with growth of transmitted capacity. But depending on a level of thermal capacity and frequency of vibration it could be as higher, as below thermal resistance, which was registered for a not vibrated heat pipe (Fig. 3).

The analysis of experiments outcomes (see tables 1 – 6) has shown also, that on frequency 40 Hz and at amplitude of 3,5 mm takes place full isothermal surface of a pipe (№ 1 – 5 the thermocouple on surface condenser; № 6 – on surface evaporation).

Table 1

Value temperature on surface heat pipe °C under frequency 20 Hz (1 series)

a, mm /s^2	A, mm	T_1	T_2	T_3	T_4	T_5	T_6
0	0	94	94	94	94	94	98
25	1,6	94	94	94	94	94	98
50	3,1	94	94	94	94	94	98
70	4,7	71	72	72	72	72	78

Table 2

Value temperature on surface heat pipe °C under frequency 10 Hz (2 series)

a, mm /s^2	A, mm	T_1	T_2	T_3	T_4	T_5	T_6
0	0	117	118	118	118	118	119
25	1,6	99	99	99	100	100	101
30	1,9	86	88	88	89	89	92

Table 3

Value temperature on surface heat pipe °C under frequency 20 Hz (2 series)

a, mm /s^2	A, mm	T_1	T_2	T_3	T_4	T_5	T_6
0	0	117	118	118	118	118	119
25	1,6	117	118	118	118	118	119
50	3,1	111	111	111	111	111	111
75	4,7	96	96	96	97	97	97

Table 4

Value temperature on surface heat pipe °C under frequency 40 Hz (2 series)

a, mm /s^2	A, mm	T_1	T_2	T_3	T_4	T_5	T_6
0	0	117	118	11	118	118	119
25	1,6	117	118	11	118	118	119
50	3,1	117	117	117	117	117	117
75	4,7	116	116	116	116	116	118
100	6,3	108	108	109	109	110	111

On a = 70 mm/s^2 the temperature decrease on 25% as shown by Table 1 – 6.. The experiments indicate that vibrations have a profound effect on heat and mass transfer of a surface temperature of a heat pipe. With increase of frequency stratification of temperature curves is watched. On frequencies 100 Hz this stratification reaches a maximum at amplitudes more than 6 mm.

Table 5
Value temperature on surface heat pipe °C under frequency 60 Hz (2 series)

a, mm /s^2	A, mm	T_1	T_2	T_3	T_4	T_5	T_6
0	0	117	118	118	118	118	119
25	1,7	117	118	118	118	118	119
50	3,1	117	118	118	118	118	119
75	4,7	115	116	116	116	116	117
100	6,3	115	115	115	114	115	115

Table 6
Value temperature on surface heat pipe °C under frequency 100 Hz (2 series)

a, mm /s^2	A, mm	T_1	T_2	T_3	T_4	T_5	T_6
0	0	117	118	118	118	118	119
25	1,6	117	118	118	118	118	119
50	3,1	117	118	118	118	118	119
75	4,7	117	118	118	118	118	119
100	6,3	116	115	116	11	118	121

Is marked, that at low frequencies of oscillations (10-20 Hz) the vibrations do not render any of essential influencing on magnitude.

The oretical premises

1. The possible mechanism of influence of vibrations on heat and mass transfer processes with boiling in thermosyphons was presented in [3, 4]. In the present report we shall not repeat its interpretation, referring the reader to our published works. This mechanism is consisted of account of change of a angle of wetting owing to moving of a solid wall relatively of vapour bubbles. In a heat pipe unlike thermosyphon as the evaporation occurs not in a bubble, but on a surface of a meniscus. Therefore as a first approximation this mechanism can be used for an estimate of influence of vibrations on heat and mass transfer processes in heat pipes. But it is necessary to expect, that this mechanism is added by change of a surface of a meniscus owing to movement of a solid wall along an axis "meniscus – fluid". The change of quantity of an evaporating fluid from a surface of a meniscus of capillary – porous systems under effect of vibrations is determined by the relevant solution of a hydrodynamic problem. The law of oscillations determines the motion of a solid surface concerning the interphase boundary of a meniscus

$$x = A\cdot\sin(\omega\tau)$$

that is

$$w_\omega = A\cdot\omega\cdot\cos(\omega\tau)\,.$$

The solid rough wall, driving in one side, catches a fluid at the expense of watering. The direction of vibration acceleration (in comparison with a force direction of gravity) determines value of "slip", which increases at the growing of evaporating surface.

Unwatering a part of a surface takes place at motion in the opposite side. Thus, the surface of a meniscus is distorted depending on magnitudes of vibration acceleration, roughness of a solid wall, viscosity of a fluid, angle of wetting, surface tension, force direction of gravity. Such quality mechanism of influence of vibrations follows from the analysis of the experimental data on influence of magnitude of amplitude of vibrations on change of efficiency of heat-transfer properties of heat pipe. Let's consider a problem in common statement. Under the assumption of small thickness by a carried away wall of a fluid at tip sections of a meniscus, the flow of a fluid is flat and covered by equation of the Navier-Stokes:

$$\nu\,\partial^2 w\big/\partial y^2 = \partial w/\partial\tau\,, \qquad (1)$$

where w is speed of displacing layer of liquid; ν is kinematical viscosity; τ is time4 y is coordinate.

The boundary conditions of a considered problem are recorded in such view:

at $\tau = 0$: $w = 0$ for $0 \le y \le \infty$;

at $\tau > 0$: $w = w_R = A\omega\cos(\omega\tau)$ for $y = 0$;

at $\tau > 0$: $w = 0$ for $y = \infty$.

The solution of an equation (1) can be found through a Laplace transformation by analogy with the solution E.Dwyer:

$$w(y,\tau) = \frac{Ay\omega}{2\sqrt{\pi\nu}}\int_0^\tau \frac{\cos(\omega\cdot t)\cdot\exp\left[-y^2/4\nu(\tau-t)\right]}{\sqrt{(\tau-t)^3}}dt\,, \qquad (2)$$

where t is a integration variable.

Following Cooper M.G. - Lloyd A.J.P. [8], we shall enter an allowance about a flow continuity of a mass of a fluid which is flowing past through a boundary layer, that is we use a requirement of equality of rates of flow on the right and at the left for a plane problem:

$$\delta_0 w_\omega = \int\limits_0^\infty w(y,\tau)dy\,, \tag{3}$$

where δ_0 is thickness of carried away layer.

The left-hand part of this equation represents a rate of flow through microlayer, carried away by a moving wall, with velocity of a wall w_ω (without slipping). The right part represents a rate of liquid which is running in this microlayer. The value δ according to the theory of a boundary layer is equale displacement thickness of a boundary layer ϑ_w and it determines thickness of microlayer at the moment of its formation. Parameter ϑ_w is determined by a velocity profile $w(y)$ at flow of a semi-infinite mass of a fluid near a wall, runing on with rate w_ω . Let's rewrite (3) as follows

$$\delta = (1/w_\omega)\int\limits_0^\infty w dy\,. \tag{4}$$

Substituting here by solution (2) we obtain a ratio

$$\delta = \frac{A\omega}{2w_\omega\sqrt{\pi\nu}}\int\limits_0^\infty y\int\limits_0^\tau \frac{\cos(\omega\cdot t)\exp\left[-y^2/4\nu(\tau-t)\right]}{\sqrt{(\tau-t)^3}}dtdy\,. \tag{5}$$

Calculation of this integral does not represent the special difficulties. Final relation (5) is resulted in a following view

$$\delta = \frac{A\omega}{w_\omega}\sqrt{\nu/\pi}\int\limits_0^\tau \frac{\cos(\omega\cdot t)}{\sqrt{\tau-t}}dt\,. \tag{6}$$

We enter a new variable $z = \tau - t$. Then (6) is rewritten as follows:

$$\delta = \frac{A\omega}{w_\omega}\sqrt{\nu/\pi}\int\limits_0^\tau (\cos(\omega\cdot t)\cos(\omega\cdot z)/\sqrt{z} + \\ + \sin(\omega\cdot t)\sin(\omega\cdot z)/\sqrt{z})dz. \tag{7}$$

This integral can be divides into two parts

$$\delta = \frac{A\omega}{w_\omega}\sqrt{\nu/\pi}\cdot\cos(\omega\tau)\int\limits_\tau^0 \frac{\cos(\omega\cdot z)}{\sqrt{\omega\cdot z}}d(\omega\cdot z) + \\ + \frac{A\omega}{w_\omega}\sqrt{\nu/\pi}\cdot\sin(\omega\tau)\int\limits_\tau^0 \frac{\sin(\omega\cdot z)}{\sqrt{\omega\cdot z}}d(\omega\cdot z). \tag{8}$$

This integral is reduced to a sine and cosine to an Frenel' integral (or can be computed approximately after expansion trigonometric function into a series)

$$\delta \approx \frac{2A\sqrt{\omega\tau}}{w_\omega}\sqrt{2\nu\left[1-(\omega\tau)^2\right]}\,. \tag{9}$$

The surface of a meniscus grows, if the liquid film does not come back in an initial position. It is possible to find the change of a watering angle and surface of a meniscus from geometrical constructions, if value of δ is known.

Approximately efficiency of vibration action is determined by the formula

$$\eta = 1 + \frac{A\cos^2\theta}{r_c(2-\theta/45)}\,, \tag{10}$$

where r_c is a capillary radius; θ is a watering angle, in degrees.

2. The mechanism of influence of vibrations offered by us earlier for boiling [3, 4] is suitable for an explanation of these phenomena in thermosiphones. This mechanism may explain also driving force of influence of vibrations in thermal pipes. The basic hypotheses is in an assumption of action of vibration on boiling by changed wetting angle θ_0. Moving force in heat pipes is capillary pressure:

$$\Delta p = 2\sigma\{\cos\theta_e/r_e - \cos\theta_c/r_c\}. \tag{11}$$

Rewriting Eqs. (11) assuming (in terms of the result [3, 4]) that wetting angle θ changesaccording to the same law $x = A\cdot\sin(\omega\tau)$ i.e.

$$\theta = \theta_0 + A_\theta\ \sin\omega\tau, \tag{12}$$

we obtain formula for analyses of impact the vibration on heat transfer in oscillating heat pipes:

$$\Delta p_c = 2\sigma\{\cos\,[\theta_{e0} + A_\theta\sin\omega\tau\,]\,/r_e - \\ - \cos\,[\theta_{c0} + A_\theta\sin\omega\tau\,]\,/r_c.$$

Conclusion

Thus, in the submitted work on the basis of the analysis of experimental data the consistent physical model of influence of vibration for work of a thermal pipe is offered. At the construction of this model the classical inverse problem was solved: the most rational explanation of behaviour of complex heat and mass transfer systems under influence of vibrations was chosen from set of possible.

Unfortunately, the physical model given here, does not describe all features of registered experimental results. In particular, this model does not give the answer to a question about the mechanism of influence of transmitted capacity on a sign of effect of influence of vibrations. Therefore, the calculated model for definition of thermal resistance and the maximal transmitted capacity of thermal pipes, which are subject to vibration, can be constructed only after accumulation of a plenty of experimental data.

As it is visible, the problem of definition of influence of vibrations on heat and mass transfer of heat pipe and thermosyphon very composite and requires the further study both theoretically and experimentally.

Nomenclature

A –vibration amplitude;

a – vibration acceleration;

ΔT – surface over heating;

T_s – temperature of liquid saturation;

θ – wetting angle;

ω – frequency of vibration;

τ – time ($\tau = {}^1\!/_f$);

ρ – density;

σ – surface tension;

Δp – capillary pressure;

index: e – evaporation, c – condenser.

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