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RESEARCH A PHYSICAL PICTURE OF HEAT AND MASS TRANSFER PROCESSES IN VIBRATING HEAT PIPES

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ABSTRACT

Results of research of heat and mass transfer processes in the thermal pipes subjected to vibrating influence are submitted. The vibrations influence on thermal resistance of thermal pipes and the maximal transferred ability was experimentally investigated. Characters of this influence determine the incomplete adequacy of the existing now representations to a real picture of processes of heat and mass transfer in porous systems. In particular, it is experimentally established, that thermal resistance of a thermal pipe can both decrease and rise at action of vibration. On the basis of experimentally established dependences the new concept of influence of vibrations on processes in thermal pipes is offered. The statement of a task of the wide theoretical and experimental researches of influence of vibrations on heat and mass transfer intensity in the porous systems is submitted.

INTRODUCTION

Energy stations and units of modern technology are characterized by high values of thermal capacity and mechanical pressure. These characteristics have a main influence on a choice of a material and a design data of this devices [2, 6]. Thus, joint influence of thermal capacity and mechanical pressures is shown, as a rule, only in the account of change of properties of the constructional materials at the increased temperatures [5].

However, other aspect of such interference exists: variable pressure causes the vibration of power unit elements, that can result in change of intensity of heat and mass transfer processes, proceeding in it under certain conditions. Effect of vibrations on the intensity of heat exchange, including in heat pipes, was investigated and earlier [1,3, 6]. Results of these researches testify to ambiguity of such influence - vibration of a heat-transmitting surface or the liquid can both to increase, and to reduce effective factor of heat exchange. In represented work preliminary results of experimental researches of influence of vibrations on the thermal resistance and the maximal transmitted capacity of heat pipes are given.

EXPERIMENTAL RESEARCH

For realization of experimental researches thermal pipes with the gas channel diameter from 1 up to 20 mm made of a thin-walled metal pipe and supplied with matches made from metal grid were selected. Working bodies of thermal 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. In case of need creations of the big gradients of temperatures as a source of heat the electric heater (spiral from nichrome on a warmed site of a heat pipe) was used. A transport site of a thermal pipe with the purpose of reduction of losses of heat was covered with a thick layer of thermoresistance material.

For an estimation of a thermal condition of a pipe on an external surface of transport site were welded the thermocouple conductors, allowing to measure absolute values and differences of temperatures of a working body in different areas of a thermal pipe. Besides to measurement the difference between the temperature of cold water

on an input and on an output from cooling chamber was subject. For this purpose the differential thermocouple of graduation cuprum - copelium was used.

On a platform of the vibrating stand the frame of fastening of a thermal pipe and the acceleration gauge, connected to the specialized measuring device was settled. Model calculations of ther-mal resistance of a pipe wall (results here are not represented) have shown, that at intensity of heat transfer at a level up to 100 W/sm^2 temperature drop on thickness of a metal wall and a match of a thermal pipe does not exceed 0.1K. At the same time the error of measurement of a differe-nce of temperatures of surface heat pipe was estimated by us at a level 0.2 K. Therefore, we neglected by thermal resistance of pipe wall and believed, that the measured temperature of pipe surface is approximately equal to working body vapor temperature of the appropriate zone.
During experiments the following parameters were measured and registered:

- temperature increase of cool water on a cooled site of thermal pipe;
- temperatures of thermal pipe surface in places, where the thermocouples was setting, at the established mode of heat exchange;
- the mass speed of current of cold water was determined by measurement of time which was necessary for the filling of measuring volume;
- vibration acceleration of fastening frame of thermal pipe ;
- the frequency of vibrations, which was generated by vibration stand.

Processing results of measurements was consisted in calculation of thermal resistance of a heat pipe and the maximal transmitted capacity at the various parameters of vibrating influence. Further, among the parameters of system describing its thermal and mechanical condition, were searched such, for which influence on the thermal resistance and transmitted capacity appeared the strongest and unequivocal.

Definition of parameters of vibrating influence (amplitude of fluctuation and vibration speed) was carried out on known dependences

$$a = uw, \quad u = w A, \quad w = 2p f,$$

where a is vibration acceleration,- u is vibration speed; A is amplitude of vibrations; f is frequency; w is circular frequency.

Thermal resistance of a thermal pipe was understood as size, return to effective factor of heat conductivity

$$R = \frac{(T_1 - T_2)\cdot}{W \cdot l},$$

where R is thermal resistance, K / Wm; T_1, T_2- are temperatures of a surface of warmed and cooled sites, accordingly, K; W is transmitted thermal capacity, W; l is length of a transport site of a thermal pipe, m.

Some results of experimental researches are submitted on fig. 1-3.

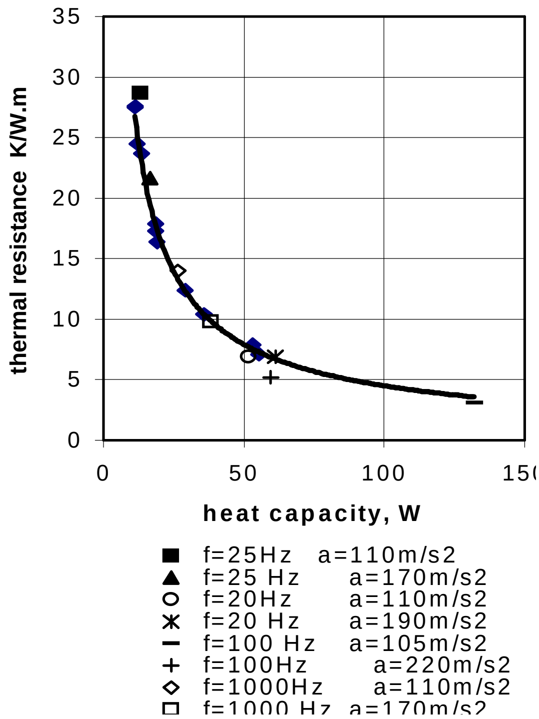

Fig 1. Dependence of thermal pipe resistance on transmitted capacity

On fig. 1 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 of different color 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 very not enough. However for more tiny pipes this dependence differs from usual (fig. 2). The positive inclination of diagram $R=f(W)$ in a range of small values of transmitted capacity first of all is

evident. Character of effects of vibration of different frequencies on this dependence is determined, basically frequency.

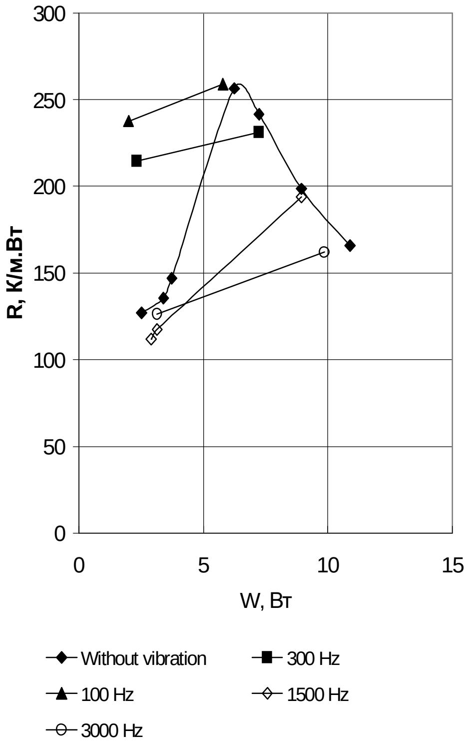

Fig 2. Dependence of heat pipe resistance on transmitted capacity at various frequencies of vibration

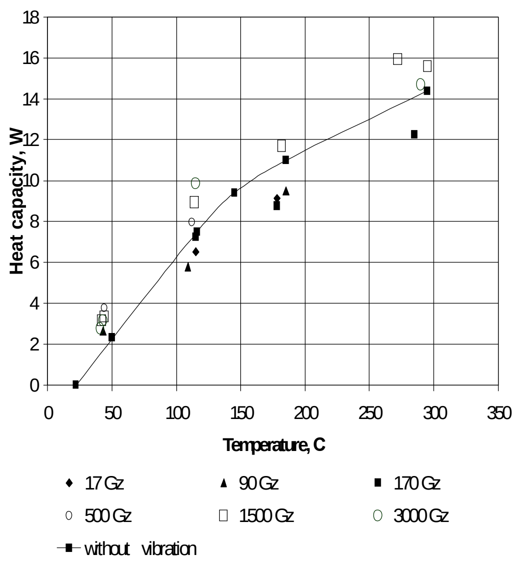

Fig. 3. Dependence of transmitted capacity of a heat pipe on temperature of a heated up site under various frequency of vibration

Rather low frequencies of vibration (100-300 Hz) sharply worsen efficiency of a heat pipe in the field of small values of transmitted thermal capacity. Vibrations of higher frequencies (1500-3000 Hz), on the contrary, reduce thermal resistance in the field of average and high values 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. 3.. These data qualitatively correlate with the data fig. 2: high-frequency vibrations increase 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 here experiments results have not by universal character unfortunately. The strong experiment dependence of 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.4 dependence of thermal resistance of a heat pipe on parameters of vibrating influence are given.

The given in figure 4 data 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. 4 (a) influence of vibration of various frequencies on the thermal resistance is shown at the fixed vibrating acceleration equal of 100 m/s^2.

Apparently from figure, appreciable influence on a mode of operation of this heat pipes the vibrations of a narrow frequency range - about 17

- 25 Hz is showing. On fig. 4 (b-d) dependence of thermal resistance from the amplitude of fluctuations, vibrating speed and vibrating acceleration for this frequency range are represented.

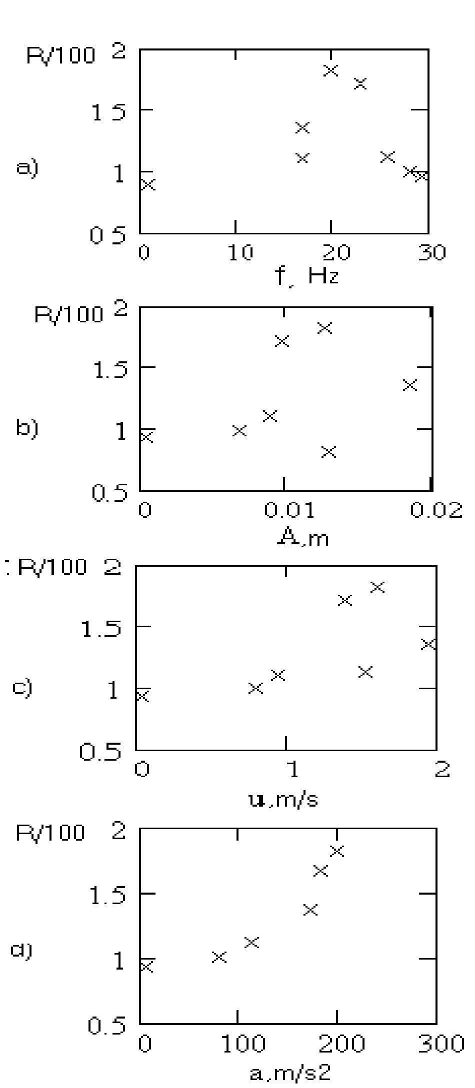

Fig. 4. Thermal resistance of a heat pipe as function of parameters of vibration

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 can not 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. 2).

DISCUSSION

The possible mechanism of influence of vibrations on heat and mass transfer processes with boiling in thermosyphons was presented in [1, 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

$$x = A \cdot \sin(wt)$$

that is

$$w_w = A \cdot w \cdot \cos(wt)$$

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 "parachute extraction", 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 values 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 value 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:

$$n\,\partial^2 w / \partial y^2 = \partial w / \partial t \qquad (1)$$

where ***w*** is speed of displacing layer of liquid, *n* is kinematical viscosity, *t* is time, ***y*** is coordinate.

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

at $t=0$: $w=0$ for $0£y£¥$;

at $t>0$: $w=w_R=Aw\cos(wt)$ for $y=0$;

at $t>0$: $w=0$ for $y=¥$.

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

$$w(y,t) = \frac{Ayw}{2\sqrt{pn}} \int_0^t \frac{\cos(w \cdot t) \cdot \exp\left[-y^2/4n(t-t)\right]}{\sqrt{(t-t)^3}} dt \qquad (2)$$

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:

$$d_0 w_w = \int_0^\infty w(y,t)\,dy \qquad (3)$$

where d_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_w (without slipping). The right part represents a rate of liquid which is running in this microlayer. The value d according to the theory of a boundary layer is equale displacement thickness of a boundary layer J_w and it determines thickness of microlayer at the moment of its formation. Parameter J_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_w . Let's rewrite (3) as follows

$$d = (1/w_w)\int_0^\infty w\,dy \qquad (4)$$

Substituting here by solution (2) we obtain a ratio

$$d = \frac{Aw}{2w_w\sqrt{pn}} \int_0^\infty y \int_0^t \frac{\cos(w \cdot t)\exp\left[-y^2/4n(t-t)\right]}{\sqrt{(t-t)^3}} dt\,dy \qquad (5)$$

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

$$d = \frac{Aw}{w_w}\sqrt{n/p}\int_0^t \frac{\cos(w \cdot t)}{\sqrt{t-t}} dt \qquad (6)$$

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

$$d = \frac{Aw}{w_w}\sqrt{n/p}\int_0^t (\cos(w \cdot t)\cos(w \cdot z)/\sqrt{z} + \sin(w \cdot t)\sin(w \cdot z)/\sqrt{z})\,dz \qquad (7)$$

This integral can be divides into two parts

$$d = \frac{Aw}{w_w}\sqrt{n/p}\cdot\cos(wt)\int_t^0 \frac{\cos(w\cdot z)}{\sqrt{w\cdot z}}d(w\cdot z) + \qquad (8)$$
$$+\frac{Aw}{w_w}\sqrt{n/p}\cdot\sin(wt)\int_t^0 \frac{\sin(w\cdot z)}{\sqrt{w\cdot z}}d(w\cdot z)$$

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)

$$d \approx \frac{2A\sqrt{wt}}{w_w}\sqrt{2n}\left[1-(wt)^2\right]$$

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 d is known.

Approximately efficiency of vibration action is determined by the formula

$$h = 1 + \frac{A\cos^2 q}{r_c(2 - q/45)}$$

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

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.

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