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THEORETICAL AND EXPERIMENTAL STUDY OF OSCILLATING HEAT PIPES WITH FEW TURNS

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A theoretical model of few-turn heat pipes is suggested. The equation for boiling liquid flow in a capillary of the pipe, which allows for the pressure difference of saturated vapor and for gravity and viscosity forces, is written. The parameters at which self-oscillations of the liquid occur have been estimated. It is shown that the period of self-oscillations is determined by the characteristic time of heat exchange between the liquid in the capillary and the surrounding medium. The time of self-oscillations obtained theoretically is in good agreement with the experimental one.

Oscillating heat pipes (OHP) are of interest because of their capability to operate in all orientations in space [1]. However, the operating principles of OHP and classical heat pipes differ. In heating from below, operation of OHP is similar to that of an ordinary thermosiphon with slightly superheated liquid, whereas in heating from above, boiling-up with large superheatings and, correspondingly, the same pressure and temperature differences are typical of them. We studied 25-, 20-, 15-, 10-, and 5-turn OHP. OHP were made of a stainless tube with an inner diameter d = 1.6 mm; the total length was 0.55 m and acetone was used as a heat carrier. Earlier, both return-flow and non-return-flow OHP circuits were tested. The experiments showed that the former circuit is more effective, since OHP manufactured according to it operated under all conditions and the results presented refer to this circuit (Fig. 1).

The main objective of the study is operation of OHP in the most unfavorable orientation, viz., the evaporator is at the top ($\varphi = 90^o$). All pipes operated satisfactorily in heating from below ($\varphi = -90^o$) and in a horizontal position ($\varphi = 0^o$); 25- and 20-turn pipes — in heating from above; 15- and 10-turn pipes — in heating from above but with weak (air) cooling. Sometimes, in re-switching on of OHP, it was necessary for a short period of time to arrange the heating zone below the cooling zone. In heating from above, a 5-turn pipe did not work at all [2]. Figure 2 shows the characteristic histogram of time intervals between boiling-ups for a 20-turn OHP ($\varphi = 90^o$) in air cooling. In this case, a mean time of oscillations is 26.9 sec.

Experimental Study of Few-Turn OHP. The inability of the few-turn OHP (in particular, a 5-turn pipe) to transfer heat in the field of gravitation can be explained by the fact that due to a small number of turns the probability of the presence of the heat carrier in the upper part of the turn is very low. Therefore, attempts were made to carry and keep the heat carrier in the upper part of the turn by any means.

Heat pipe with a liquid accumulator (Fig. 3a). To improve the probability of the presence of the heat carrier in the zone of heating, an additional vessel for the liquid — a hollow pipe with an inner diameter of 2 mm, which was hermetically sealed at the bottom — was inserted in the upper part of one of the turns. Accumulators of length 50, 100, and 150 mm were manufactured. The tests of this structure showed that if this vessel was initially filled by the liquid, two or three initial oscillations originated and thus the operation of the OHP stopped. The attempt to fill the 150-mm-long accumulator by a capillary-porous structure led to the same result. The liquid in the accumulator did not likely participate in general circulation, and its amount in the accumulator decreased with each boiling-up.

Heat pipe with an additional turn filled by a capillary structure. For the operation of a few-turn OHP with heating from above ($\varphi = 90^o$) it was suggested to double the upper part of one turn by a half-turn with a capillary-porous insert (Fig. 3b). To provide constant feeding of this half-turn by liquid, the places of its connection with the

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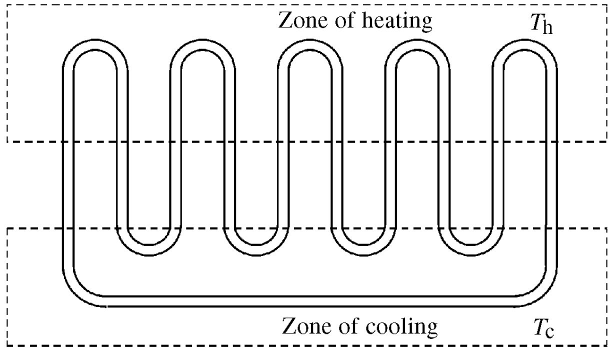
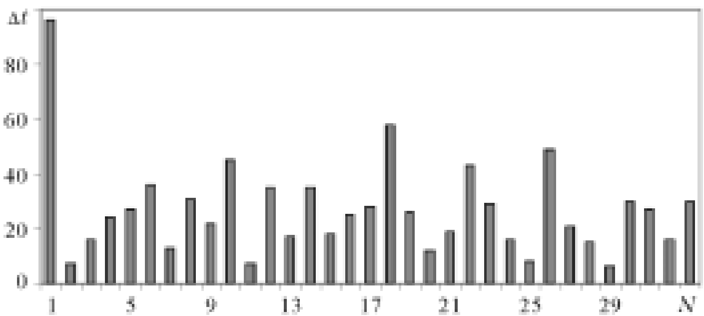


Fig. 1. Schematic diagram of OHP.



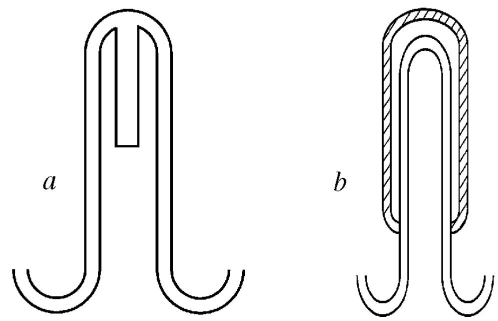


Fig. 2. Histogram of time intervals between boiling-ups for a 20-turn OHP. Δt, sec.

Fig. 3. OHP with a liquid accumulator (a) and an additional half-turn filled by a capillary-porous structure (b).

main structure were positioned below the level of pipe filling. The capillary structure was made of a nickel net with a mesh of 40 μm. This structure operated successfully. All experiments were conducted with filling of 0.4 of the total volume of the pipe. Air- and air-water cooling was executed. The histograms of time intervals between boiling-ups for a 5-turn pipe in air cooling are shown in Fig 4a, in air-water cooling — in Fig. 4b. The mean time of oscillations was 12.1 sec in the first case and 18.4 sec in the second case.

Theoretical Study of Oscillating Heat Pipes. Self-oscillations of all main parameters (temperature, flows of substance) are observed in oscillating heat pipes [1, 2]. In the case where the evaporator is positioned below, this structure operates as a classical thermosiphon. With the opposite orientation the pipe operates in an oscillating, i.e., unstable, mode. The cases of wide and narrow (compared to a bubble size) heat pipes must be considered separately. If the heater is placed below, the former will operate as a classical thermosiphon, while in the case of the upper position of the heater and when the pipe is filled by liquid not completely, heat transfer in this system is very small and is determined only by heat conduction. Thus, the effects of self-oscillations are related to the narrowness of the channel (tightness for vapor bubbles).

Let the heat pipe be partially filled by water. At the initial stage, the liquid in the upper part is heated till it begins to boil. In this case, at the place of boiling the vapor pressure is much higher than in the lower part. As a result, the liquid columns begin to move due to a considerable difference of pressures. Thus, the hot portions are brought to the cooler and the cold portions to the heater. As soon as the whole liquid leaves the heater (at the place where boiling occurred), boiling will stop and will resume only when the next portion of liquid, which came from the cooler to the heater, is heated to the temperature of boiling. Thus, organization of self-oscillations which are unstable relative to finite disturbances is possible in the system. If the whole liquid is accumulated in the lower part of the turns, boiling (and, thus, self-oscillations) will not begin. This situation resembles the oscillations of the pendulum of a clock, which begins to swing if it is rather strongly disturbed from the equilibrium condition. Self-oscillations can be implemented when the characteristic time of a tube liquid flow under the effect of the pressure difference is much smaller than the characteristic time of heat exchange between the liquid and the surrounding medium. To execute self-oscillations, it is necessary that, due to the pressure difference, the liquid column could rise at the height of the heater.

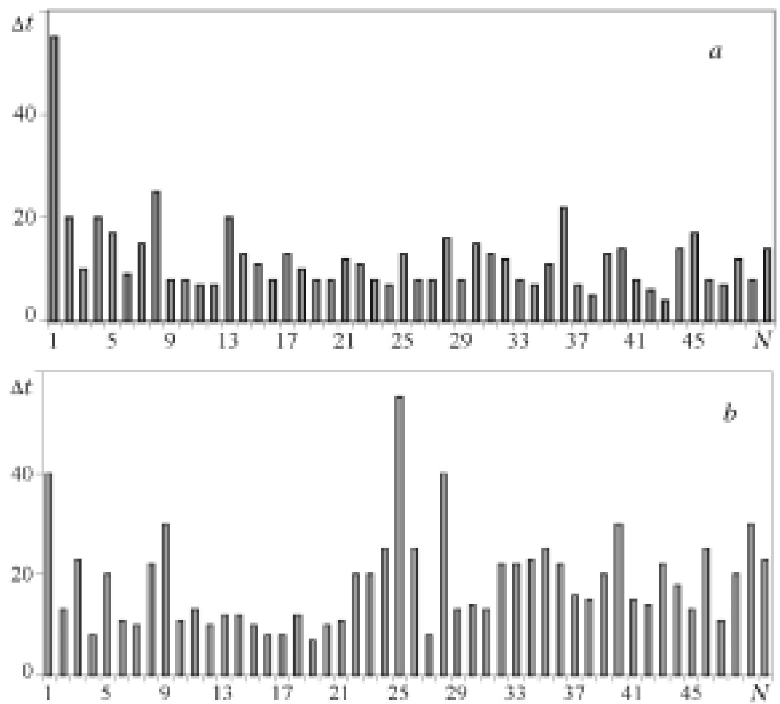


Fig. 4. Histogram of time intervals between boiling-ups for a 5-turn OHP in air cooling (a) and air-water cooling (b). Δt, sec.

The formed vapor also cannot immediately leave the liquid surface because of the hydraulic drag of the channel. Since, however, the viscosity of vapor is much smaller than the viscosity of liquid, we assume that the time of establishment of vapor equilibrium is small. We assume that the temperature distribution of the thermostat is set. Thus, we can find the coordinate where boiling will begin. We calculate the time of heat exchange between the liquid and the surrounding medium as

$$\alpha S (T_h - T_c) = \frac{C\rho V (T_h - T_c)}{\tau}, \quad \tau = \frac{C\rho L}{2\alpha}.$$

If the liquid boils up, then its temperature will be equal to the temperature of boiling (it will not increase), i.e., the part of the path the liquid will move in boiling and the part of the path without boiling and each part of the path requires its own equation of motion.

We consider a portion of liquid in one turn of the heat pipe (Fig. 5). In motion of liquid under its own momentum, under the level of equilibrium the vapor begins to condense (as in an ordinary heat pipe) and there is virtually no vapor on the right. On the left, the vapor pressure is small and, therefore, only a hydrostatic difference of pressures will affect the liquid (until it boils up). This quantity must not be high, otherwise the liquid will quickly drain back, having no time to boil up, and on the right the pressure will be low (since the evaporation rate is small). The height of the equilibrium column of liquid in the communicating vessels is determined as

$$a = \frac{L - b}{2}.$$

Let, at the initial instant of time, the height of the liquid column in the right capillary be h_0. If there were no boiling, oscillations would begin to damp. Since the surface tension is small (the characteristic height of the column is of about a millimeter), we neglect it. We write the equation of liquid motion:

$$-\rho SL \frac{du}{dt} = \Delta p S + 2\rho g (h - a) S - 8\pi\eta u L. \quad (1)$$

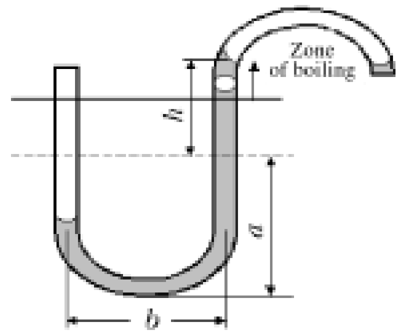


Fig. 5. An OHP turn partially filled by liquid. *h*, *a*, *b*, m.

From the estimation of the quantities from (1) we can distinguish several characteristic times: (1) accelerating, when the accelerating liquid moves virtually with equal acceleration until it crosses the boundary of boiling; (2) viscous, when, having passed some path, the liquid is retarded due to the forces of viscosity; (3) heat-exchanging, when the liquid stops (slowly drains) and is heated (cooled) till boiling begins again. The latter time is most lengthy and amounts to several seconds, which is in satisfactory agreement with the experimental data obtained in the present work. We transform Eq. (1) as

$$\frac{d^2y}{dt^2} + \frac{2g}{L}y - \frac{dy}{dt}\frac{8\pi\eta}{\rho S} = 0 , \tag{2}$$

where $y = \Delta pS + 2\rho g\ (h - a)S$. Then the solution of the equation $y(t)$ is standard and represents damping oscillations. For the mode without boiling, we take the pressure difference equal to zero. The solution is similar for this case. Thus, if the initial condition $y(0)$ and the governing parameters of the system are set, we first find the velocity of the liquid at the boundary of boiling cessation. It will represent the initial condition of liquid flow without boiling. The solution of Eq. (2) yields the coordinate of the liquid boundary as a function of time. It may appear that upon passage of the liquid column to the right part of the tube it will succeed to boil up (or even will not reach the region of boiling). Then, oscillations will be damping (the attractor is the point which corresponds to the equilibrium position of the liquid in the communicating vessels). With the different governing parameters there can exist solutions in the form of self-oscillations when the liquid will boil up in the left part of the tube and begin to move backward. In this case, the attractor is the limiting cycle. By nature these oscillations are close to self-oscillations in nonlinear systems [3]. It is obvious that self-oscillations will occur only in the presence of a rather large thermodynamic force — the difference of the heater and cooler temperatures. If this difference is not large, then the first term on the right-hand side of Eq. (1) turns out to be small compared to the second term. This will lead to a situation where the liquid moves slowly along the channel and will succeed in reaching thermal equilibrium with the surrounding. More precisely, the liquid simply will not reach the left portion of boiling. Consequently, the whole liquid will be accumulated at the bottom of the turns and the heat pipe will not operate.

As for the heat pipe as a whole, its behavior depends on the initial distribution of liquid. Since the boiling process is fast, having started in one of the turns, it impedes the origination of boiling in other turns, as cold portions of liquid will get to the heater.

Thus, we have suggested and experimentally tested the structure of the few-turn oscillating heat pipe, which is capable of operating in all orientations in space. We described the behavior of this heat pipe and showed that, with a small number of turns and a rather large difference of the heater and cooler temperatures, oscillations (self-oscillations) are observed in operation of the heat pipe. Based on the suggested theoretical model of the heat pipe we estimated the parameters at which these self-oscillations will occur.

NOTATION

T, temperature of the zone, $^{\circ}$C; φ, angle between the heat pipe axis and the horizon line, deg; Δt, time interval between the oscillations, sec; *N*, number of oscillations; *C*, heat capacity of the liquid, J/(kg·$^{\circ}$C); ρ, liquid density, kg/m^3; V and L, volume and length of the liquid column, m^3 and m; α, heat-transfer coefficient, W/(m$^2 \cdot {}^{\circ}$C); S, surface area of heat transfer, m^2; τ, time of heat exchange between the liquid and the surrounding, sec; $\Delta p(T)$, difference of saturated vapor pressures on both sides of the liquid column, N/m^2; g, acceleration of gravity, m/sec^2; η, liquid viscosity, nsec/m^2; u, velocity of the liquid, m/sec; d, inner diameter of the channel; h, height of the liquid column; a and b, dimensions of the turn. Indices: h, heating; c, cooling; 0, at the initial instant of time.

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