carrier fluid; ω_0, rotational frequency of the magnetic field; C_{vol}, volume concentration of particles; T, period of rotation; q, specific heat flux; Δt_{av}, average temperature difference between the walls; $K^i{}_{eff}$, effective heat transfer coefficient of the suspension in the rotating magnetic field.

LITERATURE CITED

1. I. S. Jacobs and F. E. Luborsky, J. Appl. Phys., 28, No. 4, pp. 460-463 (1957).
2. S. R. Gorodkin, B. É. Kashevskii, V. I. Kordonskii, and I. V. Prokhorov, Pis'ma Zh. Tekh. Fiz., 10, No. 2, 94-98 (1984).
3. H. Seiwatz, J. Appl. Phys., 29, 994-995 (1958).
4. S. R. Gorodkin, Hydrogasdynamics, Heat and Mass Exchange in Power Plants [in Russian], Minsk (1984), pp. 28-35.

HEAT-TRANSFER DEVICE FOR HEATING OF EXTENDED HORIZONTAL OBJECTS

L. L. Vasil'ev, M. I. Rabetskii,
and V. G. Kiselev

UDC 536.248

A heat pipe with total separation of vapor and liquid flows is described. The contruction allows transfer of high thermal fluxes over a significant distance with horizontal orientation of the object being heated.

In existing heat pipes the main limitations on the maximum thermal flux are the pressure and flow characteristics of the wick capillary structure. With increase in length of the heat pipe there is a decrease in thermal flux since hydraulic losses in the wick increase. For negative inclination of the heat pipe, where the evaporator is located above the condenser, a portion of the wick capillary potential is expended in overcoming the hydrostatic pressure of the heat-transfer agent column, which also leads to reduction of the achievable thermal load. Wickless heat pipes, i.e., thermosyphons, cannot transfer large quantities of heat in the horizontal position due to the braking action of vapor on the condensate, and they are not usable at all in a negative orientation.

The basic technique for improving the heat-transfer parameters of long heat pipes operating in a horizontal position or with negative inclination is the elimination of interaction between vapor and liquid fluxes by the use of separator inserts [1]. Use of individual channels for vapor and condensate and capillary-porous packing in the evaporator, playing the role of a hydraulic seal, led to development of antigravity heat pipes (AGTT's), which can operate with unfavorable orientations [2]. However, because of their complex structure and poor thermotechnical characteristics their use has been limited.

Heat-transfer devices have been proposed [3-7] which organize the interaction of the vapor and condensate to produce a positive effect. Constructions which produce this effect have permitted increasing the length of the heat-liberating surface and the limiting thermal flux by a factor of several times as compared to the parameters of known heat pipes. A diagram of the simplest such device, called a vapor-dynamic thermosyphon (VDTS), is shown in Fig. 1.

The vapor-dynamic thermosyphon consists of four major components: the evaporator 6, condenser 3, auxiliary reservoir-condenser 4, and transport zone, including the hydrostatic seal 5 and vapor guide 1. The evaporator is partially filled with the heat transfer agent, which is located in contact with the heating surface of the heating elements 9. The main condenser consists of tubes of different diameters arranged coaxially to form a vapor supply zone 2 and an annular gap zone 3 with heat liberating surface 7. At one end the annular condenser channel communicates with the evaporator through vapor guides 2 and 1, and at the other end

---

A. V. Lykov Heat and Mass Transfer Institute, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 52, No. 1, pp. 62-66, January, 1987. Original article submitted November 28, 1985.

0022-0841/87/5201-0048$12.50

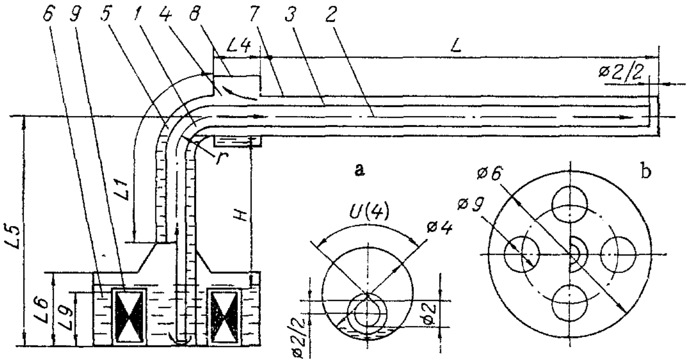

Fig. 1. Diagram of vapor-dynamic thermosyphon for heating extended horizontal objects: a) reservoir-condenser section; b) evaporator section.

is connected to the auxiliary condenser which consists of the reservoir 4 and heat exchange surface 8. It is designed to create a moving head and accumulation of uncondensed heat transfer agent components. The auxiliary reservoir-condenser is located between the annular channel 3 of the main condenser and the liquid channel 5 of the transport zone. During operation the transport zone annular channel is filled with heat transfer agent, thus forming a liquid hydrostatic gate which compensates the pressure loss during circulation of the heating agent through the VDTS and eliminates oppositely directed motion of the vapor and liquid phases of the working medium. Aside from the hydrostatic force, various types of vapor-dynamic devices use other forces to return heating agent from the condenser to the evaporator as in known evaporation-condensation devices, for example, capillary, osmotic centrifugal, electrodynamic, etc. Several variants of the vapor-dynamic principle for return of condensate to the evaporator are shown in Fig. 2. The devices under consideration can be divided into three classes: vapor-dynamic heat pipes (VDTT), vapor-dynamic thermosyphons (VDTS), and vapor-dynamic heat guides (VDHG).

For the VDTS the maximum moving head which can be produced by the liquid seal depends on the height of the heating agent column in annular channel 5 of the transport zone:

$$\Delta P_{\mathrm{max}} = \rho_l gH\cos U. \tag{1}$$

The total pressure loss in vapor and liquid over the entire circuit cannot exceed the value of this head

$$\Sigma\Delta P_{\mathrm{fr}} + \Sigma\Delta P_{\mathrm{acc}} + \Sigma\Delta P_{\mathrm{loc}} \leqslant \Delta P_{\mathrm{max}} \tag{2}$$

In contrast to conventional heat pipes, a second condition for stable operation of the VDTS follows from the Clapeyron–Clausius equation

$$\Delta P_{\mathrm{max}} = \frac{dP}{dT}\bigg|_T (T_{\mathrm{e}}^{\mathrm{v}} - T_{\mathrm{r.c}}^{\mathrm{v}}) \simeq \frac{2r\rho_l\rho_{\mathrm{v}}}{\rho_l - \rho_{\mathrm{v}}}\,\frac{T_{\mathrm{e}}^{\mathrm{v}} - T_{\mathrm{r.c}}^{\mathrm{v}}}{T_{\mathrm{e}}^{\mathrm{v}} + T_{\mathrm{r.c}}^{\mathrm{v}}}. \tag{3}$$

Thus, depending on orientation, the internal thermodynamic limitations on the limiting thermal load of a VDTS can be determined by simultaneous solution of Eqs. (3) and

$$\Sigma\Delta P_{\mathrm{fr}} + \Sigma\Delta P_{\mathrm{acc}} + \Sigma\Delta P_{\mathrm{loc}} = \rho_l g(H\cos U - L\sin U). \tag{4}$$

Results of calculations with Eq. (4) are shown in Fig. 3.

Three fundamental facts distinguish the operation of the VDTS: 1) presence of only unidirectional motion of the condensing two-phase flow in the annular channel, where because of dynamic action of the vapor on the condensate film removal of liquid from the condensation surface occurs; 2) creation of a moving pressure differential in the vapor, removal of impurities, and encouragement of high speed phase interaction due to use of a portion of the vapor flow energy by its condensation in a special auxiliary reservoir-condenser; 3) presence of a liquid seal to compensate pressure losses in the VDTS and prevent recirculation of vapor.

The unidirectional flow of the two-phase mixture achieved by use of the auxiliary condenser and liquid seal causes a thinning of the liquid film on the wall, intensifies the condensation process, and encourages removal of condensate from the annular gap of the main condenser due to friction forces and dynamic action of the vapor on the liquid.

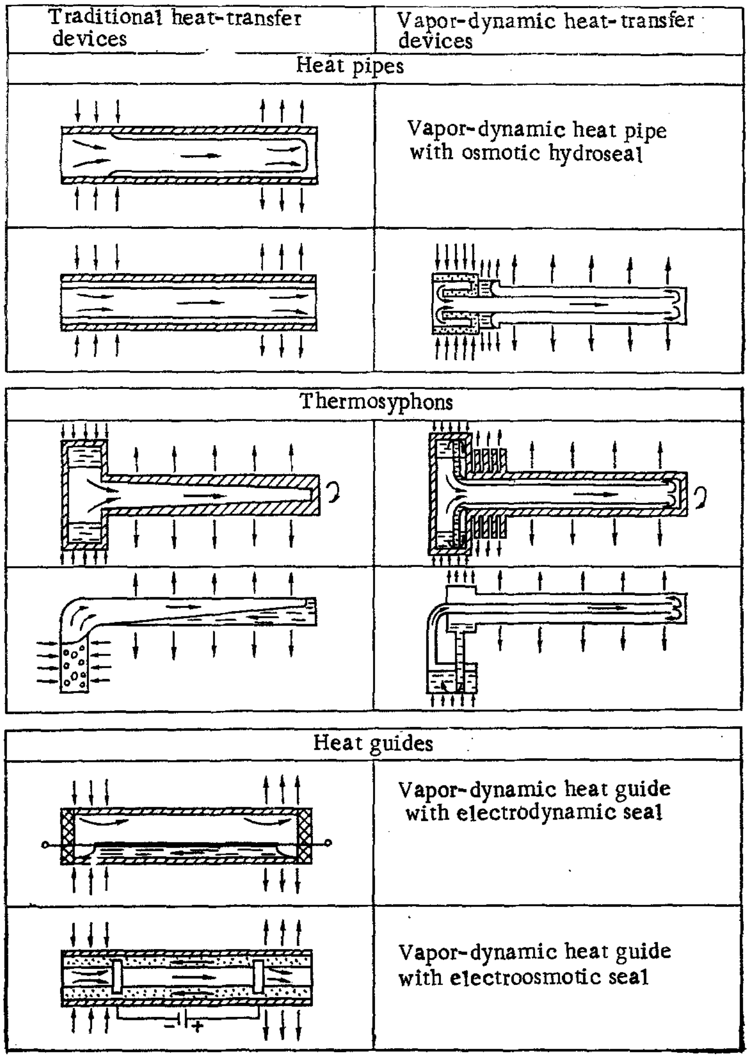

Fig. 2. Classification of vapor-dynamic heat transfer devices.

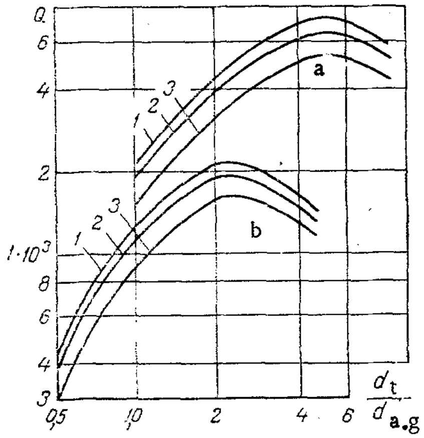

Fig. 3. Limiting thermal flux vs ratio of hydraulic diameters of vapor-dynamic thermosyphon condenser for vapor—vapor (a) and vapor—liquid (b) regimes; $L_c = 4.5$ m, $d_c = 16$ mm, $H = 0.5$ m, $T_v = 100°C$: 1) inner condenser tube wall thickness 0.2 mm; 2) 0.5; 3) 1.0. Heat-transfer agent, water.

The operating mechanism of the VDTS considered here is the device's distinguishing feature, allowing its effective functioning with unfavorable orientation and significant extent of the condenser heat-liberation zone.

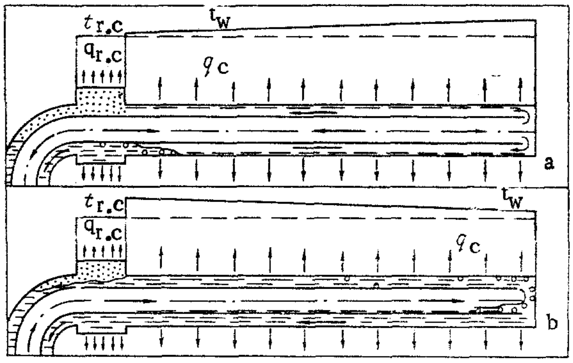

Fig. 4. Distribution of heat-transfer agent liquid and vapor phases in VDTS channels for operation in vapor—vapor (a) and vapor—liquid (b) regimes.

To obtain further information, primarily on the hydrodynamics of the two-phase flow in the coaxial condenser, experiments involving visualization of the flow structure were performed in an experimental model of a vapor-dynamic thermosyphon 1.2 m long. The results indicated the presence of two significantly different regimes of VDTS condenser operation — vapor—vapor and vapor—liquid (Fig. 4).

In the vapor—vapor regime in the glass model VDTS with water as the working substance at inclinations of ±5° a limiting thermal flux of 3.2-3.5 kW at an axial density of about 60 MW/m^2 was reached.

Full-scale experiments were also performed with devices using the vapor-dynamic principle of operation at condenser lengths of 6, 10, 10, 20, and 40 m. The 6-m VDTS was used successfully to protect railroad switches from snow and ice under winter conditions.

A positive advantage in such applications as compared to direct electrical heating is the ability of evaporation—condensation devices to automatically redistribute the thermal flux along zones with differing heat-exchange intensity. This permits rational exploitation of the heat used to warm the object.

The analysis performed and test results indicate that the proposed working liquid circulation technique significantly improves the heat-transfer characteristics of heat pipes and expands their range of use.

NOTATION

d, diameter, m; g, acceleration of gravity; L, length, m; q, thermal flux density, W/m^2; r, latent heat of evaporation, J/kg; P, pressure, N/m^2; T, temperature, °K; U, angle of inclination; N, height of hydroseal, m; ρ, density, kg/m^3; subscripts: v, vapor; ℓ, liquid; w, wall; e, evaporator; c, condenser; r.c, reservoir-condenser; a.g, annular gap.

LITERATURE CITED

1. A. P. Shlosinger, USA Patent No. 354839, Multichamber Controllable Heat Pipe (1970).
2. Yu. E. Dolgirev, Yu. F. Gerasimov, Yu. F. Maidannik, et al., Inzh.-Fiz. Zh., 34, No. 6, 988-993 (1978).
3. L. L. Vasil'ev, V. G. Kiselev, V. I. Morgun, et al., Inventor's Certificate No. 1081409, "Heat Pipe," Byull. Izobret., No. 11 (1984).
4. V. M. Bogdanov, L. L. Vasil'ev, and V. G. Kiselev, Inventor's Certificate No. 1104350 "Heat Pipe," Byull. Izobret., No. 27 (1984).
5. L. L. Vasil'ev, V. G. Kiselev, V. A. Morgun, et al., Inventor's Certificate No. 1105745, "Heat Pipe," Byull. Izobret., No. 28 (1984).
6. L. L. Vasil'ev, V. G. Kiselev, and M. I. Rabetskii, Inventor's Certificate No. 1111014, "Heat Pipe," Byull. Izobret., No. 32 (1984).
7. L. L. Vasil'ev, V. G. Kiselev, V. A. Morgun, et al., Belgium Patent No. 879630, Heat Transfer Device (1984).