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# HEAT PIPES BASED ON NAPHTHALENE


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The authors describe an experimental investigation of heat pipes for the mean temperature range. Data for tests of a heat exchanger of air–air type are given.


Heat pipes, thermosiphons, and heat exchangers based on them are finding wider application as efficient heat-transfer devices, offering intensification of heat-transfer processes and also good heat energy economy [1].

The temperature region in which heat pipes operate is very wide, from low cryogenic to very high temperatures. The temperature range of stable operation of heat pipes is determined mainly by the wall material and the properties of the heat-transfer agent. Heat-transfer agents include water, liquefied gases, organic liquids, and fusible metals. Liquid metal heat-transfer agents, which give large specific heat-transfer flux, operate, as a rule, at high temperatures, not spanning the mean temperature range (150-600°C). Therefore, it is an urgent matter to find, investigate, and apply practically to heat pipes a rather inexpensive and reliable heat-transfer agent capable of long-term stable operation in the above temperature range. In the use of sulfur with iodine additives [2-4], a number of problems arise, connected with the high reactivity of the sulfur–iodine mixture and also the strong dependence of the viscosity of sulfur on temperature, leading to instability of the characteristics of these heat pipes. Therefore, it is more promising to use naphthalene as a heat-transfer agent.

Naphthalene is a product of oil production, its chemical formula is $C_{10}H_8$, and its molecular weight 128.16. At ordinary temperature it is a white-colored solid with a fusion temperature of 80.3°C and a boiling temperature of 218°C. Liquid naphthalene has very low viscosity, which decreases considerably with increase of temperature. Thus, its basic properties are quite suitable for use as a heat-transfer agent in heat pipes and heat exchangers of the mean temperature range.

The aim of this paper is to investigate heat-transfer equipment with naphthalene as heat-transfer agent in long-term operation, to explore the desirability and the promise of creating heat exchangers in heat pipes with naphthalene. Tests were made with two types of two-phase thermosiphons with steel and tantalum walls and with a vapor-dynamic thermosiphon. The geometric parameters of the thermosiphons and the naphthalene mass in them are given in the legend of the appropriate figures. The experimental equipment contained traditional nodes and elements necessary to investigate heat pipes: a test thermosiphon with an ohmic heater, a source of stabilized and regulated power, and instruments for measuring the electrical power and the thermal emf, and thermocouples. Chromel–Alumel thermocouples were welded along the generator of the thermosiphon at equal distances. The experimental technique and the facility were described in detail in [5].


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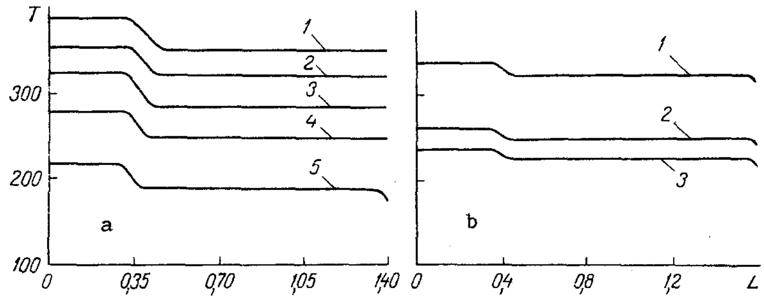


Fig. 1. Temperature distribution along a titanium (a) and a steel (b) thermosiphon with naphthalene for different values of the heat flux supplied: a) 1) Q = 1200 W; 2) 1000; 3) 800; 4) 600; 5) 400; L = 1.4 m, d = 22.4 m, D = 27 mm, m = 100 g; b) 1) Q = 1600 W; 2) 1000; 3) 800; L = 1.4 m, d = 24.0 mm, D = 27 mm, m = 200 g. T, °C; L, m.

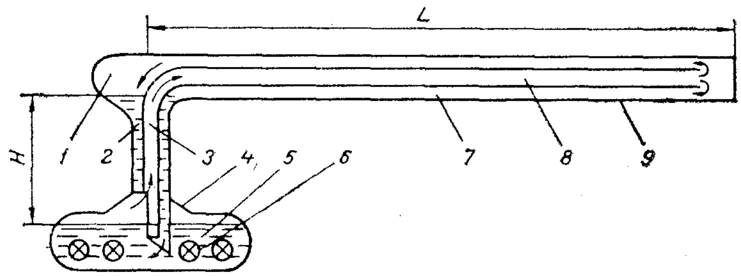


Fig. 2. Structure of the vapor-dynamic thermosiphon.

During the experiments we investigated the temperature fields of the thermosiphons as a function of the electrical power supplied, with free convective cooling of the condenser, to evaluate subsequent use of the devices in heat exchangers of air—air type.

The experiments were conducted over a period of 3 years, with a total operating time of about 3000 h. No substantial deviations in the operation of the thermosiphons was observed. The mean operating temperature was 320°C. The slope angle of the thermosiphons to the horizontal was varied from 10 to 90°. Here the nature of the temperature distribution along the heat pipe did not change appreciably. Figure 1 shows a typical dependence of the temperature along the thermosiphons, averaged over the data of many experiments. The temperature fields in the condensation zone were distinctive for being highly isothermal and stable.

From the good reproducibility of the results in the long-term reliability tests, one can conclude that naphthalene is compatible with steel 20 and titanium up to temperature of 350°C.

The long-term and multiply repeated experimental investigations have shown stable operation of thermosiphons in different thermal regimes, stable characteristics of thermosiphons, and the possibility of using them up to temperatures on the order of 350-400°C, which is evidence of the absence of any kind of irreversible process in the interaction of the heat-transfer agent with the wall material. We have performed analogous investigations with the so-called vapor-dynamic thermosiphon (BDTS), which has been described in detail in the literature [6-13].

The vapor-dynamic thermosiphon combines in its construction the different features of horizontal heat pipes and vertical thermosiphons, which give in the combination a new type of equipment for heat transfer to a considerably greater distance with a low temperature difference. Figure 2 shows a schematic diagram of the vapor-dynamic thermosiphon. Its mechanism of operation is as follows. Upon supply of heat flux from the heater 6 to the heat-transfer agent 5 the vapor moves along the conduit 3, through the internal tube 8 and reaches the annular channel 7 of the condenser 9 and condenses there. The condensate formed under the action of the vapor flux moves along the annular gap, reaches the supplementary condenser 1, and thence returns along the merging channel 2 under the action of gravity to

TABLE 1. Temperature of Air (1, 2) and Stack Gases (3, 4) during Tests of the Heat Exchanger – Utilizer

| Degree of overlap of bypass channel, % | Temp., °C | | | |
|---|---|---|---|---|
| | № 1 | № 2 | № 3 | № 4 |
| 0 | 59±2 | — | 270±10 | 1000±50 |
| 0 | 100±2 | 96±2 | — | — |
| 65 | 146±2 | 135±2 | 460±5 | 850±10 |

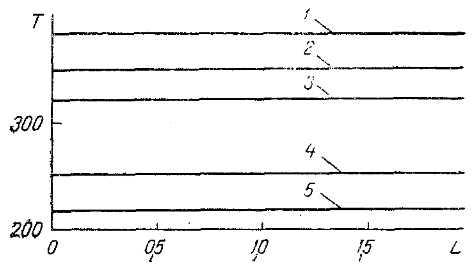


Fig. 3

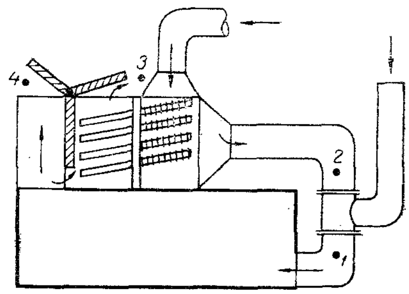


Fig. 4

Fig. 3. Temperature distribution along a vapor-dynamic thermosiphon with naphthalene, with free-convective cooling of the condenser: 1) Q = 2200 W; 2) 1800; 3) 1500; 4) 1300; 5) 900.

Fig. 4. Diagram of the recuperator equipment in the heating oven: 1-4) number and location of the temperature sensors in the tests.

the evaporator 4. In [6] water and acetone were used as heat-transfer agents for a vapor-dynamic thermosiphon. In the present work we investigated that equipment with naphthalene. The basic parameters of the thermosiphon are as follows: the wall material is 12Kh18N9T, the length is 2222 mm, the height is 500 mm, and the naphthalene mass is 2800 g. The naphthalene was charged into the vapor generator and warmed up above the fusion temperature. By further increase of the power supplied to the evaporator we could force out residues of non-condensible gases with naphthalene vapor under excess pressure through a special valve of the supplementary condenser.

Figure 3 shows the temperature characteristics of the vapor-dynamic thermosiphon obtained under free convection cooling of the condenser. The highest temperature level (380°C), corresponding to a heat flux of 2.2 kW, is not a limit for the vapor-dynamic thermosiphon.

The results of the investigations on thermosiphons with naphthalene were used to create a recuperative heat exchanger of air–air type to utilize the heat of stack gases in the heating oven of a forge and press workshop. The scheme for testing the recuperator is shown in Fig. 4. The temperature of the efflux gases was in the range 800-1000°C. The heat load in the heat exchanger was controlled by varying the degree of overlap of the damper of the bypass channel for the stack gases. Table 1 shows the results of the last tests, conducted after 1500 h of operation of the heat exchanger in the heating oven.

The tests of the heat exchanger–recuperator using thermosiphons with naphthalene have confirmed that it is suitable and efficient in natural operating conditions, and have identified a number of problems for further study in this direction.

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# PERIODIC STATES IN A PRESSURIZED FLOW SHOWING A PHASE TRANSITION

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The scope for long-term operation in periodic mode is examined for a pipeline carrying a liquid that can freeze.

A phase transition may occur in a pressurized liquid in a pipe, an example being provided by a pipeline carrying a liquid when the environmental temperature is below the freezing point [1, 2]. There are several papers [3-5] on the effects of phase transitions on flow-pressure characteristics. The studies concern states where a layer of frozen liquid is formed on the inner surface, which increases the hydraulic resistance and thus raises the pumping energy required. Therefore, when a pipeline is designed for such conditions, the insulation parameters are usually chosen to prevent a frozen layer from forming. However, the insulation may be damaged on some parts of the line, and if those are sufficiently extended, this is immediately reflected in the thermal and hydraulic conditions, and one can detect the insulation damage from the changes in flow-pressure and temperature characteristics. The operations are only slightly affected by short damaged parts, but the growth of a frozen layer there may block the pipe. One therefore has to examine the long-time operation for a pipe having damaged insulation.

A pipeline may be operated with pumping halts, which greatly increase the blocking hazard. It is therefore of interest to estimate the permissible halt time and to examine the scope for periodic operation.

Here we consider flow in a circular pipe for a viscous liquid at temperature $T_1$, where the freezing temperature $T_*$ is above the environmental temperature $T_0$. Under those conditions, the liquid may freeze and form an internal surface $r_*$. We consider a short pipe ($2\pi k_2 R/\rho_2 c_2 Q\ell \gg 1$), through which the liquid is pumped with flow rate Q.

We assume that the characteristic thermal and hydrodynamic relaxation times are much less than the characteristic phase-transition time, so

$$\rho_1 c_1 \frac{\partial T}{\partial t} = \frac{\lambda}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right), \; r_* < r < R, \qquad (1)$$

$$\lambda \frac{\partial T}{\partial r} + k_1 (T - T_0)|_{r=R} = 0, \qquad (2)$$

$$T|_{r=r_*} = T_*, \qquad (3)$$

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