TWO-PHASE LOOP THERMOSYPHONS

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Abstract
The paper presents the results of development and investigation of two-phase loop thermosyphons with different working fluids operating in the temperature range from 40 to 150 °C at heat loads from 10 to 3000 W and also various heat-transfer devices created on their basis.

KEYWORDS
loop thermosyphon, heat transfer, cooling system, heating system, evaporation, condensation.

INTRODUCTION
Among two-phase heat-transfer devices, such as heat pipes [1], loop heat pipes [2], oscillating heat pipes [3] and thermosyphons [4], the last ones are the simplest both in design and manufacture and for the description of thermophysical and hydrodynamic processes observed in them. At the same time two-phase thermosyphons (TS) are efficient enough heat-transfer devices, which may be used both for heat transfer in heating and heat-supply systems and for cooling various devices, including electronics. These devices may be separated into two main types: conventional thermosyphons and loop thermosyphons (LTS) [5–14].

The schematic diagram of these devices is presented in Fig. 1.

Fig. 1. Schematic diagram of two-phase thermosyphons: a – conventional thermosyphon, b – loop thermosyphon.

A conventional thermosyphon consists of a vacuum-sealed pipe, which is partially filled with a working fluid in the vapor and liquid phase. The volume fraction of the liquid phase of the working fluid in a TS is usually 30–50%. When heat is supplied to the evaporation zone, the liquid begins to boil. The beginning of boiling is, as a rule, preceded by a certain superheating, whose magnitude is determined by the thermal properties of the working fluid. The vapor generated in this case rushes into the condensation zone, where it
condenses and passes the heat through the condenser wall to an external heat sink. The motions of the liquid and the vapor phase of the working fluid are countercurrent to each other. The upward current of vapor moves along the pipe axis from the evaporation zone, where the pressure is higher, into the condensation zone, where the pressure is lower. The downward current of the condensate in the form of a film flowing down over the inner surface of the pipe returns into the evaporation zone under the action of gravity forces.

This circumstance leads to a limitation on the TS heat-transfer capacity owing to an additional hydrodynamic resistance resulting from the viscous interaction between the counter flows of vapor and liquid, which increases with an increase in the heat load, and also a decrease in the diameter and an increase in the device length.

The problem mentioned may be solved by using the loop scheme presented in Fig. 1, b. The first information about realization of this scheme in this device under the name of “evaporation-condensational apparatus”, designed for electronics cooling, related to 1967 [5]. The fundamental difference of such a scheme consists in the fact that the motion of vapor and liquid flows here proceeds in different pipelines separated spatially. This makes it possible to avoid a negative hydrodynamic and thermal interaction between the opposite flows of the vapor and liquid phases of the working fluid.

When heat is supplied to the evaporation zone, the vapor speeds into the condensation zone, where it condenses and gives up heat to an external heat sink. The condensate returns into the evaporation zone through the liquid line under the action of the hydrostatic pressure \( \Delta P_g \) arising from the difference of the liquid levels in the evaporation and condensation zones:

\[
\Delta P_g = \rho_l - \rho_v \rho_l h_1 - h_2 g,
\]

where \( \rho_l \) and \( \rho_v \) are the liquid and vapor densities, respectively; \( h_1 \) and \( h_2 \) are the heights of the liquid levels; \( g \) is the free fall acceleration.

Thus the return of the condensate into the evaporator in both a conventional and a loop thermosyphon is realized under the action of gravity forces. Hence follows the obligatory condition of serviceability of these devices which requires that the “vapor-liquid” interface in the condenser be higher than such an interface in the evaporation by \( \Delta h = h_2 - h_1 \).

In this case it is necessary to fulfill the condition:

\[
\Delta P_g = \Delta P_v + \Delta P_l,
\]

where \( \Delta P_v \) is the pressure losses for the motion of vapor; \( \Delta P_l \) is the pressure losses for the liquid motion. The LTS serviceability in this case may be retained in a sufficiently wide range of slopes towards a horizontal plane, as pressure losses in this adiabatic zone are considerably lower.

Among additional advantages of LTS is the possibility to use flexible pipelines connecting evaporation and condensation zones, which may have relatively small diameters. This allows simplifying considerably their tracing during the location of LTS in various objects. Besides, there appears a possibility of different embodiments of evaporation and condensation zones, which may be made in the form of separate elements - evaporator and condenser - specially adapted to the conditions of heat load supply and removal (Fig. 2).
The paper generalizes and presents the results of development and investigation of two-phase loop thermosyphons, and also various heat-transfer devices created on their basis. This work has been performed at the Institute of Thermal Physics of UB RAS and aimed at the solution of problems connected with both heating and cooling of different objects.

INVESTIGATION OF LTS THERMAL CHARACTERISTICS

Among the main thermal characteristics of two-phase heat-transfer devices are the maximum capacity, the heat flux in the evaporation zone and thermal resistance. For analysis use is also often made of the dependence of the characteristic operating temperature on the heat load supplied to the evaporation zone. For the characteristic temperature one can use the temperature of the evaporator wall or the vapor, whose heat-load dependence have qualitatively similar forms. To determine the thermal resistance of a device, which is usually written as:

$$R = \frac{T_e - T_c}{Q},$$

where $T_e$ and $T_c$ are the average wall temperatures of the evaporator and the condenser, respectively, and $Q$ is the heat flow transferred, it is also necessary to know the temperature of the condenser wall.

Several experimental devices made of stainless steel with water as a working fluid have been developed for investigating the thermal characteristics and peculiarities of LTS. The scheme of one of them is presented in Fig. 3.

![Fig. 3 Scheme of an LTS with air-liquid cooling of the condenser](image)

The main structural characteristics of an LTS are given in Table 1.

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<tr>
<td>Evaporator active zone length / diameter, mm</td>
<td>140 / 24</td>
</tr>
<tr>
<td>Condenser length / diameter, mm</td>
<td>400 / 18</td>
</tr>
<tr>
<td>Vapor line length / diameter, mm</td>
<td>750 / 6</td>
</tr>
<tr>
<td>Liquid line length / diameter, mm</td>
<td>1300 / 4</td>
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The volume of filling with a working fluid was 60% of the total internal volume of the device.

The LTS was tested at different slopes towards a horizontal plane in the range from 0 to –90°. The zero slope corresponded to the device position shown in Fig.3, where the height difference between the upper end of the evaporator and the lower generator of the condenser was equal to 45 mm. At an LTS orientation with a slope of –90° the condenser was situated vertically, and the evaporator occupied the lower horizontal position. To cool a condenser made in the form of a pipe-in-pipe heat exchanger, use was made of running water with a temperature of 7.5±0.5 °C, and also forced air convection. The latter was created by three compact fans connected in parallel, which blew over the aluminum annular radiator enveloping the outer surface of the condenser. An electrical heater was used for heating the evaporator. Its active length
corresponded to the length of the evaporation zone. The heat load magnitude varied stepwise with a step of 50 W to a maximum value of 900 W and was limited by the heater capacity. Measurements were also made of the wall temperatures of the evaporator and the condenser, and also of the temperatures of the vapor and condensate lines. Standard copper-constantan thermocouples with data acquisition unit were used for the measurements.

Figs. 4 and 5 present experimental results in the form of heat load dependences of the evaporator wall temperature at various slopes for different means of condenser cooling.

**Fig. 4.** Heat-load dependence of the evaporator temperature under liquid cooling of the condenser.
Slope: o - 0°, x - 15, ж - 30°, + - 45°, 0 - 60°, □ - 75°, Δ - 90°

**Fig. 5.** Heat-load dependence of the evaporator temperature under air cooling of the condenser.
Slope: o - 0°, ◊ - 60°, Δ - 90°

The test results have shown that an LTS is capable of operating at all slopes both with liquid and with air cooling of the condenser. In both cases the highest efficiency was achieved at slopes close to -60°, when the thermal resistance of the device had a minimum value equal to 0.05 °C/W for liquid cooling and to 0.03 °C/W for air cooling at a heat load of 900 W. At the same time minimum values of the operating temperature were attained at a zero slope, when the evaporator orientation was the most favorable for the beginning of boiling. However, the maximum capacity of the device operating in such a position did not exceed 300 W. It should also be mentioned that one can trace well the range from 50 to 400 W, where the
operating temperature varies rather slightly with increasing heat load at slopes from $-15$ to $-90^\circ$. Such a behavior is not observed during the operation of conventional thermosyphons, but it is quite typical of loop heat pipes operating in variable-conductance behaviour. This peculiarity manifests itself as a result of a progressive displacement of the liquid from the condenser with an increase in the heat load up to a certain value. Also specific is the process of LTS operation accompanied by pulsations of the operating temperature and sound effects typical of the operation of oscillating heat pipes [16]. The amplitude and the frequency of these pulsations changing with increasing heat load and also depending on the slope. A characteristic temperature diagram for an LTS operating at a slope of $-45^\circ$ is given in Fig. 6.

![Fig. 6. Operating temperature diagram of an LTS at slope $-45^\circ$.](image)

It should be mentioned that at slopes exceeding $-15^\circ$ no heat-transfer crisis has been attained in the LTS evaporation zone. A further increase in the heat load was limited only by the capacity of the heater. According to calculations made for different vapor temperatures, whose results are presented in Fig. 7, the value of the limiting capacity for the LTS under discussion, on the basis of hydrodynamic restrictions, may be considerably higher than that obtained in experiments.

![Fig. 7. Calculated dependence of LTS limiting capacity on $\Delta h$ at different vapor temperatures.](image)

Vapor temperature: 1 – 80 °C, 2 – 100 °C, 3 – 120 °C, 4 – 140 °C

HEATING DEVICE
The high heat-transfer capacity of loop thermosyphons, which is determined by the product of the magnitude of the heat flow transferred by the heat-transfer distance, makes it possible to use them, in particular, for heating or thermostating objects far removed from the heat source. A number of experimental devices on the basis of LTS with water as a working fluid have been created for these purposes. The scheme of one of them is presented in Fig. 8.

![Fig. 8. Scheme of a heating device.](image)

The device was equipped with a cylindrical evaporator 48 mm in diameter and 330 mm in length, inside of which there was a heater with a maximum capacity of 3 kW. The condenser-heat exchanger made in the form of a bundle of tubes connecting the liquid and vapor collectors had a finning formed by parallel plates with a total area of about 1 m² and was located in a casing together with a fan. The evaporator and the condenser were joined by a flexible vapor and liquid lines with an internal diameter of 6 mm and a length of 120 mm. The evaporator heater was connected with an electronic controller, which made it possible to maintain the vapor temperature in the device at a prescribed level. Fig. 9 shows the characteristic dynamics of temperature variation during the operation of a device with a heating controller.

![Fig. 9 Dynamics of temperature variation during the operation of heating device at a heat load of 3000 W](image)

**COOLING SYSTEM “LTS-TEM”**
The use of an LTS in combination with a thermoelectric module (TEM) operating on the basis of the Peltier effect allows creating an efficient system for cooling compact objects, in particular, optical sensors operating at temperatures lower than the outside ambient. It is known that for maintaining a low temperature on the “cold” side during the operation of a TEM it is necessary to remove heat from its “hot” side. Special radiators are usually used for this purpose. If such radiators operate under natural air convection, they have a large heat-transfer surface and a sufficiently massive base for providing acceptable isothermality as the area of their thermal contact with the TEM is relatively small. Such a system has an extra mass and an increased thermal resistance. Besides, the radiator has always to be in direct thermal contact with the TEM, which is far from being acceptable in all cases.

Fig. 10 presents one of experimental versions of a cooling system based on a loop thermosyphon and a thermoelectric module of MDI-127 -1,4/1,6 type. Such a system was used to cool an electric simulator of a heat source.

In this system use was made of an LTS with ammonia as a working fluid, which had a compact cylindrical evaporator 70 mm in length and 9 mm in diameter. Evaporator was equipped with a copper thermal interface with dimensions of the thermocontact surface 40×40 mm² corresponding to the dimensions of the TEM. The condenser was made in the form of a flat coupled with a light aluminum radiator with corrugated finning, which measured 400×400×10 mm³. The diameter of the tubes of the vapor line, the liquid line and the condenser was equal to 4 mm. The TEM ensured a maximum refrigerating capacity of 55 W at an inherent power consumption of 37 W.

Fig. 11 presents the heat-load dependence of the temperature of the object being cooled in cooling the radiator by means of natural air convection at an ambient temperature of 25 °C.

Fig. 11 Heat-load dependence of the temperature of the object being cooled: □ – LTS, o – LTS-TEM
The results obtained show that the cooling system “LTS-TEM” allows maintaining the temperature of the object being cooled below that of outside ambient at heat loads up to 15 W. This exceeds considerably the maximum heat flow dissipated by optical sensors or quantum-electronic modules, for cooling of which this system may be used.

**TRANSFORMER COOLING**

One of the first experimental developments aimed at the industrial application of LTS was a cooling system for windings of electric transformers with capacities of 100 and 160 kVA [18].

The scheme of the device is given in Fig. 12.

![Fig. 12. Scheme of transformer cooling](image)

The distinctive feature of this cooling system consisted in the fact that the LTS had a coaxial cylindrical evaporator located vertically in the gap between the transformer windings. The cylindrical condenser was situated horizontally right above the evaporator. The entrance of the liquid line and the exit of the vapor line which had diameters of 6 and 8 mm, respectively, were located in the upper butt-end part of the evaporator. The finning the condenser was equipped with was intended for operation with cooling by means of natural convection.

**COOLING OF PERSONAL COMPUTERS**

The most heat-tensioned components of personal computers (PC) are central (CPU) and graphic (GPU) processors, which can dissipate heat flows up to 130 W and more. In this case the admissible temperature at the surface of their shell may not, as a rule, exceed 70-80°C. Since the temperature inside the body of a PC may reach 50 °C, the thermal resistance between the shell and the surrounding air, which is to be provided by a cooler, must be about 0.23 °C/W. Modern coolers with appropriate thermal characteristics, which have in their composition from 4 to 6 conventional copper-water heat pipes from 6 to 8 mm in diameter and a radiator with a finning area of about 1 m², are equipped, as a rule, with a fan 120 mm in diameter with a number of rotation per minute from 1800 to 2200. Besides, all of them must be located right on the object being cooled, which limits the possibilities for optimum arrangement of the system block. In this case the finned heat sink has to operate at a higher temperature of the surrounding air as it is situated inside the PC case.

The use of LTS for cooling computers has a number of advantages which allow locating the heat sink at a certain distance from the object being cooled in the coldest place, for instance, right on the wall of the case of the PC. This enables one to use forced-ventilation fans, which direct to the radiator colder air with a
temperature close to room temperature. In its turn, this makes it possible to decrease the finning area and, as a result, to reduce the mass and the dimensions of the cooler.

Fig. 13 presents the scheme of a cooler developed on the basis of a copper-water loop thermosyphon for a PC graphic processor.

![Scheme of a cooler for a PC graphic processor.](image)

The LTS had a flat-oval evaporator 7 mm thick with an evaporation zone measuring $40 \times 40$ mm$^2$. The condenser in the form of a flat coil was located between two aluminum radiator plates with appropriate hollows and through holes for the passing of an air flow directed by a forced-ventilation fan 120 mm in diameter. The total finning area was 0.48 m$^2$. The diameters of the tubes of the liquid line and the vapor line were respectively equal to 4 and 5 mm.

The results of testing a cooler with a thermal simulator of a graphic processor are presented in Fig. 14.

![Heat-load dependence of the temperature of a GPU thermal simulator.](image)

Tests were conducted at an ambient temperature of 22 °C with the heat sink blown by an air flow at a rate of 2 m/s. The heat load varied in the range from 20 to 400 W. Judging from the operating characteristic,
no crisis phenomena were observed in this case. At a nominal heat load of 130 W the thermal resistance of the cooler was 0.23°C/W, the temperature of the thermal simulator not exceeding 55 °C.

PASSIVE COOLING SYSTEMS OF ELECTRONICS

Among passive systems there are such ones which do not require for operation any means consuming additional energy, in particular, fans or pumps of different types. The main advantages of passive cooling systems are their economical operation, high reliability and long service life, and also the absence of noise and mechanical vibrations. One of the drawbacks is the necessity to use sufficiently large heat – transfer surfaces connected with the condenser, which make it possible to dissipate the heat flow being removed by means of natural convection and radiation.

Loop thermosyphons as passive and at the same time simple and highly efficient devices, which adapt well to different conditions of location and operation, in many cases are an ideal variant for using in such systems as a heat-transfer link between the heat source and the heat sink.

Presented in Ref. [19] are the results of development and tests of different versions of a passive cooling system on the basis of LTS for electronic components used in automotive industry. The maximum power dissipated by such components is 30W, and the temperature may not exceed 155 °C. The main problem which arose in solving this issue consisted in the choice of a working fluid as, by the specifications, the cooling system is to operate in the range of ambient air temperatures from −40 to +105 °C. As a result, the choice was made of heptane, which does not freeze at low temperatures and has acceptable thermal properties in the whole range of operating temperatures. The scheme of one of the experimental versions of a passive cooler on the basis of LTS is given in Fig. 15.

![Fig. 15. Scheme of a passive cooler for electronic components.](image)

The LTS was equipped with a copper disk-shaped evaporator 30 mm in diameter and 10 mm in thickness with a flat thermocontact surface, on which the object being cooled was situated. The condenser was joined with an aluminum heat sink measuring 120×120×30 mm³. The distance from the evaporator to the radiator was 200 mm. The diameter of the vapor line and the condenser was equal to 4 mm, and that of the liquid line to 3 mm.

The device was tested at an ambient air temperature of 22±2 °C in condition of natural convection. The results of the tests are presented in Fig. 16 in the form of a temperature - time dependence of the heat source on the heat load, which varied in the range from 10 to 40 W. It can be seen here that at a heat load of 30 W the temperature of the object being cooled is at a level of 73 °C. On conversion to the given maximum ambient air temperature of 105 °C the equivalent temperature of the heat source must be equal to 156 °C, which does not practically differ from the value prescribed.
Fig. 16. Temperature - time dependence of a heat source on the heat load.

CONCLUSION

Two-phase loop thermosyphons are rather simple and at the same time quite efficient heat-transfer devices capable of operating in a wide range of variation of mode parameters and slopes. The possibility of using these devices in various fields of technology both for heating and for cooling objects remote from heat sources and sinks has been demonstrated.

References


