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THERMOSYPHONS WITH INNOVATIVE TECHNOLOGIES

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ABSTRACT

Thermosyphons of the long length are of great interest for being used as heat exchangers for recuperation of alternative energy sources and upgrading their potential with the aid of heat pumps. In this presentation some examples of the use of two-phase thermosyphons in combating snow drifts and icing on the active parts of the railway transport track structure, air conditioning systems, foodstuff baking ovens and roasters, driers, etc. are given. It is concluded that thermosyphons for the ground heat exchangers and seasonal thermal storage systems connecting with solar thermal collectors, are extendable to more comprehensive applications

***Keywords*:** thermosyphon, ground; cooling, heating, railway transport, air conditioning systems, drying, baking ovens and roasters

INTRODUCTION

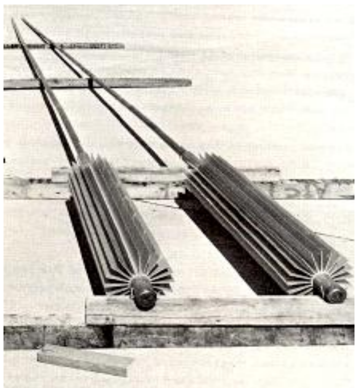
The effective use of low-potential ecologically pure alternative energy sources (ground, solar energy, bio fuels, etc.) is often associated with the development and application of heat exchangers as a long vertically or horizontally disposed tubes, since the heat flux density of the alternative heat sources is relatively small [1–5]. The most convenient heat exchangers in this case are two-phase thermosyphons: vertical and horizontal (Fig.1a,b). Two-phase thermosyphons represent a hermetic one-piece welded structure which is a thin-walled tubular casing whose cavity is partially filled with a working fluid (ammonia, propane, CO_2, etc.). Its length can be from several to dozen meters and the diameter, from 20 mm to 300 mm. Thermosyphons are fabricated from carbon steels (St20 or 09625), stainless steel, aluminum allows. Recently designed polymer composites having a high effective thermal conductivity (5–15 W/m deg) can successfully replace traditional metals in fabrication of thermosyphon or heat pipe casings [6].

1. THERMOSYPHONS FOR COOLING AND FREEZING OF GROUND

One of the important applications of vertical and inclined two-phase thermosyphons (Fig.1a) is its ability of cooling and freezing the ground. In particular, this procedure is needed to realize for thermal stabilization of highways and railroads and for the freezing of ground in the permafrost zone. It is known that the maintaining of ground in frozen state and the elimination of unforeseen heat generation under the railway bed is an urgent problem in the building and usage of railroads in the North. All of the practical actions associated with the problem of controlling the temperature of pavement are reduced in winter to the removal of snow, freezing of a thawed ground, and cooling of frozen ones. The freezing of the ground to the desired depth and keeping it in a frozen state for the whole year is provided by the environmental cold air in winter or with partial application of additional cooling facilities. In winter thermosyphons are also used for melting the snow and ice on crucial parts of railroads, bridges, tunnel entries, etc. The thermal energy of the ground is transferred to its surface. This technique of ground heating has the following advantages:

1) there is no need in using an organic fuel;

2) reliability and long service life (15–20 years) of thermosyphons is ensured. As thermosyphons are installed in parallel, they can be used numerous to supply the needed amount of heat for snow thawing;
3) highway pavement heated by thermosyphons do not fail under thermal stresses.



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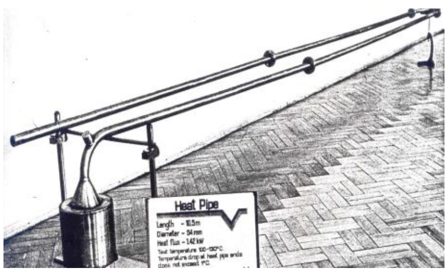

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FIGURE 1. Vertical two-phase thermosyphons (a) and horizontal vapor-dynamic thermosyphons (b)

Such a means of heating roads can be recommended for those regions where the mean year temperature exceeds 10°C and in winter there are no strong winds with intense snowfalls and severe colds. The heat accumulating ability of the ground depends on its heat capacity and can be increased substantially if the additional underground heat accumulators are used contacting with thermosyphons. The thermal energy of the ground spent in the cold time of the year (winter) is recovered in the hot time (summer) due to the natural heat exchange with the air and solar radiation. The main advantage of thermosyphons is its independent operation, high heat transfer, and unidirectional heat flow transmission. The thermal efficiency of thermosyphons application depends on the ability to completely wet its inner surface by the falling liquid rivulets and organize its evaporation on the extended surface. To achieve a high evaporation rate a liquid film falling down to the lower part (evaporator) of the thermosyphon is required. The quality of liquid film depends on several properties of thermosyphon like the envelope material, surface roughness, angle of thermosyphon inclination, its length as well as the operating regime. The formation and structure of falling liquid films have been studied by various experimental methods [1]. Different characteristics of the liquid waves have been analyzed based on visual observations of such liquid films as water and isopropanol flowing down inside vertical, or inclined tubes under isothermal conditions [2, 3]. Special measures were taken for the improving the wetting of the entire inner surface of the long evaporator and provision of uniform liquid film distribution all over the thermosyphon perimeter. To ensure the additional intensification of heat transfer inside thermosyphons the special inserts (such as screw, worm) were used to initiate the swirling vapor flow in the condenser and to swirl liquid rivulets in the evaporator [4]. This technology improves the wetting ability of the evaporator (Fig.2).

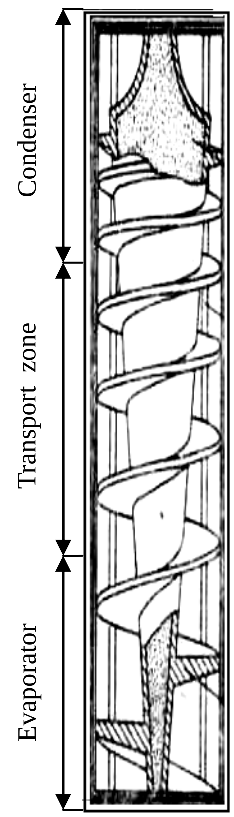

FIGURE 2. Thermosyphon with screw inside to enhance the heat transfer in the condenser and evaporator

One of the methods to reduce the thermal resistance of a layer of non-condensible gases is based on turbulence artificially organized in the vapor flow. A typical feature of low-temperature thermosyphons is that they usually operate with laminar flow of vapor. Axial and radial Reynolds number R_v of the vapor flow does not exceed the value of 300. It is well known that the heat and mass transfer process is much more intensive in turbulent boundary layer than in laminar one. From this point of view, it is very tempting to produce artificial turbulence in the vapor flow and, hence, intensify heat transfer in the condenser and evaporator. A method for creating a swirl vapor flow by means of a worm placed into heat pipes and thermosyphons has been proposed in [5]. Turbulent mixing of the vapor in condensation zone offers a possibility to intensify condensation process in the presence of non-condensible gases, if, incidentally, it appears within thermosyphon volume. Non-condensing gases are pressed away from the condensing surface. Swirling of the vapor flow in the evaporator permits an improvement on boiling and evaporation heat transfer, as it facilitates partition of vapor from liquids drops formed by boiling of the liquid and ejects these droplets on the heated surface. Centrifugal forces throw liquid droplets again onto the heated surface thereby providing an increase in dryness of vapor of up to 99% at the evaporator outlet, and stimulate uniform wetting of the heated surface. Swirling of the vapor flow on the evaporator stabilizes growth of the bubbles, facilitates their compression, and intensifies evaporation and boiling.

A disadvantage of thermosyphons, or heat pipes with swirl vapor flow by means of a worm is somewhat increased pressure drop in vapor flow ΔP_v. The worm not only serves as a turbulent-producing device and stimulator of evaporation and boiling enhancement, but it can be employed as a rigid armature, onto whose ribs give a possibility to use the flexible polymer envelopes. The worm itself may be built of metal (aluminum, steel), porous ceramic, or polymer composite [4].

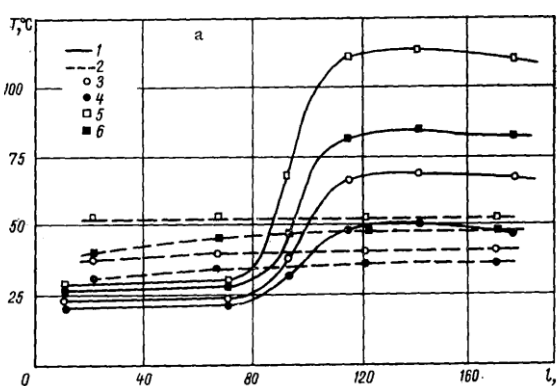

FIGURE 3. Temperature distribution along conventional heat pipe and heat pipe with a worm [4]. Q=100W. 3 – HP without worm; 4 – HP with worm. Q = 125W; 5 – HP without worm, 6 – HP with worm.

The temperature distribution along the HP in the vapor flow for conventional HP and HP with worm are shown in Fig.3 (dashed lines for Q=100W and Q=125W). The experimental sample of such HP was constructed from stainless steel and was 190 mm long with inner diameter of 39 mm; thickness of HP walls was 0.3 mm.SS mesh of o.16 mm and wire thickness of o.12mm was fastened in two layers over the inner HP walls to serve as a wick. The porosity of the wick was 70%. Maximum height of capillary rise 5.1 cm and permeability K=1.35 $10^{-9}m^2$.

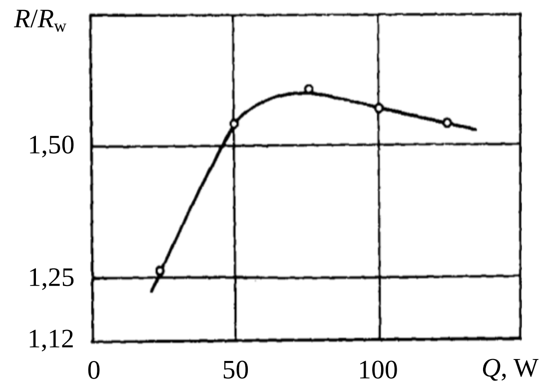

FIGURE 4. The ratio of thermal resistance R of HP and HP with worm R_w as the function of heat flow Q.

A worm with variable pitch of threads, 187 mm long and 38 mm in diameter, was used as a turbulence producer and artery for the axial transport of liquid from condenser to the evaporator zones. Temperature fields along the HP with and without the worm and heat flow transferred up to 125W along the HP are shown on Fig.3 and Fig.4. The dependence of the ratio of thermal resistance of conventional HP and HP with worm is shown in Fig. 4. The turbulent motion of vapor flow in the condenser intensifies the heat transfer especially in the presence of the remnants of non-condensed gases. The swirling vapor flow in the evaporator makes it possible to improve heat removal through the thermosyphon wall to the ground. It favors the separation of the vapor flow and liquid microdroplets in the evaporator. The heat transfer enhancement in the thermosyphon by screw allows one to decrease the thermal resistance of the thermosyphon down to 30 - 50 %. The technique of determination of the main thermosyphon parameters consists of the following stages:

- calculation of the external heat transfer intensity of thermosyphon condenser with the surrounding medium (air, water);
- calculation of the heat and mass transfer parameters inside the thermosyphon condenser (vapor condensation on the inner surface of thermosyphon);
- calculation of the working fluid hydrodynamics in the adiabatic (transport) zone of thermosyphon;
- calculation of the heat and mass transfer parameters in the evaporator.

When thermosyphons are immersed (inserted) into the ground, they need the protection from corrosion, since they are in direct contact with a moist soil. To ensure their long service life the special anticorrosive coatings are used. The full-scale tests of thermosyphons designed at the Luikov Heat and Mass Transfer Institute as season-operating cooling facilities were carried out under the conditions of the river Middle Ob' area and demonstrated their good operation in freezing ground by means of natural cold. During the experiments the maximum depth of freezing ground was 3.5 m, with the width of the frozen zone being 4–5 m [4].

2. POLYMER THERMOSYPHONS

Another interesting solution is to apply polymer thermosyphons insensitive to the moisture destructive action. At the present time the application of horizontal flat polymer thermosyphons (Figs.5, 6) to apply the energy of alternative energy sources, cooling and heating of the buildings and storehouses has a good future. The second part of the experiments was devoted to the design of a polymer loop thermosyphon with a flat interface (for attaching heat-generating elements) and flexible transport lines between the flat evaporator and condenser. The evaporator and condenser of such thermosyphon have the form of slabs located horizontally inside the soil at different depth. The evaporator and condenser are connected by flexible polymer pipes used for the transmission of vapor and liquid streams [6].

The distance between the evaporator and condenser can constitute several meters. It is recommended to use such thermosyphons for heating the floors of storehouses for vegetables and other agricultural products, heat exchangers contacting with ground heat pumps. The proposed system operates autonomously under the action of the gravity forces and under the temperature drop between the deep ground and the air. The prototype of thermosyphon used in the experimental set-up has rectangular mini grooves as a capillary structure inside the evaporator and condenser (Fig.6a,b). Its frame (Fig.6b) is made from the polyamide composite with carbon nanofilaments and nanoparticles to increase its effective thermal conductivity.

The jacket of the polymer composite is formed around the core of carbon fibers to form a highly thermally conductive heat transfer device. The width and length of the experimental set-up (thermosyphon) is 50 and 250 mm, respectively. The width of the grooved surface inside the evaporator and condenser, where two-phase heat transfer occurs is 30 mm. The width and depth of the rectangular minigrooves inside the evaporator and condenser are 2.5 mm. The thickness of the evaporator and condenser is 10 mm. There are flexible vapor and liquid transport pipes (200 mm length, 5 mm diameter, respectively) made from pure polyamide to connect the evaporator and condenser, which are disposed in parallel one below the other. The width and thickness of the rectangular parts of frames are 10 mm, respectively. The working fluid of the thermosyphon is isobutene (R600). The experimental setup (Fig. 5) with temperature sensors located on the evaporator, condenser, vapor and liquid pipes of the thermosyphon was used during experiments.

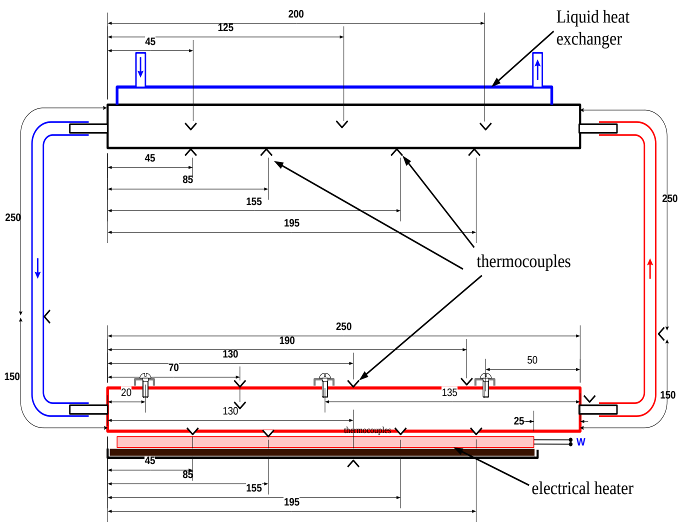

FIGURE 5. Experimental setup with thermocouples attached to the evaporator, condenser, and the transport zone (vapor and liquid) of horizontal flat polymer thermosyphon

The heat flow enters at the bottom of the evaporator. The heat sink is located at the top of the condenser. The difference between the temperature of the external walls of the evaporator T_w and the saturated temperature of the adiabatic (vapor transport) zone T_{sat}, i. e., $T_w - T_{sat}$, was measured directly by four thermocouples, one junction of which was on the evaporator wall, while the other was placed in a thermally controlled liquid bath. The vapor saturation inside the thermosyphon was maintained using the liquid heat exchanger and thermostat. The total thermal resistance of the thermosyphon R_{ts} was calculated as

$$R_{ts} = \frac{T_e - T_c}{Q}, \qquad (1)$$

where T_e is the mean temperature of the evaporator (°C), T_c is the mean temperature of the condenser (°C), and Q is the heat flow (W).

The experimental technique was used to perform some necessary operations including temperature measurements (Agilent Data Acquisition Agilent Data Loger HP-34970A with a set of thermocouples connected to the computer), measurements of the heat flow Q from the evaporator to condenser and of the effective thermal conductivity of the thermosyphon envelope.

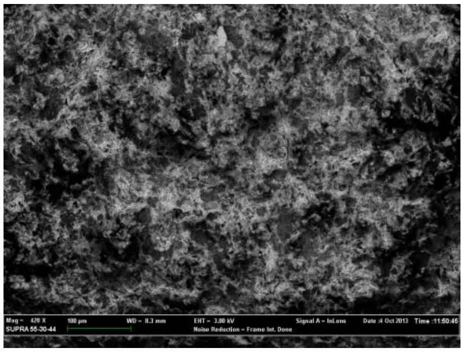

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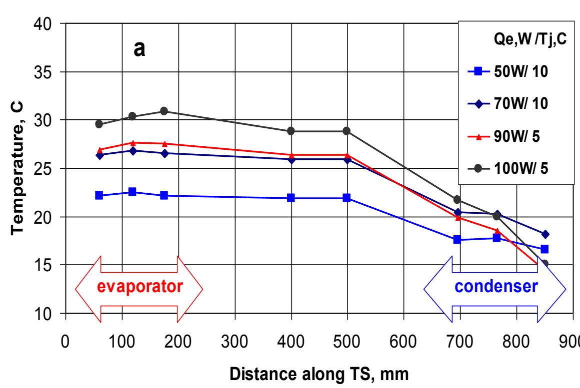
FIGURE 6. Flat loop thermosyphon made from polymer composite – polyamide reinforced with carbon nanofilaments and nanoparticles: a) structure of polymer composite, b) flat evaporator (cross section) with rectangular mini-channels with porous coating

To cool the thermosyphon condenser (liquid loop) a Joulabo F12 recirculation thermal bath with temperature-regulated accuracy of ±0.5 °C was used. The heat flow was supplied by an electric cartridge heater located on the bottom surface of the evaporator. The heat sink (liquid heat exchanger) was attached to the top of the condenser. All measurements were performed in a steady-state regime for the heat flow range of 50–100 W. The temperature distribution along the evaporator, transport zone, and condenser as a function of the heat load is shown in Fig.7.



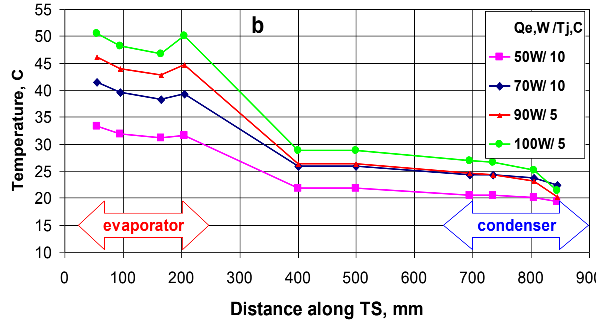


FIGURE 7. Mean temperature distribution along the evaporator and condenser top surfaces (a) and bottom surfaces (b) of the thermosyphon as a function of heat flux Q

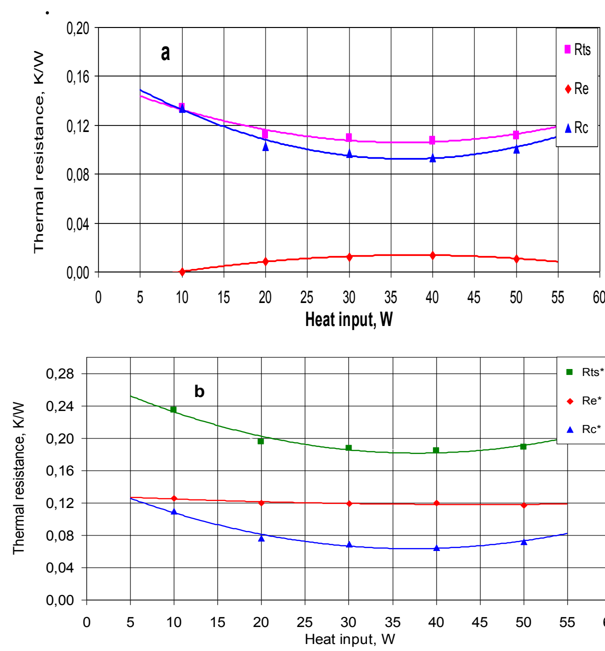


FIGURE 8. Thermal resistance of evaporator (R_e), condenser (R_c), and of the entire thermosyphon (R_{ts}) as a function of the heat input (top surface) (a) and of the heat load (bottom surface) (b)

The mean temperature profiles on the top surface of the evaporator and condenser are shown in Fig. 7a, while the temperature profiles on the bottom surface of the evaporator and condenser are shown in Fig. 7b. The temperature of saturated vapor inside the thermosyphon was varied from 20 C to 40 C with the help of thermostat thermal control. The thermal resistances of the evaporator and condenser as a function of heat input are shown in Fig. 8a,b.

For the case (Fig.8b), R_{ts} is nearly two times higher as compared with the top surface heating (Fig.8a). It is important to note that the thermosyphon is sensitive to the mass of the working fluid charged. The design of such a thermosyphon guarantees a weak influence of the evaporator inclination to the horizontal axis in the limit of 0–20 °

3. VAPORDYNAMIC THERMOSYPHONS

Vapordynamic thermosyphon (VDT), Figs.9, 10, was patented in 1985 [7]. The first principal distinction of VDT from conventional thermosyphons of the same diameter and size is related with its horizontally oriented elongated annular condenser. VDT can transfer the heat flow in horizontal position over a long distance. Its condenser is nearly isothermal with the length of tens of meters, Fig.1b. The VDT evaporators may have different form and length, Fig.10. The second principal distinction consists in the fact that the vapor flow from the evaporator and two-phase liquid flow in condenser are separated spatially (tube in tube heat exchanger). This makes it possible to avoid a negative hydrodynamic interaction between the flows of the vapor and liquid typical for conventional thermosyphons.

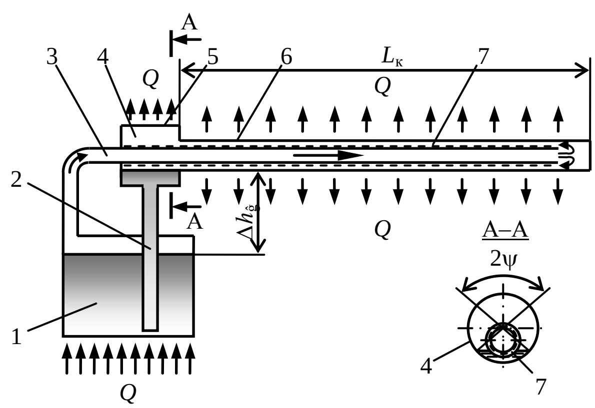


FIGURE 9. Vapor-dynamic thermosyphon: 1 – evaporator, 2 – liquid pipe, 3 – vapor pipe, 4 – compensation chamber, 5 – heat sink, 6 – condenser, 7 – annular channel with porous coating, Δh– hydrostatic pressure drop

The heat transfer intensification in VDT is related with the porous coating of the heat loaded surface. The VDT with porous coating ensures a heat transfer enhancement up to 5 times compared to the plain tube thermosyphon. Furthermore it starts to work without a temperature overshoot typical for conventional thermosyphons. The vapor generated in the evaporator enters through the vapor pipe into the annular gap of the condensation zone, where it condenses. There is an intense radial heat transfer with phase change between the vapor pipe and the condenser envelope.

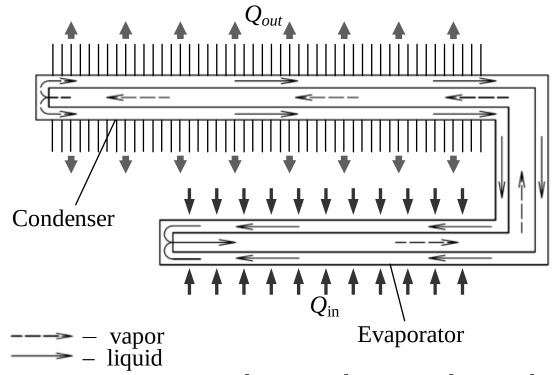


FIGURE 10. Vapor-dynamic thermosyphon with horizontal elongated evaporator and condenser, longitudinal cross

The experimental data obtained on a flooded and partially flooded vapor pipe in confined space (annular channel 0.2 to 2 mm thick) testify the phenomena of micro heat pipe inside a porous coating of the vapor pipe and mini heat pipe in the annular gap between the porous coating and the condenser envelope. Visual analysis (glass condenser) and experimental results show, that such combination is favorable for the enhancement of the heat transfer in the VDT condenser [7]. The main VDT thermal parameters are: the maximum heat load $Q_{\max}$, the heat flow in the evaporation zone Q and thermal resistance R. The VDT thermal resistance is determined as

$$R = \left(T_e - T_c\right) \qquad (2)$$

where T_e and T_c are the average wall temperatures of the evaporator and the condenser, respectively, and Q is the heat flow.

The VDT condenser can be made flexible if fabricated from small-diameter polymer pipes. Such VDT is anticorrosive and can be placed in the ground for many years. One of the characteristic features of this device is the presence of an extended annular gap (mini-channel) between the vapor pipe and the external wall of the condenser. When a two-phase flow moves along the annular gap, the working fluid is cooled by the heat exchange with the environment and the concentration of vapor bubbles in it decreases gradually along the condenser. The formation of a two-phase flow in the annular gap of the condenser is the reason of the heat transfer enhancement and maintain the condenser surface temperature uniform close to the saturation one [8].

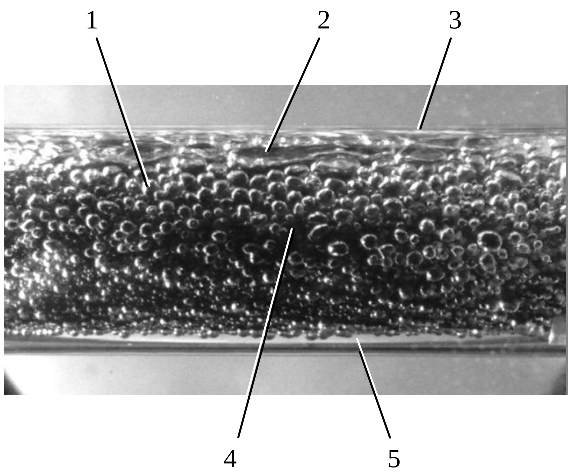


FIGURE 11. Visualization of the bubbles generation on the porous coating of vapor pipe in the annular gap of the condenser (Propane): 1 – vapor bubble, 2 – vapor cluster, 3 – glass tube, 4 – heat-transferring tube, 5 – coaxial annular channel

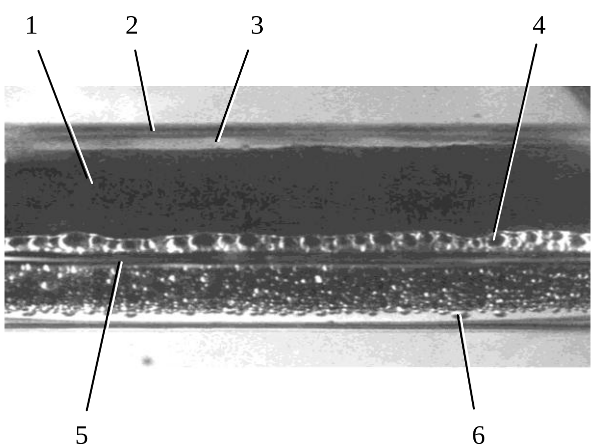


FIGURE 12. Visualization of the bubbles generation in the lower part of the porous coating of vapor pipe immersed to the liquid pool (Propane) in annular gap: 1 – vapor pipe non-flooded part, 2 – glass tube, 3 – annular channel, 4 – vapor bubbles above the liquid – vapor interface, 5 – liquid – vapor interface, 6 – vapor bubbles on the flooded part of the vapor pipe

The hydraulic diameter of the annular gap is usually smaller than the capillary constant of the working fluid of the VDT, therefore there occur alternations of vapor and liquid plugs in the gap. When the annular gap of the condenser has a hydraulic diameter greater than the capillary constant, $\kappa = [2\sigma/(\rho_{liq} - \rho_v)\ g]^{1/2}$, the stratification of the vapor and liquid in it is observed, Fig.12. Among the basic advantages of the VDT there are the large length of the heat release zone (condenser), the high heat transmitting ability (tens of kW), the low sensitivity to the refilling of the working fluid, and possibility to store non condensible gases in the heat sink, Fig.9. VDTs are constructed in diverse forms including bent, flexible, or assembled elements. To confirm the efficient application of vapordynamic experimental specimens VDT were successfully tested in winter time for heating the railroad switches in the city of Minsk [1,4], which made it possible to prevent their icing and ensured intense thawing of snow. Electric current was used as an energy source, as well as miniature gas burners of closed type. The heater for railroad switches had the length of 4.5–6 m, the outer diameter 16 mm, working fluid – ammonia. The transmitted heat flow amounted to 2 kW. At an environmental temperature of minus 10 °C, the snow fall intensity being 100–150 mm per 24 h, and a wind velocity of 5–10 m/s the VDT-based heater ensures reliable operation of a switch. The temperature of the rail top is maintained at no less than 10–12 °C. When a railroad switch is covered by a snow layer of thickness 50-100 mm, the switches are free from snow and ice in 25–30 min after the turning-on of the thermosyphon heater. VDTs begin to be used as the basic components in the systems that utilize solar energy [1], the heat of exhausted gases, baking ovens, drying facilities, systems for warming up vessels with liquid and gaseous fuels, concrete, asphalt, etc. [4], as well as of the heat exchangers of heat pumps, heat and cold accumulators [5–8].

It is interesting to compare VDT and conventional thermosyphon having the same form and size (Figs.13). Both are made from the copper tube with the same diameter and length. The working fluid is R600. The VDT (Fig.13, left) is less sensitive to the angle of its inclination to the horizon comparing with the conventional thermosyphon (Fig.13, right). VDT has low thermal resistance (R = 0.22 K/W) (Fig.14). The conventional thermosyphon has its thermal resistance (R=0.25–0.3) for the near horizontal position of the evaporator, and (R > 0.5 K/W) for its negative inclination to horizon (Fig.14). The heat flow (Q=100 W) transferred by VDT is near 1.7 time more to compare with conventional thermosyphon (Q = 60 W) at the same mean temperature of the condenser.

Ground coupled heat exchangers based on VDT design can be recommended as the elements of the air-condition systems. Their application allows to cool the air in the summer time and to heat the air in the winter time with strict control of the air humidity. So it is possible to cool the air to a comfortable temperature and remove moisture, but without the need for expensive reheat. With VDT application both vertical and horizontal arrangements of the heat exchangers are available [9-10].

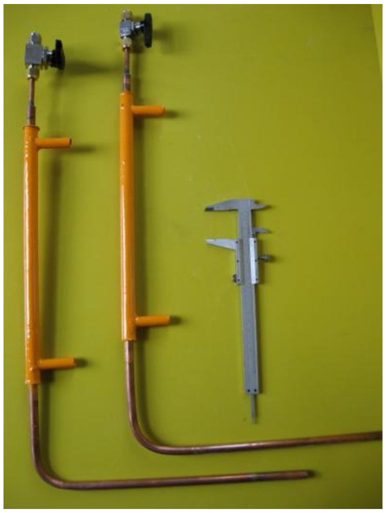


FIGURE 13. VDT with horizontal evaporator and vertical condenser (left) and traditional thermosyphon with horizontal evaporator and vertical condenser (right)

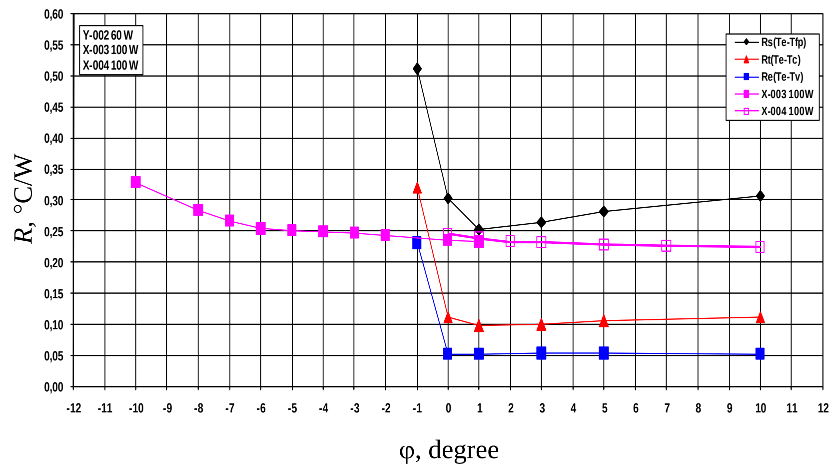


FIGURE 14. Thermal resistance of thermosyphons as a function of the degree of its inclination. VDT (Q = 100 W) ■, □ – total thermal resistance of VDT; Conventional thermosyphon (Q = 60W); ■, ▲, ♦ – thermal resistance of its evaporator, condenser and total thermal resistance

4. CONCLUSIONS

Experimental investigations with long thermosyphons identical in construction operated with different working fluids (ammonia, propane, isobutene, water etc.) are carried out. It is experimentally shown that the thermosyphon thermal resistance can be lowered by employing screw placed inside, polymeric loop two-phase and VDT thernosyphons. A significant lowering of the thermal resistance due to the application of VDT is found for the different angle φ of thermosyphon inclination. Some types of thermosyphons has been developed in the Luikov Institute as experimental specimens of the air-conditioning heat exchangers, house heaters, side-walk heaters, heaters for the runways of aerodromes, railroad beds on bridges and crucial portions of the railroads.

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