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HEAT PIPES, NANOFLUIDS, AND NANOTECHNOLOGIES

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A survey of the constructions of heat pipes and thermosiphons with nanofluids, nanocoatings, and nanocomposites based on metal oxides and carbon materials for volume absorption of solar energy and cooling of electronic components is presented. Nanofluids are considered as actual working media intended for application in transparent heat miniexchangers, heat pipes, and thermosiphons for volume heating a nanofluid by laser or solar radiation. Nanocoatings of the evaporator walls of heat pipes are created for intensifying two-phase heat transfer in cooling the devices of high-current electronics. Nanocomposites applied as heat pipe and thermosiphon casings possess thermophysical and mechanical properties that in a number of cases are best than those from metals.

Keywords: *nanofluids, nanocoatings, nanocomposites, heat pipe, thermosiphon, evaporator, condenser, cooling system.*

Introduction. Recent investigations [1–5] have shown that nanofluids can substantially improve the heat transmitting capability of heat pipes and the efficiency of using the systems of direct solar power supply. Intensification of the operation of heat pipes and thermosiphons depends on various factors such as the type of a suspension of nanoparticles and of base fluid, volume fraction, size and form of nanoparticles, as well as the temperature. Theoretically, nanofluids based on carbon nanomaterials are among the best candidates for replacing conventional working fluids. There are some problems, however, that inhibit the development of this area such as the instability of the properties of nanofluids, effect of vapor formation in them, high cost, increased power of the system of repumping the working medium, as well as the erosion and corrosion of heat transfer equipment. Moreover, to achieve a high effective thermal conductivity of heat pipes, one has to consider the possibility of applying hybrid carbon nanocomposites and metal oxides (CuO, Al_2O_3) in solar systems of heat supply and systems of cooling high-current electronics used for cooling electric transport.

Nanofluids can be used for forming nanostructures (a porous wick) located on the inner surface of the evaporators of heat pipes and thermosiphons, for increasing the heating surface, decreasing the contact angle of wetting [2], intensification of heat transfer, and for increasing the critical heat flux [1–8]. Nanocomposites consisting of nanoparticles with high thermal conductivity (carbon, silicon carbide, metals, and metal oxides) located uniformly in a solid matrix (copper, aluminum, steel, polymers) are structures suitable for creating casings of two-phase heat exchangers. They retain their high parameters in a wide temperature range [6–14]. The modern electronic chips are tightly packed microfacilities. As a result of miniaturization of highly integrated electronic components, the generated heat flux attains 100–200 W/cm^2 or greater. The miniaturization of chips increases the density of released heat flux that diffuses into the surrounding medium, which is one of the barriers that limits the development of this branch of nanotechnology. Active control of the temperature regimes of chips with the aid of heat pipes and thermosiphons ensures their reliable operation and maximally increases the average time between the failures of electronic devices.

Nanofluids. Due to better thermal characteristics, nanofluids are considered as a new generation of heat transmitting and heat accumulating media. The influence of the properties of base fluids, materials, and dimensions of nanoparticles and of their concentration and morphology on the thermophysical properties of nanofluids was analyzed in works [1–4]. Because of the high thermal conductivity of carbon materials, nanofluids containing carbon nanoparticles have a higher coefficient of effective thermal conductivity and of heat transfer than other nanofluids containing metals or metal oxides [5]. The use of a nanofluid in minichannels provides high heat transfer efficiency, compactness, and a low thermal resistance of heat pipes. Over the past few years, nanofluids based on molten salts and ionic fluids have been developed for accumulating and transmitting heat at moderate and relatively high temperatures [6]. Their properties are affected not only by the

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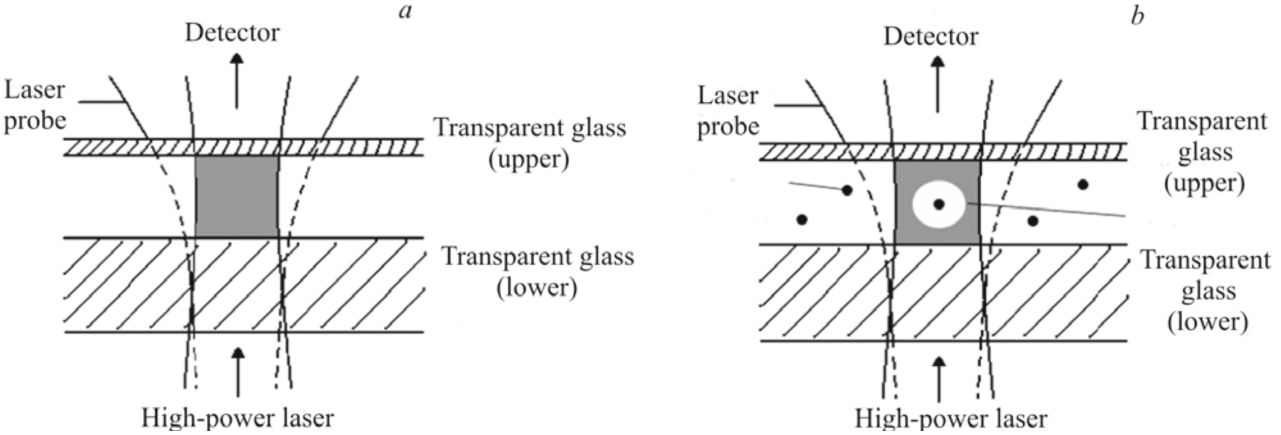


Fig. 1. Visualization of minibubbles around Al_2O_3 nanoparticles in a nanofluid (water) prior to the action (a) and under the action (b) of laser radiation [4].

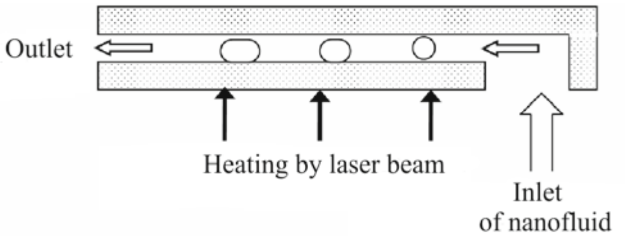


Fig. 2. Transparent walls of the thermosiphon evaporator partially filled with a nanofluid [7].

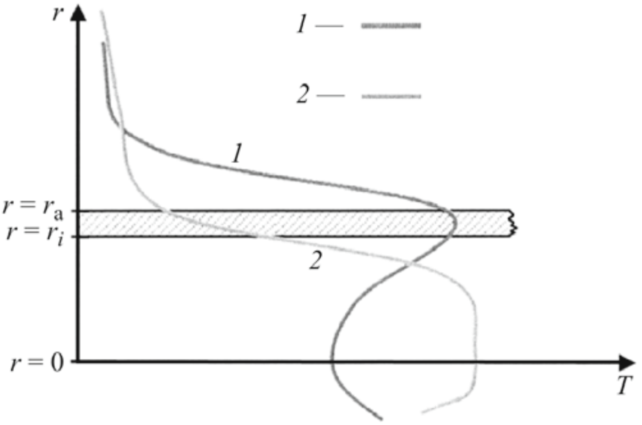


Fig. 3. Absorption of solar radiation by a metal wall (1) and by a glass wall of a vapor-dynamic thermosiphon (2).

characteristics of nanomaterials and base fluids, but also the methods and technologies of synthesis, such as the intensity and duration of treatment by an ultrasound.

A transparent thermosiphon partially filled with a nanofluid is a good tool for volume absorption of solar radiation and transformation of it into heat [7]. Figures 1 and 2 demonstrate minibubbles around Al_2O_3 nano- and microparticles in a nanofluid (water) under the influence of laser radiation. Application of the methods of photothermal microscopy makes it possible to visualize the formation of individual bubbles in a transparent evaporator of a heat pipe [7].

Work [1] describes a new nanofluid containing nanoparticles of size less than 100 nm and having effective thermal conductivity an order of magnitude higher than that of the base fluid. A detailed description of their properties and of

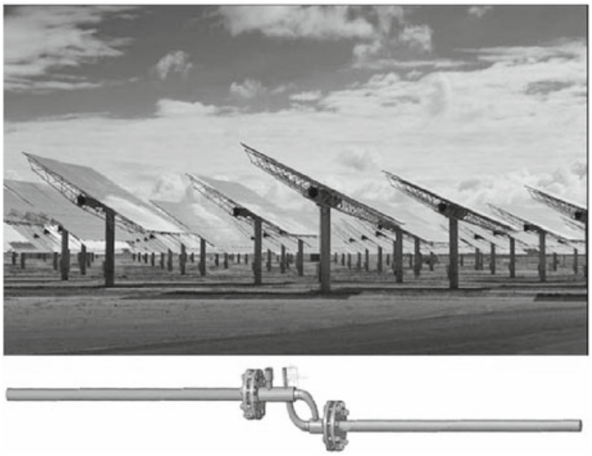


Fig. 4. Cooling of photoelectric transformers of the solar collectors by vapor-dynamic thermosiphons with metal and glass walls [7, 8].

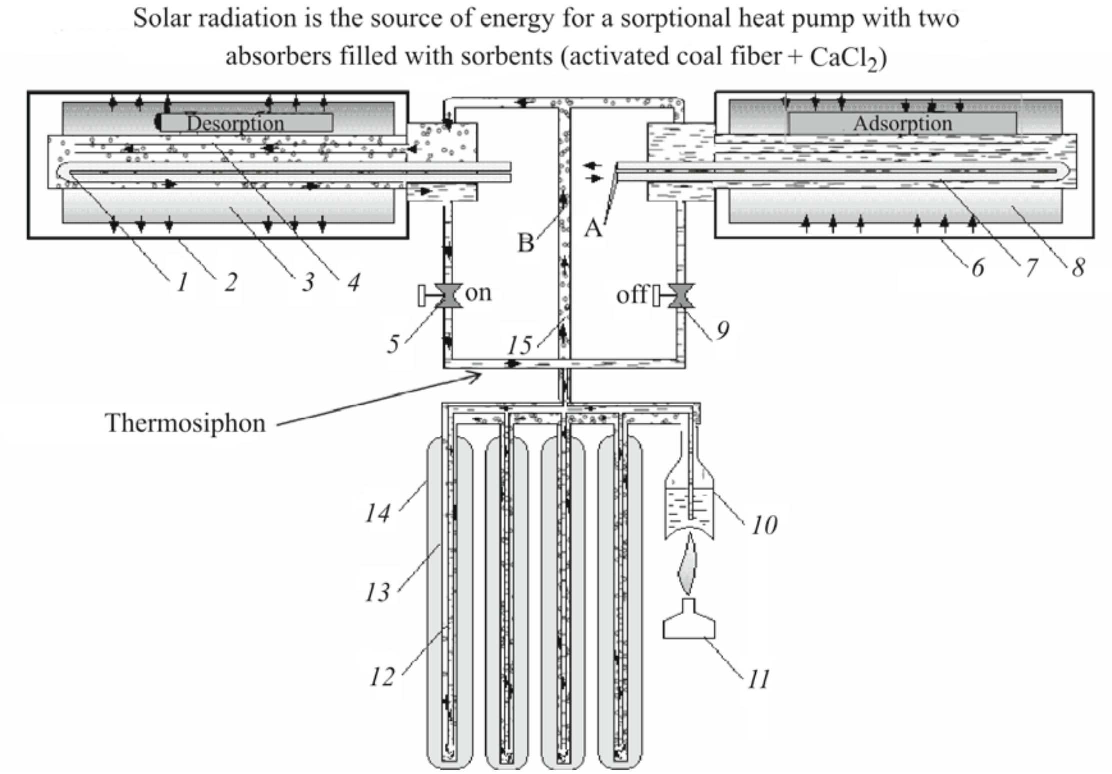
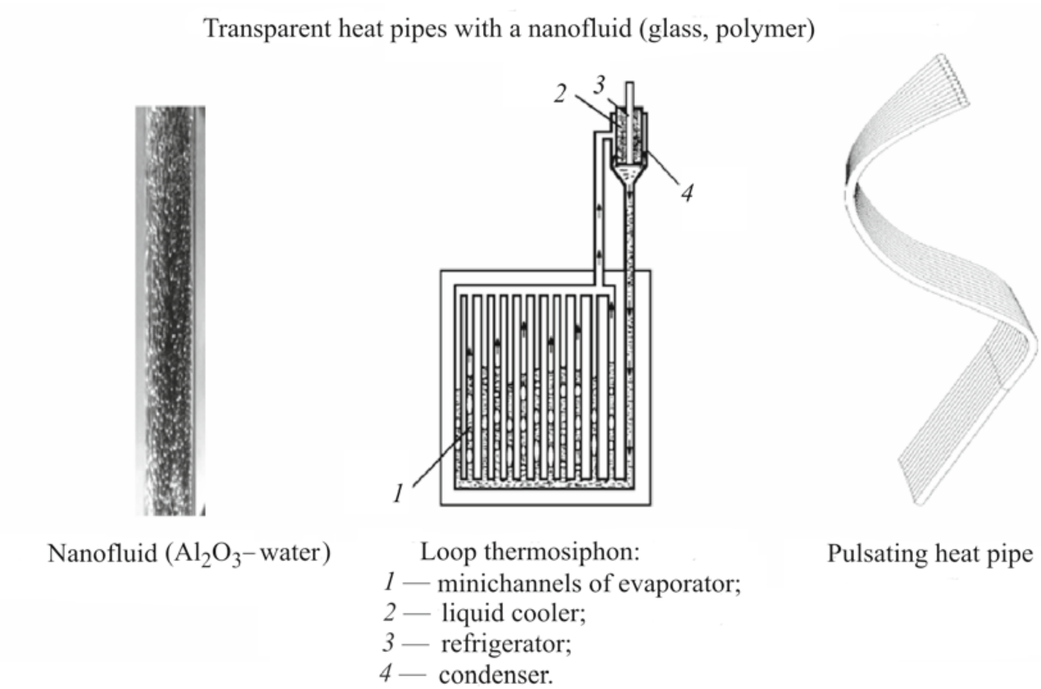


Fig. 5. Schematic of a sorption heat pump using a transparent thermosiphon for bulk heating of a nanofluid by solar radiation [4].

their interaction with the solid wall of a heat exchanger can be obtained in investigating the nature of the wall liquid flow (boundary layer). When nanoparticles are uniformly distributed in the nanofluid volume, the nanofluid acquires significant advantages over the ordinary fluid [2], since the possibility of absorbing a radiant flux in the bulk of the nanofluid appears. In is shown in work [3] that nanofluids ensure a considerable increase in the convective heat transfer rate.

Visualization of hydrodynamic flow and heat transfer of a two-phase flow in a horizontal minichannel allows one to analyze the efficiency of the influence of nanoparticles on the hydrodynamics and heat transfer in the minichannels of



Transparent heat pipes with a nanofluid (glass, polymer)

Nanofluid (Al_2O_3–water)

Loop thermosiphon:
1 — minichannels of evaporator;
2 — liquid cooler;
3 — refrigerator;
4 — condenser.

Pulsating heat pipe

Fig. 6. Various constructions of transparent heat pipes and thermosiphons [8].

heat pipes and thermosiphons (Figs. 3–6). Due to the efficient volume absorption of solar radiation by a nanofluid or a nanocoating, these heat transmitting devices can be recommended for use in solar power engineering.

Nanocoating of the Walls of Heat Pipe Evaporators. The porous coating of the minichannels of an evaporator substantially intensifies heat transfer, since it is a source of multiple nucleation sites in liquid–vapor phase transition without strong overheating of liquid [9–13]. A biporous sintered copper powder (thickness of layer 25–100 μm) intensifies two-phase heat transfer [11, 12], decreases the thermal resistance of the heat pipe evaporator, and increases the capillary pressure and the permeability of the wick (Figs. 7 and 8).

Micro- and nanoporous coatings produce pronounced roughness of the heating surface and afford a great number of microcavities in the range from several hundreds of nanometers to a few microns in a porous structure convenient for nucleation of bubbles on heating the working fluid. Copper coatings of the evaporators of heat pipes in the form of a porous layer of nanoparticles with a thickness of a few microns furnish a large heat transfer surface, minimum erosion and corrosion, and decrease the coating density [11]. Carbon materials (graphene and carbon nanotubes) have a high thickness of the surface and a high capability for absorbing solar radiation. Based on the analysis of the aluminum surface carried out with the aid of a scanning electron microscope (Figs. 9 and 10), the micropores (of volume 0.2–0.6 cm^3/g and specific surface 800–1000 m^2/g) and mesopores (0.2–0.10 cm^3/g, 20–700 m^2/g) in activated composite materials constitute the greatest part of the surface and make the greatest contribution to their capillary and adsorption properties. The macropores of diameter 100–200 nm (0.2–0.8 cm^3/g and 0.5–2.0 m^2/g) serve as transport channels for removal of the vapor formed at the intersection of micropores and macropores on phase transformations in a porous coating under the action of the heat flux supplied to the wall of the heat pipe evaporator [8]. Nanodiamond particles as a porous coating of a heat pipe have a high specific surface and exclusive thermophysical and mechanical properties.

Loop Thermosiphons for Cooling the Components of Power Electronics. The technology of cooling the components of electronics based on loop thermosiphons, vapor chambers, and heat pipes, outlined in the present article has become particularly important at the present time. The loop thermosiphon is one of the most indispensable heat transmitting devices due to its low cost, long service life, simplicity, and reliability of construction. The application of the loop thermosiphon encompasses the traditional areas of heat transfer including cooling of electronic articles, accumulator batteries, nuclear reactors, basins of used fuel, air conditioning, cooling accumulation, and recuperation of energy [14–16].

The results of the experiments carried out [17] show that in thermosiphons the heat transfer coefficient is improved by 600%, and there is a maximum increase in the critical heat flux by 55% on deposited surfaces of porous structures

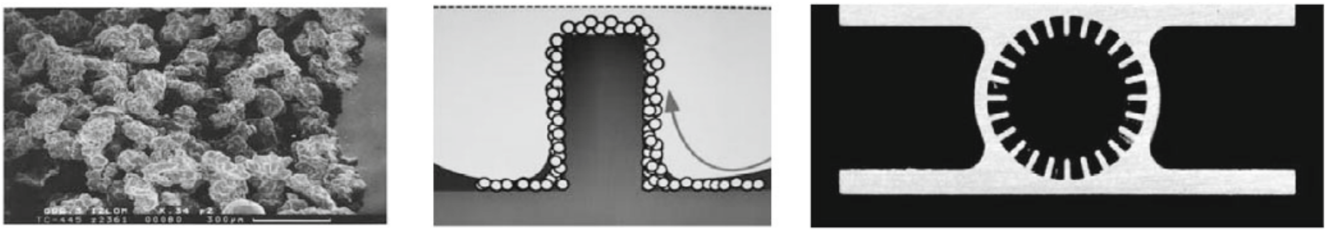


Fig. 7. Sintered biporous copper powder on the inner surface of a heat pipe evaporator [11].

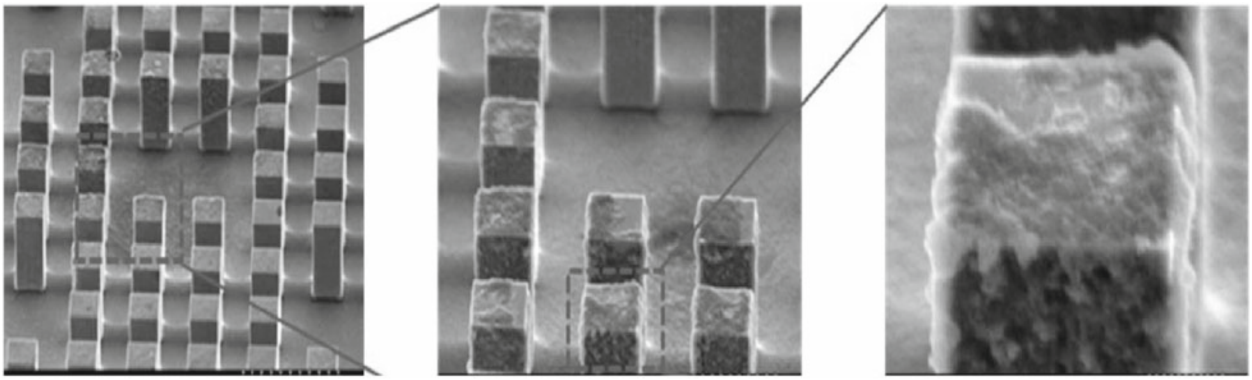


Fig. 8. A layer of CuO nanoparticles on the surface of minicolumns of the heat pipe evaporator [12].

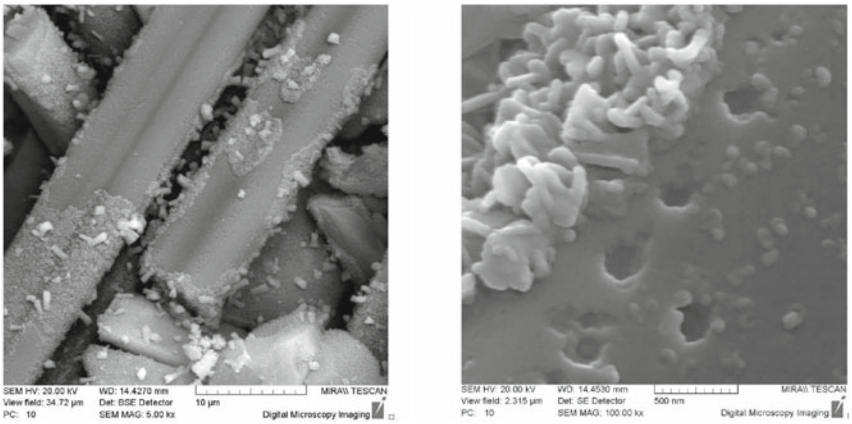


Fig. 9. Coal fiber covered by a layer of Al_2O_3 nanoparticles [9].

compared with a smooth heating surface. Creation of carbon polymer and carbon–metal–polymer nanocomposites represents an appreciable breakthrough in material science and in the development of nanotechnologies. Nanosize particles can increase the strength of metal retaining or even improve its plasticity [18, 19]. For example, a metal nanocomposite containing nearly 14% of silicon carbide nanoparticles and 86% of magnesium has a high strength and thermal conductivity and can be recommended for wide use as casings for high-temperature heat transmitting devices.

Polymer composites reinforced with carbon nanofiber and nanoparticles are considered as a promising alternative to metals. The reliability of radioelectronic instrumentation is determined in accordance with modern notions [2] and in the first place with its working temperature. At the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus together with the Institute of Metal Polymer Materials of the National Academy of Sciences of Belarus, a new loop thermosiphon has been developed, designed, and tested [19, 20]. The casing of the thermosiphon is made as

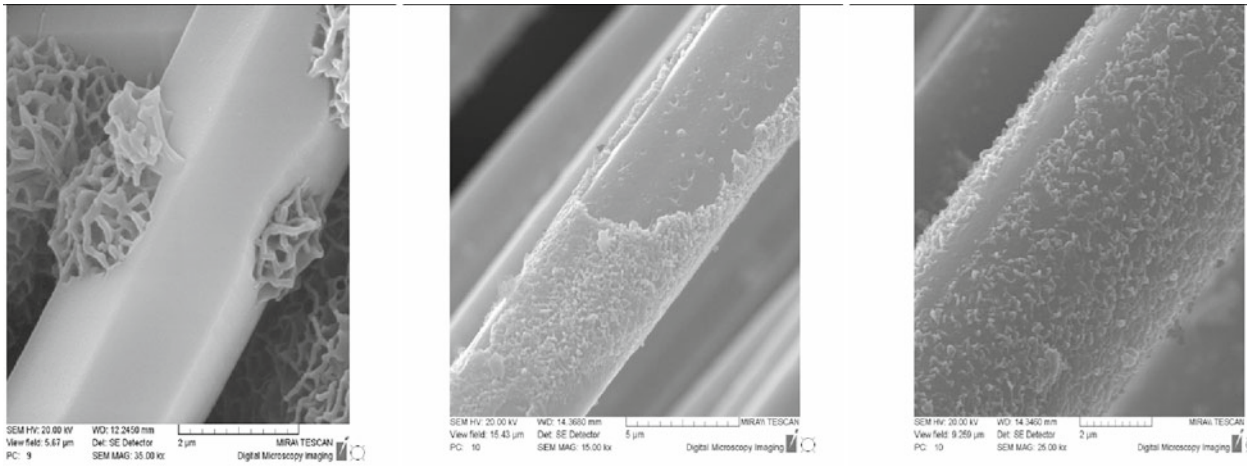


Fig. 10. Scanning electron microscope image of carbon fiber modified by aluminum hydroxide nanoparticles [10].

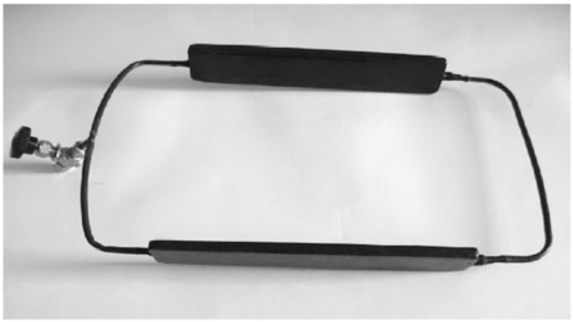


Fig. 11. Loop thermosiphon with the casing made from a nanocomposite (polyamide with introduced micro- and nanodiamond particles reinforced by coal microfibers); with isobutene as the working fluid.

a thin polymer nanocomposite plate, and the evaporator and condenser are connected by vapor and liquid small-diameter pipes (Fig. 11). The shell of the thermosiphon is made of polyamide compounds with nanocarbon fibers and diamond nanoparticles. Such a construction of the thermosiphon casing has efficient thermal conductivity of 11 W/(m·$^{\text{o}}$C), which more than 40 times exceeds the thermal conductivity of pure polyamide. In certain areas of application, polymer composites reinforced with carbon nanofibers and nanoparticles may successfully replace the metal shell of heat pipes.

The heat-transmitting characteristics of a polymer ring thermosiphon are presented in Fig. 12. It was found that the thermal resistance of a plane evaporator of a polymer loop thermosiphon is commensurable with the thermal resistance of a metal thermosiphon.

The new thermosiphons developed at the Laboratory of Porous Media of the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus (ring and vapor-dynamic ones) with a long horizontal evaporator (Fig. 13) are of great interest as they can be used as components of heat exchangers intended for cooling sorption natural gas accumulators, recuperation of the energy of renewable sources, and increasing their potential with the aid of heat pumps [21, 22].

At the present time, extremely important is the use of heat pipes and thermosiphons for cooling and thermal regulation of the electric transport components [23–25]. With increase in the power of an electric vehicle engine, the complex systems of controlling and functioning of the vehicle unambiguously require intense heat removal and a smaller space for disposition of cooling systems. The problem of removal of excess heat from an electric engine and from heat generating electronic equipment can be solved successfully with the aid of new ring thermosiphons. These facilities are autonomous, noiseless, and their operation does not need energy, which is very important for electric transport. They can

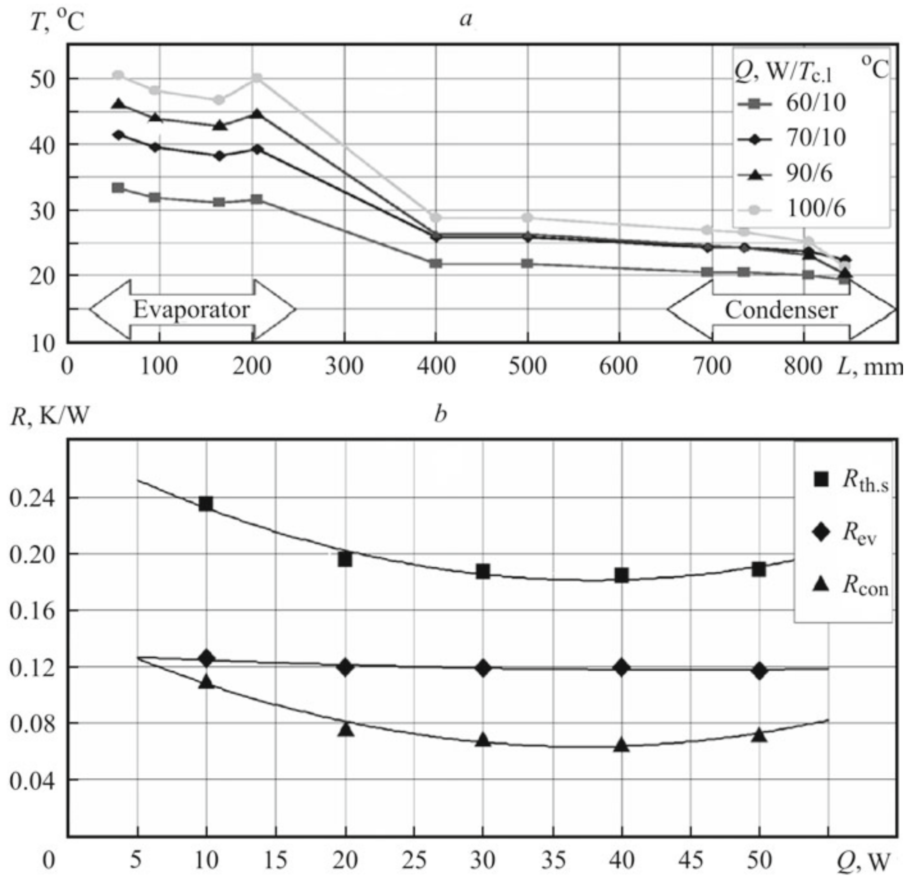


Fig. 12. Heat transmitting characteristics of a polymer ring thermosiphon: a) temperature distribution over the length of the evaporator, transport zone, and condenser ($T_{c.l}$, temperature of the cooling liquid at the inlet of the condenser heat exchanger); b) thermal resistance of evaporator (R_{ev}), condenser (R_{con}), and of thermosiphon ($R_{th.s}$).

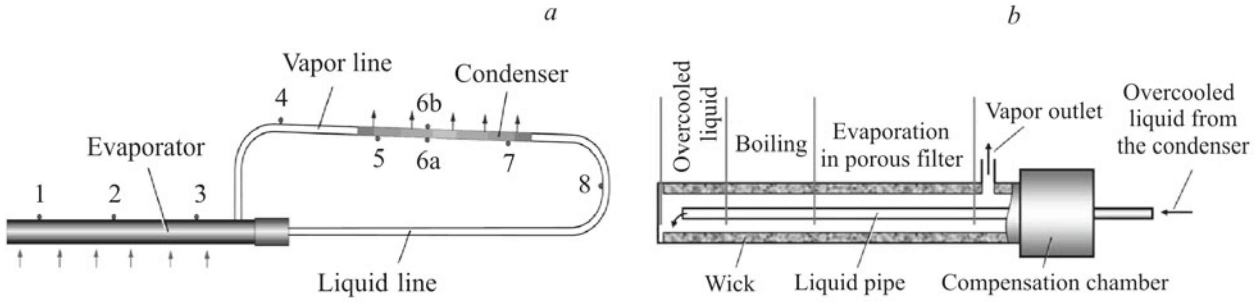


Fig. 13. Long ring thermosiphon (1–8, locations of thermocouples) and its horizontal evaporator with porous micro- and nanocoating on the wall (a); longitudinal cut of the evaporator of the ring thermosiphon (b).

receive heat from a cooled object, remove it beyond the volume filled by equipment, and then to transfer it to a cooling liquid or air. Such a system is efficient, reliable, and convenient for operation. New constructions of thermosiphons [26] provide a possibility for the best solution of the problem of cooling and thermal regulation of the engine, transmission, and power electronics of the carry-on equipment of hybrid and electric cars.

The stability of operation of new constructions of ring thermosiphons is attained by separating the flows of vapor and liquid, intensification of heat transfer in the circular minichannels of the evaporator with a heterogeneous porous

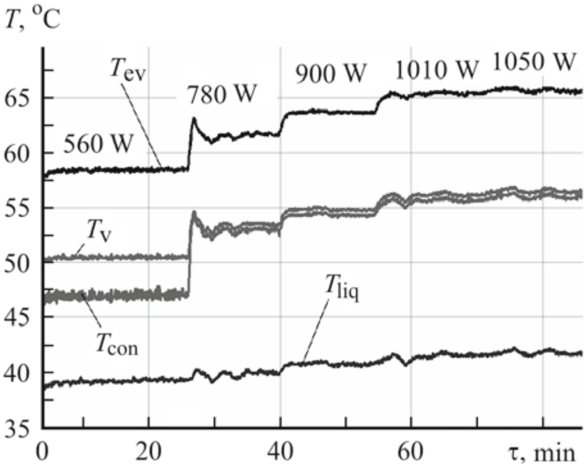


Fig. 14. Change in temperature of the thermosiphon elements with increase in heat load (water as a heat carrier) in the evaporator (T_{ev}), condenser (T_{con}), liquid (T_{liq}), and vapor (T_v).

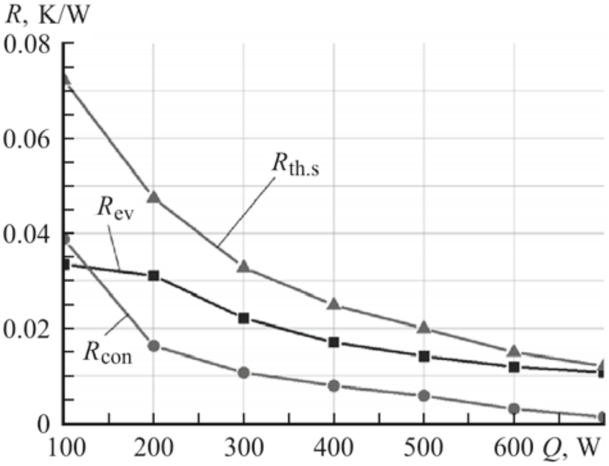


Fig. 15. Thermal resistance of a thermosiphon as a function of heat loads of evaporator (R_{ev}), condenser (R_{con}), and of thermosiphon as a whole ($R_{th.s}$); with water as a heat carrier.

coating, and by fitting the facility with a compensation chamber filled with a porous material that accumulates the liquid phase of the heat carrier (Figs. 13–15). The construction of a ring thermosiphon is an elaboration of the earlier developed loop thermosiphon with a porous coating on the inner surface of the evaporator [23]. The difference is in the value of the Bond number (Bo < 1) and the presence of cyclic pulses providing the motion of the vapor and liquid phases in the closed system, which, in combination with the effect of gravity that returns the condensate to the evaporator, increases the intensity of mass transfer of the heat carrier and correspondingly of heat between the zones of heating and cooling. The thermosiphon is capable of transmitting heat fluxes exceeding 1000 W (Fig. 14) with the thermal resistance from 0.07 K/W at heat load Q = 100 W and up to 0.012 K/W at Q = 700 W (Fig. 15). It has small inertia, which is ideal for rapid tuning of the required thermal regimes.

CONCLUSIONS

1. Nanofluids, nanocoatings, and nanocomposites open up a new area in the development and use of heat pipes and thermosiphons for recovery of solar energy, cooling electronic articles, electric transport, and refrigerating facilities. Use of minichannels filled with a nanofluid in the evaporators of heat pipes ensures the efficiency of their operation, compactness, and low thermal resistance.

2. Transparent thermosiphons (vapor-dynamic and ring ones) with nanofluids and the surface of the liquid pipe covered by nanoparticles inside the evaporator represent a good instrument for absorbing solar radiation and for utilization of solar energy.

3. A porous nanocoating (of thickness 25–100 μm) on the surface of minigrooves of heat pipes and of thermosiphons makes it possible to decrease their thermal resistance (by 2–3 times) as compared with traditional heat transmitting facilities and simultaneously to increase the capillary pressure and penetrability of the working fluid.

4. Polymer composites reinforced by nanowire and nanoparticles are considered as a promising alternative of metals to be used for casings of heat pipes and thermosiphons.

5. Long thermosiphons (vapor-dynamic and ring thermosiphons with plane evaporators and condensers made from polymer composites) are of great interest as heat exchangers for cooling the components of high-current electronics, recuperation of the energy of renewable sources, and increasing their potential with the aid of heat pumps.

NOTATION

L, length, m; Q, heat flux, W; R, thermal resistance, K/W; r, central axis of the thermosiphon evaporator; r_{in} and r_{out}, radii of internal and external surfaces of the glass pipe of a thermosiphon; T, temperature, $^{\text{o}}$C; τ, time, min.

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