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Flat polymer loop thermosyphons

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Abstract The flat horizontal polymer loop thermosyphon with flexible transport lines is suggested and tested. The thermosyphon envelope consists of a polyamide composite with carbon based high thermal conductive micro-, nanofilaments and nanoparticles to increase its effective thermal conductivity up to 11 W/(m °C). Rectangular capillary mini grooves inside the evaporator and condenser of thermosyphon are used as a mean of heat transfer enhancement. The tested working fluid is R600. Thermosyphon evaporator and condenser are similar in design, have a long service life. In this paper three different methods (transient, quasi-stationary, and stationary) have been used to determine the thermophysical properties of polymer composites used as an envelope of thermosyphon, which make it possible to design a wide range of new heat transfer equipment. The results obtained contribute to establish the viability of using polymer thermosyphons for ground heat sinks (solar energy storage), gas-liquid heat exchanger applications involving seawater and other corrosive fluids, efficient cooling of superconductive magnets impregnated with epoxy/carbon composites to prevent wire movement, enhance stability, and diminish heat generation.

Keywords: Thermosyphon; Heat pipe; Heat transfer; Cooling technologies; Air conditioning; Refrigeration; LED cooling systems

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Nomenclature

a	–	thermal diffusivity, m^2/s
c_p	–	specific heat at constant pressure, J/(kg °C), J/(kg K)
F	–	area, m^2
Fo	–	Fourier number, non-dimensional
J_0	–	terms of Laplace transformation equation
k	–	thermal conductivity, $\frac{W}{m\,K}$
L,	–	length of the polymer cylinder, m
l	–	intermediate dimension along the length of the cylinder, m
m	–	mass, kg
n	–	quantity of time intervals of the temperature evolution
Q	–	heat flow, W
q	–	heat-flux, W/m^2
R	–	radius of polymer cylinder, m
r	–	current (intermediate) value of radius of the sample, m
R_{ts}	–	heat resistance of thermosyphon, $\frac{W}{m\,K}$
t	–	temperature, $\frac{W}{m\,K}$
V	–	volume, m^3

Greek symbols

μ_n	–	roots of Laplace transformation equation
π	–	mathematical constant
τ	–	time, s

Subscripts and superscripts

1, 2	–	the first point and the second point (in a polymer complex compound cylinders)
c	–	condenser
e	–	evaporator
sat	–	saturation
ts	–	thermosyphon
w	–	wall

1 Introduction

Loop thermosyphons are efficient heat transfer devices [1–3], that are widely used for different applications such as electronic components cooling, renewable energy sources and many others. Thermosyphons are able to transfer heat flow in vertical, inclined and horizontal position over a long distance. Loop thermosyphons are of great interest for being used as heat exchangers for renewable energy sources and upgrading their potential with the aid of heat pumps. These heat transfer devices are used as the ground heat exchangers and seasonal thermal storage systems connecting with solar thermal collectors. They are extendable to more comprehensive applications. A new technology has been developed to produce loop polymer thermosyphons capable of long-term operation without air or working fluid permeation through their walls. Actually the polymer compounds of high effective thermal conductivity are used to design a wide range of new heat transfer equipment. The subject of the present paper is related to the field of cooling technologies in air conditioning, refrigeration, light-emitting diods, superconductive devices, and electronics packaging and is based on the innovative means of thermal energy handling under better operating conditions in comparison with traditional technologies. The discovery of high-temperature superconductors has stimulated theoretical and experimental investigation of composite polymer materials based on high-molecular polymers with fibrous fillers and polymer reinforced plastics used as the envelope of magnet and advanced polymer heat exchangers for the cooling of magnets. Actually, polymer heat transfer equipment have been studied in various devices [1,4–6]. Polymer-metal composites are becoming an attractive subject due to their unique surface morphology [7]. They can be made of polymeric plates whose one or both sides are metalized with a noble metal (gold or platinum) [8,9]. Considerable efforts have been made to design and fabricate controlled organic/inorganic composites with novel properties, including optical, electrical, chemical, biological, and mechanical [10,11]. In these hybrid systems, phase separation occurs naturally because they are composed of two materials with totally different chemical characteristics [12]. Also of interest for designing polymer loop thermosyphons and heat pipes the polymer-metal composites, the carbon fiber-reinforced carbon composites, epoxy and phenolformaldehyde composites reinforced with glass and carbon wires, polyamide composite materials with carbon microfilaments and nanoparticles [13,14] are attracted the attention for the heat exchangers design. The effective thermal conductivity of the envelope of such heat pipes is 10–40 times higher to compare with a pure polymer material. It is of interest to use the evaporator and condenser flat interface of such thermosyphons and heat pipes for cooling heat-generating elements and transferring the heat load to the heat sink. Unfortunately some polymers (for example, epoxy complex compound) can act as a source of localized heating and initiate thermal wave movement when it is stressed to the point of fracture by a combination of the magnetic hoop stress and the stress introduced by different thermal contractions between the epoxy and superconducting wire during the cooldown and thermal cycling. The latter stress could be considered as a source of generation of cracks and porous media inside of reinforced polymers as a function of a number of thermal cycles. The effect of aging on the thermal conductivity and thermal diffusivity of the composite is of interest, because many applications of polymers are expected to be in service for 20 or more years. Linear thermal expansion is also of importance in designing insulation system, since the opening of cracks and generation of porous structures around slabs can cause a prohibitively high increase in convective heat transfer [15]. Fiber reinforcement of polymers increases the mechanical resistance and decreases the thermal expansion, with the thermal conductivity of the composite tending to increase. Experiments on the thermal conductivity of the composite are a most useful tool for investigating scattering processes, and interaction between electrons and phonons.

2 Experimental investigation of the thermophysical properties of polymer compounds used as an envelope of heat pipes and thermosyphons

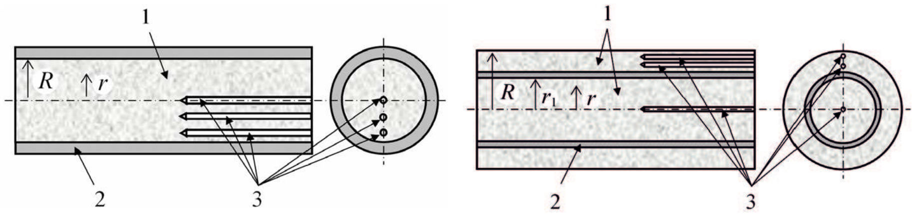
The measurements of the thermophysical properties of polymer composites (epoxy-carbon and glass filaments, phenol formaldehyde-carbon filaments and polyamide with carbon nanofilaments and nanoparticles, etc.) are useful for the designing of new heat pipes and thermosyphons.

In this research program three different methods (transient, quasistationary, and stationary) have been used to determine the thermal conductivity, $k(t)$, thermal diffusivity, $a(t)$, and specific heat, $c_p(t)$, of the polymer compounds with different forms and size (cylinders and plates) in the low-temperature range 10–400 K.

3 Transient method

Two modifications of the samples were made for the tests. The first prototype was made as a cylinder with the heat source on its surface, Fig. 1a. The second was made as a hollow cylinder (tube) made from the same material, Fig. 1b. The tube is put on the cylinder; electrical heater disposed between them. Cylinder is convenient for experiments when the samples are small. The tube on cylinder is convenient to ensure more precise measurements of the thermal properties. Both prototypes are made from the same material.

The transient method (adiabatic calorimetry) is based on the analytical solution of the thermal conduction equation for an unlimited cylinder (Fig. 1), heated by a constant source of energy under adiabatic conditions. The transient method is based on the analytical solution of the heat conduction equation inside a solid sample:



a) a cylinder with the heat source on its surface

b) a hollow cylinder (tube) made from the same material

Figure 1: Samples of polymer complex compound cylinders used to determine the effective thermal properties (thermal conductivity, thermal diffusivity, and heat capacity), with thermocouples inside: 1 – polymer compound, 2 – heater, 3 – thermocouples.

For the region $0 < r < r_1$ (cylinder)

$$\frac{\partial t_1}{\partial \tau} = a\left(\frac{\partial^2 t_1}{\partial r^2} + \frac{1}{r}\frac{\partial t_1}{\partial r}\right) , \tag{1}$$

the time $\tau > 0$, $t_1(r, \tau)_{\tau=0} = 0$; $\frac{\partial t_1}{\partial r}_{r=0} = 0$, where r_1 is the radius of the inner polymer cylinder and t_1 denotes the temperature of the inner polymer cylinder surface.

For the region $r_1 \le r \le R$ (tube on cylinder)

$$\frac{\partial t_2}{\partial \tau} = a\left(\frac{\partial^2 t_2}{\partial r^2} + \frac{1}{r}\frac{\partial t_2}{\partial r}\right) , \tag{2}$$

the time $\tau > 0$, $t_2\,(r, \_\tau)_{\tau=0} = 0$, $\frac{\partial t_2}{\partial r}_{r=R} = 0$, where R is the radius of the polymer sample and t_2 denotes the temperature on the surface of a cylinder of radius R.

On the contact surface of the electric heater disposed between the cylinder and tube the conjugated conditions are:

$$(t_1)_{r=r_1} = (t_2)_{r=r_1} , \quad \frac{\partial t_1}{\partial r}_{r=r_1} - \frac{\partial t_2}{\partial r}_{r=r_1} = \frac{q}{k} . \tag{3}$$

To solve these equations the Laplace transformation was used [15].

Let us consider the temperature evolution at the point (0, $L/2$) of the cylinder with the length L for the time of cylinder heating equal to τ. For small Fourier numbers Fo = 0.03–0.05) the temperature distribution in the region with $0 \leq r \leq r_1$, $r = r_1$, and $q =$ const is

$$t = \frac{qr_1}{k}\left[\frac{2a\tau}{R^2} + \frac{r_1^2}{2R^2} + \ln\frac{R}{r_1} - \frac{3}{4} - 2\sum_{n=1}^{\infty}\frac{J_0\left(\frac{r_1}{R}\mu_n\right)}{\mu_n^2 J_0^2\left(\mu_n\right)}\exp\left(-\mu_n^2\frac{a\tau}{R^2}\right)\right] , \quad (4)$$

where J_0 and μ are the terms and roots of Laplace transformation equation. Equation (4) can be represented as $t = \frac{qr_1 f(\mathrm{Fo})}{k}$, where $\frac{qr_1}{k} =$ const. For the temperature evolution between the time intervals $n\tau$ and $2n\tau$ we have

$$\frac{t_{2n\tau}}{t_{n\tau}} = \frac{f\left(2n\,\mathrm{Fo}\right)}{f\left(n\,\mathrm{Fo}\right)} , \quad (5)$$

where the function symbol f represents the time dependence of the change in thermal conditions on the properties of the system under consideration and n is the quantity of time intervals of the temperature evolution. We can calculate $f\,(n\,\mathrm{Fo})$ and $f\,(2n\,\mathrm{Fo})$ for two different values of Fo, and define the thermal properties of the testing solid materials as

$$a = \frac{\mathrm{Fo}\,R^2}{\tau} , \quad k = \frac{q\,r_1\,f\,(\mathrm{Fo})}{t} = \frac{Q\,f\,(\mathrm{Fo})}{2\pi\,Lt} . \quad (6)$$

4 Quasi-stationary method

For the Fo numbers greater than 0.2 we have the so-called quasi-stationary temperature distribution inside of the polymer cylinder as a function of time:

$$t = \frac{qr_1}{k}\_\left(\frac{2a\tau}{R^2} + \frac{r^2 + r_1^2}{2\_R^2} + \ln\frac{R}{r_1} - \frac{3}{4}\right) , \quad (7)$$

for $0 \leq r \leq r_1$

$$k = \frac{qr_1}{\Delta t}\left(\frac{r_A^2 - r_B^2}{2R^2}\right) = \frac{Q\left(r_A^2 - r_B^2\right)}{4V\Delta t} , \quad (8)$$

where r_A and r_B are the points of a sample and Δt is the temperature drop over the measured sample length, and V is the volume of the polymer cylinder.

5 Steady-state method for thermal conductivity determination

For the steady-state method the accuracy of the thermal conductivity measurements is good (1–2%). In this case, the heat flux is supplied to one end of the sample, with the temperature being recorded at two points. The thermal conductivity of the flat plate of polymer is determined as

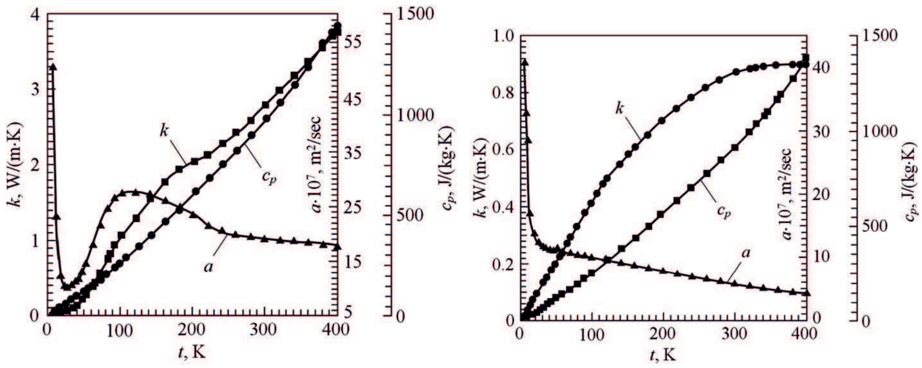
$$k = \frac{Ql}{(t_1 - t_2)\,F} \,, \tag{9}$$

where Q is the heat flow through the sample, F is the cross section of the sample, l is the length of the sample, and $(t_1 - t_2)$ is the temperature drop over the measured sample length.

The experimental set-up with the square plate samples of polymer compounds was considered in detail in [16–18].

6 Test results of thermal properties of polymer composite (epoxy-carbon filaments) and composite (polyamide-carbon micro/nanofilaments and nanoparticles)

The thermal conductivity, thermal diffusivity, and heat capacity of cylindrical prototypes of polymer composite (27-63C) (epoxy – carbon filaments) were measured using the transient method convenient for a short period of time and quasi-stationary method. Each cylindrical polymer prototype has 10 mm in diameter and 15 mm in length. We investigated the influence of heat flow direction in the polymer compound along carbon fibers and across of them. The influence of the direction of the heat flow through the sample on the effective thermal conductivity, temperature diffusivity, and heat capacity of the carbon fiber-reinforced polymer in the temperature range 10–400 K is demonstrated in Figs. 2a and b. For the thermal conductivity measurements of the polymer compound made as the square plate (0.04 m × 0.04 m) we used the steady-state method, which is more precise. The total inaccuracy of the thermal conductivity measurements did not exceed 3%. The sample dimensions were chosen in such a way that the time necessary for the equilibrium establishment was reached and for the dilatation effects could be reduced to a minimum. As the results of measurements have shown, the thermal properties of polymers depend on the carbon fiber orientation and mass of carbon in the compound. The direction of the heat flux and orientation of the carbon fiber are responsible for the heat conduction and thermal diffusivity values. Specific heat of polymer composite practically does not depend on the heat flux direction, since it characterizes the scalar value, i.e., energy accumulation. The thermal diffusivity of the compound along the fibers has some anomaly, with its maximum located between 50 and 200 K. The dilatation effects and transformation of the crystalline structure of the polymer to its amorphous state can be the reason of this maximum.



a) b)

Figure 2: Thermal properties (k, a, c_p) of the polymer compound (27–63) as a function of temperature. The direction of heat flow along (a) and across (b) carbon fibres.

The further experiments with another polymer composite (polyamide reinforced with carbon micro-/nanofilaments and nanoparticles) at the temperature interval 20–70 °C have shown its more convenient application for the thermosyphon design due to its high effective thermal conductivity. The samples were made as two plates (0.04 m×40 m) with the cartridge electric heater between them. The experimental set-up was the same as it was described in [16]. The effective thermal conductivity of such polymer composite along the carbon filaments direction is near 11 W/(m K) at the temperature interval 20–70 °C, while the thermal conductivity of pure polyamide is 0.2 W/(m K). The flexible vapor and liquid links between the thermosyphon evaporator and condenser were made from pure polyamide.

7 Polymer flat loop thermosyphons: experimental set-up

The second part of the experiments was devoted to the design of a polymer loop thermosyphon with a flat interface of the evaporator and condenser (for attaching heat-generating elements and heat sink) and flexible transport lines between the evaporator and condenser, Fig. 3. The research was aimed at providing a prototype of the polymer thermosyphon, which can be easily transformed into a wide array of configurations. The thermosyphon has rectangular capillary mini grooves inside, covered with carbon micro-/nanoparticles as a capillary structure of the evaporator and condenser (Figs. 3a and b). Its frame (envelope) is made from a polyamide compound with carbon micro-/nanofilaments and nanoparticles to increase

a) b)

Figure 3: Flat loop thermosyphon made from polymer composite-polyamide reinforced with carbon micro-/nanofilaments and nanoparticles (a) and flat evaporator (cross-sectional view) with rectangular minichannels (b).

its wettability and effective thermal conductivity [14]. The jacket of the polymer compound is formed around the core of carbon fibers to form a highly thermally conductive heat transfer device. The width and length of the thermosyphon is 50 mm 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 mini grooves inside the evaporator and condenser are 2.5 mm. The thickness of 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 evaporator and condenser, which are disposed in parallel one below the other. A promising combination of technologies that have the potential for advancing a new generation of highly flexible, lightweight, low-cost, high-performance thermal management solutions can be realized using such thermosyphons.

The width and thickness of the rectangular parts of frames are 10 mm, respectively. The working fluid of the thermosyphon is isobutene (R600). The necessary experimental techniques was used to perform some 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 flux from the evaporator to condenser and of the effective thermal conductivity of the thermosyphon envelope. The experimental setup (Fig. 4) with temperature sensors located on the evaporator, condenser, vapor and liquid pipes of the thermosyphon was

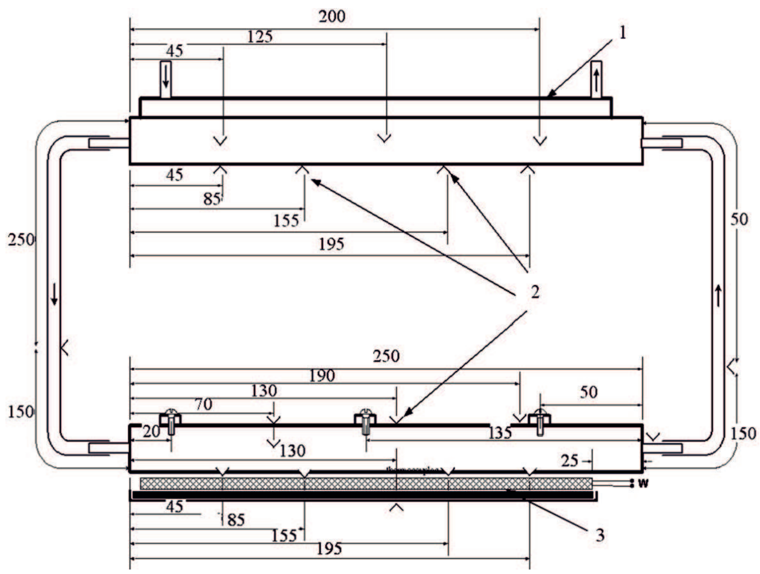


Figure 4: Experimental setup with thermocouples attached in the evaporator, condenser, and the transport zone (vapor and liquid): 1 – liquid heat exchanger, 2 – thermocouples, 3 – electrical heater.

used during experiments. The heat flux enters at the bottom of the evaporator. The heat sink is at the top of the condenser. The difference between the temperature of external walls of the evaporator, t_{w}, and the saturated temperature of 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 temperature inside the thermosyphon was changing by regulating of the temperature and fluid flow through the liquid heat exchanger disposed on the top of condenser (heat sink).

The total thermal resistance of the thermosyphon R_{ts} was calculated as

$$R_{ts} = \frac{t_e - t_c}{Q} , \tag{10}$$

where t_e is the mean evaporator temperature, t_c is the mean condenser temperature, and Q is the heat flow.

To cool the thermosyphon condenser (liquid heat exchanger) a Joulabo F12 recirculation thermal bath with temperature-regulated accuracy of ±0.5 K was used. The temperature of the liquid at the entrance of heat exchanger was maintained 10 °C for the heat load up to 60 W. The temperature of the liquid in the heat exchanger was maintained 5 °C for the heat load interval from 60 up to 100 W. 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. The temperature distribution along the evaporator, transport zone, and condenser as a function of the heat load is shown in Fig. 5a. The temperature of saturated vapor inside the thermosyphon was varied from 20 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. 5b for the temperature of the cooling liquid in the liquid heat exchanger equal to 10 °C.

It is important to note that thermosyphon is sensitive to the mass of the working fluid charged. The mass of R600 (0.013 kg) was chosen just to fill the volume of capillary channels in the evaporator, condenser, and the liquid transport pipe at room temperature for the heat load of 40 W. The analysis of the mean temperature distribution (Fig. 6) along the thermosyphon for different masses of the working fluid shows the change in the total thermal resistance of the thermosyphon as a function of fluid mass. For the mass of R600 equal to 0.013 kg the total thermal resistance is optimal, while the mass decreasing to 0.0117 kg significantly increases the thermal resistance of the evaporator and is not sufficient for its flooding.

Increasing the mass of R600 up to 0.014 kg does not significantly changes the temperature distribution along the thermosyphon. It is important to note that the tilt of the thermosyphon to the horizontal axis is not so critical (Fig. 7). The design of such a thermosyphon guarantees a weak influence of the evaporator inclination to the horizontal axis in the range of 0–20°.

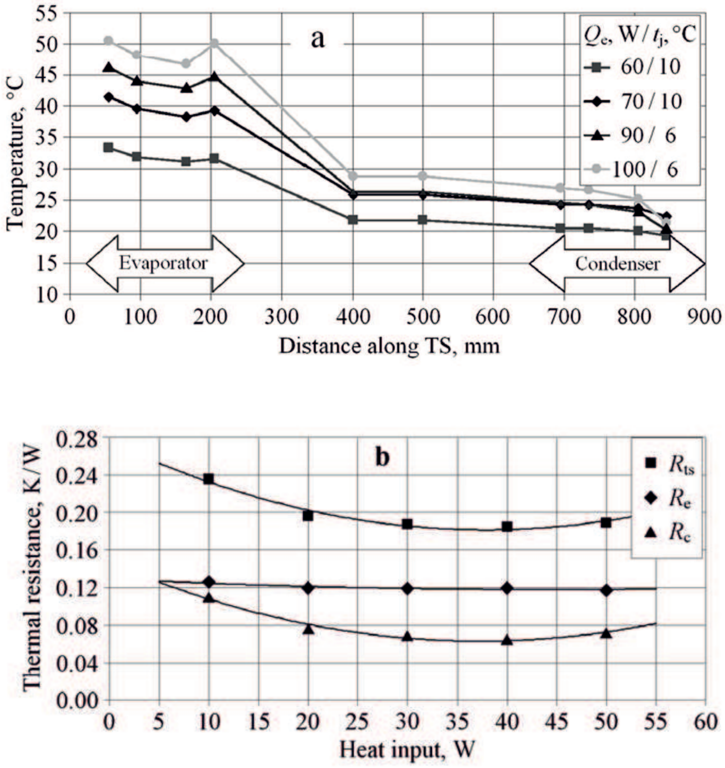


Figure 5: Mean temperature distribution along the evaporator, vapour transport line and condenser (a); thermal resistance (b) of evaporator R_e, condenser R_c and total of thermosyphon R_{ts} as a function of heat flow.

8 Loop thermosyphons: results and discussion

The set of experiments with a new type of a polymer loop thermosyphon show the possibility of applying such heat transfer devices as a low-temperature cooling device. A new polymer compound with increased thermal conductivity can be suggested as a thermosyphon envelope compatible with alcohol (methanol), water, and some hydrocarbons (R600) as a working fluids. Nanocoating of the heat-loaded surface of such thermosyphon have a significant potential for increasing the heat transfer in small-size devices, wetting and flooding the heat loaded surface [19]. Nanocoating stimulates the bubble generation in minichannels beginning from a certain heat load. Investigation of the evaporation, boiling, and condensation heat

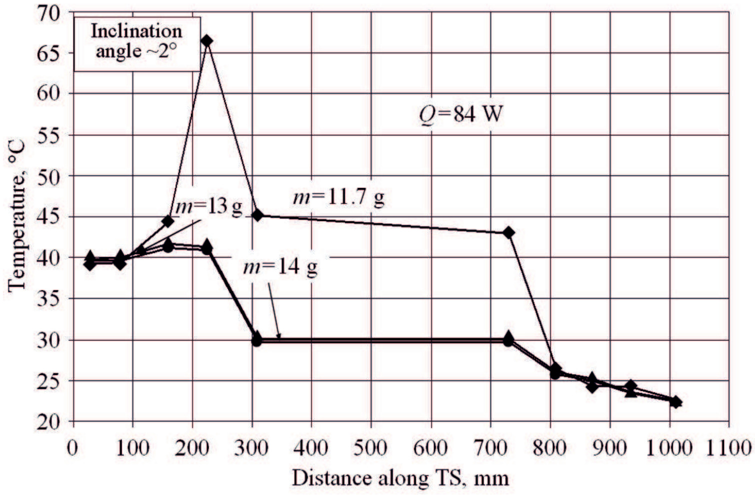


Figure 6: Mean temperature distribution along the surface of evaporator, vapor zone and condenser as a function of R600 mass. Heat input is 84 W.

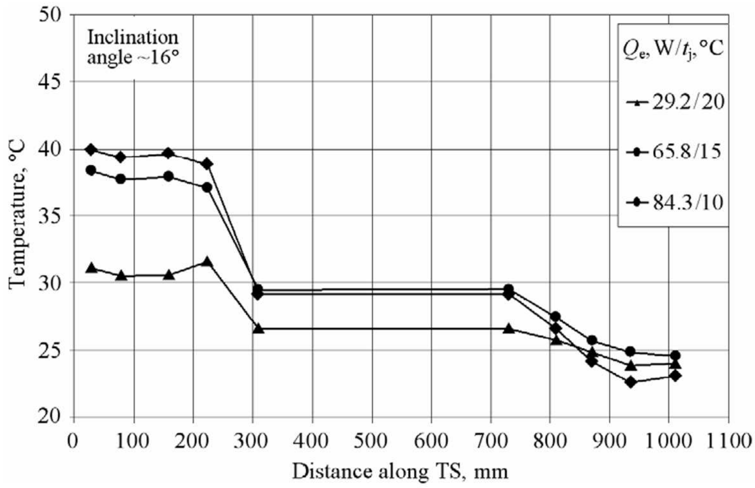


Figure 7: Mean temperature distribution along the thermosyphon as a function of heat input. The thermosyphon is inclined to the horizontal axis at 16°.

transfer in minichannels is a good tool for analyzing the cooling efficiency of such a thermosyphon. Analyzing the data in Figs. 5a and 5b it is clear that the thermal resistances of the evaporator, R_e, and condenser, R_c, depend strongly on the heat load and heat sink disposition in space.

The above-mentioned polymer thermosyphon configuration is offered only illustratively, because detailed modifications are possible, especially as to its shape, size, and disposition of the parts. An object of this research is to provide a prototype of a polymer thermosyphon, which can be easily transformed into a wide array of configurations.

9 Conclusions

1. A new type of horizontal polymer flat loop thermosyphon with nanotechnology application was suggested, designed, and tested, with the thermal resistance varying from 0.18 up to 0.24 K/W depending on the input heat flux and tilt angle. The working fluid is R600.

2. The polymer compound (polyamide reinforced with carbon micro-/nanofilaments and nanoparticles) was suggested and tested as the vacant material for such thermosyphon envelope with its effective thermal conductivity up to 11 W/(m K) at the temperature near the room. Another polymer compound (27-63C) (epoxy – carbon filaments) was tested in the temperature range 10–400 K with its effective thermal conductivity 4 W/(m K) at the temperature 400 K.

3. Three different methods (transient, quasi-stationary, and stationary) have been used to determine the effective thermal conductivity, $k(t)$, thermal diffusivity, $a(t)$, and heat capacity, $c_p(t)$, of the polymer compounds in a low-temperature range 10–400 K.

4. The tested thermosyphon is sensitive to the mass of the working fluid charge (R600). Slight undercharge increases the temperature of the evaporator and the total thermal resistance.

5. The degree of the inclination of the horizontal thermosyphon to the horizontal axis (up to 20°) only slightly increases the thermosyphon thermal resistance.

6. The combination of the working fluid R600, polymer (pure polyamide), and polyamide compound material (polyamide reinforced with carbon nanofilaments and nanoparticles) as the thermosyphon envelope is completely compatible, noncondensable gas generation inside it has not been detected.

7. Suggested thermosyphon can be used as a dielectric thermal link between the heat source and the heat sink due to the pure polyamide flexible links (vapor and liquid pipes) between the evaporator and condenser and dielectric working fluid R600 application.

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