Loop thermosyphons with porous coatings

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Abstract. The aim of this work is to experimentally evaluate the heat exchange of evaporation and condensation inside a new annular thermosyphon with horizontally located zones of evaporation and condensation, which are interconnected by a vapor line and a condensate line. The mini-tube of the liquid line is introduced coaxially into the cylindrical evaporator with a porous coating, thus an annular channel is formed between the tube and the porous coating of the evaporator. The purpose of this study is to determine the thermal resistance of the device and its components, as well as the temperature field along the thermosyphon. The considered thermosyphon guarantees a shorter start-up time, lowers the temperature of the evaporator walls, has a small temperature hysteresis with an increase/decrease in the transferred heat flux, and suppresses temperature pulsations inside an evaporator. The 130 mm long evaporator is made of copper tube ($d_{\text{out}} = 12$ mm, $d_{\text{in}} = 10$ mm). The wick is obtained by sintering copper powder. The working fluids R245fa and R600 were used. The thermal resistance of thermosyphon does not exceed 0.5 K/W, and of the evaporator 0.1–0.05 K/W).

1. Introduction

Heat pipes and similar two-phase thermosyphons are efficient, compact and passive heat transfer devices. The increase in the productivity of equipment, which is accompanied by an increase in the intensity of heat release (electronics, telecommunication systems, solar technology with concentrators of incident solar radiation) stimulates the creation and production of new devices that meet modern requirements for thermal control of equipment. The current trend in the development of equipment for micro- and optoelectronics (MEMS) is to improve its layout, reduce the assembly due to the miniaturization of units in connection with needs of their commercial applications. Loop heat pipes (LHP), loop thermosyphons (LT), mechanically pumped two-phase loops, and evaporative spray cooling, pulsating heat pipes play a vital role in heat dissipation and recently have been widely used in the electronic components cooling and some other energy applications [1–7]. Due to the aptness to transfer large heat fluxes over long length without the use of mechanical energy, as well as reliability, high resource, technical simplicity and low cost, thermal management systems based on the above devices are very suitable. The main advantage of such models is a separation of vapor and liquid flows, they move through different pipes. This technology guarantees a higher heat transfer capacity of heat pipes and thermosyphons.

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Recently a new polymer loop thermosyphon was suggested and tested [8]. The horizontally arranged flat evaporator and condenser are coupled by a flexible vapor line and a condensate line made of polymer material.

In [5], a study of a model of a two-phase loop with three evaporators is described; the movement of the coolant is carried out by forced convection. The purpose of the experiments was to determine the performance of a system with parallel operating evaporators at different levels of heat load on each of them. The applied porous evaporation surfaces made it possible to increase the heat transfer coefficients up to 20 W/(cm² K). The results of the study of a loop thermosyphon with several evaporators at various values of heat load and angles of inclination are presented in [6]. The device is a closed planar serpentine made of an aluminum tube with an inner diameter of 3 mm; FC-72 fluid was used as a working fluid. The authors of [7] studied both numerically and experimentally the effect of the angle of inclination and the degree of wettability of the evaporator surface on the heat transfer capacity of the thermosyphon.

Cryogenic loop heat pipes are of great interest for cooling and thermal regulation at low temperatures (some medical and infrared sensors, superconductive magnetic materials) [9, 10]. A low-temperature medical heat pipe probe for non-invasive, non-drug treatment by hypothermia of a local human cavity was suggested and tested in [11]. Heat transfer processes in heat pipes and two-phase thermosyphons in combination with various technologies including nanocoatings, nanofluids, and nanocomposites are analyzed in detail in some publications [12–16]. Modern loop heat pipes for the electronic components cooling with sophisticated types of porous membrane were designed and tested in [17–22]. For use in these experimental programs, three evaporators with different modifications of wicks, such as microchannel, modulated monoporous, and modulated biporous wicks, were manufactured and combined with other constituent elements of the LHP. Various types of thermosyphons have been developed and studied for use in power systems [22], nuclear reactors [23, 24], solar heat recuperators [25–27], air conditioning [28] cooling systems for microelectronics [29], electronic components in avionics [30], and other areas.

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The devices mentioned effectively work under optimal conditions. For thermosyphons this is a vertical or close to vertical position, heat pipes are less sensitive to orientation in space, but their heat transfer capacity drops at low hydrostatic pressures. Meanwhile, in some cases, when solving problems of heat removal, it is required to locate an evaporator and condenser horizontally, while from the layout conditions they should be quite long. Loop heat pipes [31] are capable of transferring heat flow in a horizontal direction and even in a direction opposite to the gravity vector, however, loop heat pipe has limitations on the length of the evaporator, and there may be some problems with starting, such as a long start-up time or thermal and hydraulic oscillations at low heat loads. The specified reasons were the motivation for the development and study of a new design of thermosyphon. This study is oriented on the tests of the loop thermosyphon with porous coating of the evaporator (LTCE). This is the new device, the main difference of it from traditional thermosyphons and loop heat pipes is the ability to transfer heat flow in a horizontal direction, while the condenser can be extended compared to loop heat pipe, this expands the possibilities of using a thermosyphon. The simplest LTCE consists of an evaporator with a compensation chamber and a condenser, which are interconnected by vapor and liquid pipes. The proposed concept is to use a new combined two-phase mode of pumping the working fluid through the mini-gap of the annular channel in the evaporator. Due to its unique characteristics (high thermal conductivity, extended, evaporator, etc.), a new loop thermosyphon with a porous evaporator is proposed for cooling objects in electronics, in medicine as a “cold finger” for cooling the human body, in solar photovoltaic and heating systems. Cryogenic infrared sensors, based on the application of LTCE coolers ensure precise thermal control at a low temperature. LTCE could solve the problem of cooling down superconductive magnetic materials directly or indirectly. It is interesting to note that the start-up of the LTCE has some advantages over the conventional LHP and LT (the transport distance and heat release capacity). The LTCE as an advanced electronic cooling device possesses the ability to handle multiple heat sources (chips, LED emitters, et.) simultaneously located along the single evaporator surface.
Based on the above mentioned problems, this study focuses on carrying out the work on the developing, designing and testing LTCE and, as a result, obtaining a solution that can significantly improve its efficiency. The results show that the thermosyphon is capable of transferring heat load of 140 W at a heat flux of 18.9 W/cm² in an evaporator. The total thermal resistance of the device is 0.36 K/W.

2. Loop thermosyphon with the evaporator having a porous coating

The copper LTCE (Figure 1) is equipped with an extended (length 100–200 mm) horizontal cylindrical evaporator, 10–12 mm in diameter, and a cylindrical condenser, which was cooled using a flow-through liquid heat exchanger in the described experiments. The inner surface of an evaporator is covered with a porous layer of no more than 1 mm thickness of sintered copper powder particles. When the volume of a compensation chamber is correctly selected and the filling ratio is optimal, a liquid supply is constantly present in a compensation chamber, and the LTCE shows an ability to self-regulate an amount of liquid in an evaporator.

![Figure 1. LTCE scheme. Points 1–8 indicate the positions of thermocouples.](image)

The LTCE evaporator (Figure 2) has some important design features, including an annular gap. A porous wick (porosity ~ 50%, average hydraulic pore diameter 0.025 mm) was made by sintering copper particles of 0.063–0.100 mm fraction (average diameter 0.082 mm). During a heat load application to an evaporator, intense heat and mass transfer occurs in a narrow annular channel. The evaporator can be divided into four conventional zones with the following heat transfer modes: subcooled flow boiling, flow nucleate boiling, and evaporation of the working fluid in an annular gap and a porous wick. The movement of the liquid phase is caused by a pressure drop due to the force of gravity, a formation and growth of vapor bubbles, and capillary forces in a porous media.

![Figure 2. Longitudinal section of the LTCE evaporator and zones of hydrodynamic and heat transfer modes disposed along them.](image)

Before the decision was made concerning the choice of the best type of porous structure and the LTCE evaporator final design, some experiments were carried out on an experimental setup, the main element of which is a boiling vessel placed in a hermetic heat-insulated box equipped with a system for maintaining the required temperature to reduce a heat exchange between the vessel and the environment (a refrigeration machine, a thermostat, a developed channel circuit on the inner walls and
a pump for circulation liquid of a given temperature). The boiling vessel has a working section with a test sample and an electric heater, a condenser, windows for observing and photographing the process, a sleeve for introducing thermocouples to control the temperature. Two sets of experiments were realized to study a heat transfer and hydrodynamics during the phase transition on the surface of the test specimen. The first set of experiments was conducted in the liquid pool (macroscale heat transfer). The second set was realized inside the system of mini-/microchannels (porous material). A more detailed description of the equipment and the method of experiments are presented in [20]. In our experiments, a sample (a horizontal tube 20 mm in diameter) was coaxially placed in a transparent glass cylinder with an annular mini-channel 0.8–1.8 mm (Figure 3).

**Figure 3.** The sectional drawing of the tested sample partially submerged (left) and put in the liquid pool (right): 1) liquid surface, 2) test sample, 3) glass tube, 4) electrical heater, $H$ is the liquid column height.

All measurements were carried out in a stationary mode of the process. The heat transfer coefficient $h$ was determined as

$$h = q / (T_w - T_l),$$

where $q$ is a heat flux; $T_w$ and $T_l$ are the temperatures of wall (heat exchange surface) and liquid.

Visual observation of two-phase heat transfer testifies that movement of vapor bubbles in an annular mini channel is complex. Bubbles generated during the nucleate boiling can be considered as micro pumps action to move vapor and liquid both perpendicular to the heat exchange surface and to create mini-pulsations of a two-phase flow along a sample axis in the direction from an entrance to an exit to a liquid pool in an upper zone of a glass cylinder. It was found that a heat transfer coefficient is affected by a position of an interface between a liquid and a vapor space in a glass cylinder: it took on maximum values when a sample was partially submerged. During experiments, it was determined that a number of menisci in pores and, consequently, a surface area of an evaporation increases with increasing heat flux.

The process modeling an evaporator of LTCE is shown in Figure 4: 1) heating of subcooled liquid zone (Fig. 4a); 2) transient zone of subcooled liquid boiling in the mini channel, Fig. 4b; 3) zone of the developed nucleate boiling in the mini channel (Figure 4c); 4) liquid rivulet at the bottom part of glass tube and evaporation inside the porous wick (Figure 4d).
Figure 4. Modes of heat transfer in an evaporator: a) subcooled liquid heating near the entrance of the annular mini channel of LTCE evaporator; b) beginning of nucleate boiling of the saturated liquid in the annular mini channel of LTCE evaporator; c) bubble flow boiling heat transfer; d) evaporation inside the wick, capillary suction of liquid from the liquid rivulet at the bottom of evaporator.

The experimental data obtained on submerged and partially submerged porous tube are shown in Figure 5. In a certain range of heat loads, the intensity of heat transfer in a narrow annular channel is 2.5–3 times higher than during pool boiling.

Figure 5. Heat transfer intensity along the evaporator depending on a height $H$ of a liquid inside the annular mini gap: 1–5 – $H = 70, 2, 1.5, 1, \text{ and } 0.5 \text{ mm}$.

Open porosity, defined as the ratio of a pore volume that can be filled with liquid to a total volume of a body, plays an important role in a development of hydraulic and thermal processes during phase transitions and, therefore, is one of the key characteristics of a porous wick. Featuring a set of mini- and macro-scale pores, the wick provides a high mass flow rate for fluid filtration. Another essential parameter of a wick is permeability, which affects a rate of fluid flow through pores.

Various processes occur in the annular mini-channel of the evaporator, including capillary pumping of the liquid phase through the pores, two-phase heat transfer in the form of evaporation and boiling in
the flow. In the case under consideration, only walls of an evaporator have a porous coating, while
channels for vapor and liquid are made of smooth-walled tubes, which significantly reduces a
hydraulic resistance and, as a result, a pressure loss inside them. A liquid line connecting the LTCE
condenser and evaporator is inserted into an evaporator in such a way that an annular mini gap is
formed between its extension inside an evaporator and a porous wall of an evaporator (Figure 2),
inside of which it provides forced nuclear boiling and evaporation with intense heat transfer.

The LTCE condenser is made as a straight copper tube 105 mm long, 6 mm diameter disposed
inside the liquid/liquid heat exchanger. A condenser envelope is cooled with water transferred from
the tank through a flow-through heat exchanger that encloses a condenser. The temperature of cooling
water is kept stably by means of the thermostat; the volumetric flow is controlled by a flow meter. The
thermal control system allows regulating the temperature of the cooling water in the range of 20-80 °C.
Thus there is a possibility accordingly to change the temperature of vapor condensation, changing the
boundary conditions of heat transfer inside the LTCE condenser. A total length of the LTCE tracts,
including vapor and liquid lines, is about 500 mm.

The pressure balance during a circulation of a vapor and liquid phases of a working fluid in the
LTCE circuit is expressed as follows:

$$\Delta P_g + \Delta P_{bg} = \Delta P_l + \Delta P_v + \Delta P_e + \Delta P_c,$$

(2)

where $\Delta P_g$ is the pressure drop due to gravitational forces, $\Delta P_{bg}$ is the pressure drop due to the
formation and growth of vapor bubbles in an annular channel; $\Delta P_v$ and $\Delta P_l$ are pressure drops in vapor
and liquid flows; $\Delta P_e$ and $\Delta P_c$ are pressure drops due to phase transitions (evaporation and
condensation). To ensure a proper functioning of the LTCE, it is necessary that the sum of $P_g + \Delta P_{bg}$
must be greater than or at least equal to the sum of all terms on the right side of equation (2). There is
also a capillary pressure drop $\Delta P_{cap}$ along the porous coating perimeter; $\Delta P_{cap}$ is responsible for a
liquid capillary suction inside a porous coating from a liquid rivulet inside an annular channel, but
does not significantly affect working fluid circulation along the LTCE.

The average difference $\Delta T_{avg}$ between the temperatures of an evaporator and a condenser when
calculating according to Eq. (3) was determined using the surface-averaged temperatures of a
condenser $T_c$ and the evaporator $T_e$, which were calculated using Eqs. (4) and (5):

$$\Delta T_{avg} = T_e - T_c,$$

(3)

$$T_e = \frac{T_1 + T_2 + T_3}{3},$$

(4)

$$T_c = \frac{T_5 + T_6 + T_7}{3},$$

(5)

where $T_1$–$T_3$ and $T_5$–$T_7$ are the temperatures on surfaces of an evaporator and a condenser, $T_4$ and $T_8$
are the temperatures on a vapor and a liquid lines. Numbers 1–8 indicate positions of thermocouples
(Fig. 1). The LTCE with an evaporator with a diameter of 10–12 mm and a length of up to 200 mm is
able to prevent heating of a cooled element above 80°C at a heat load of 200 W. The LTCE design
provides quick start-up, lowering an evaporator shell temperature, and stabilizing a temperature inside
a thermosyphon, suppressing its changes. One of the important properties of LTCE is an aptitude to
transport heat a long distance from a heat source. Heat transfer in LTCE is carried out by the action of
gravity forces and pressure impulses resulting from nucleate boiling of condensate in a mini-channel
of an evaporator.

According to published data on studies of loop heat pipes [11, 21], when testing copper-water
LHPs with wicks of copper or less thermally conductive materials, in order to guarantee a successful
start-up of a device, a vapor temperature should not be lower than 40°C even with minimal heat loads
due to low water pressure at room temperature.
A thermal resistance of LTCE decreases with increase in a temperature of a liquid used for heat removal from the condenser (liquid line). A condenser/radiator is a high-mass element with a developed surface. The rate at which liquid accumulates in a condenser is determined by a number of factors:
- temperature of a sink;
- heat load affecting a vapor generation rate;
- absolute temperature and pressure values;
- fluid thermophysical properties;
- thermal conduction in a face sheets;
- back thermal conduction;
- vapor entering into an evaporator through a condenser;
- degree of subcooling of a liquid entering an evaporator due to accumulation of liquid and changes in the temperature of a radiator.

The ability to use a “hot” cooling liquid has an important practical prospect in particular for “free cooling” technology, for example, in cooling systems of data-centers, utilization of heat dissipated inside data-centers. The cooling capacity of the LTCE condenser (heat sink) is determined by the following formula

$$ Q_{\text{out}} = m \cdot c_p (T_{\text{out}} - T_{\text{in}}), $$

where $m$, $c_p$, $T_{\text{out}}$, and $T_{\text{in}}$ are respectively the flow rate, specific heat at a constant pressure, the outlet and inlet temperature of cooling water.

3. Experiments

Many factors such as optimal geometric parameters, liquid filling ratio, heat load, tilt angle affect, and the start-up time of the LTCE were considered in the experiments. In order to establish the heat transfer capacity of the LTCE, a set of experiments was carried out using various working fluids. The diagram of the experimental setup is presented in Figure 6.

![Diagram of experimental setup](image)

**Figure 6.** Scheme of the experimental set-up for LTCE testing: 1) liquid flow heat exchanger, 2) LTCE, 3) electrical heater, 4) ammeter, 5) wattmeter, 6) computer, 7) thermostat, 8) Agilent for data acquisition/logger for data registration, 9) signal cable for thermocouples, 10) regulated power supply.

An electric heater was applied as a source of energy. Heat flow $Q$, defined as the electric power supplied to the heater, taking into account heat losses, was absorbed by the water cooling system of
the LTCE condenser. The liquid temperature inside the Circulating Thermostatic Bath Carbolite Gero Limited, Julabo FP-89 was changed from the “cold” to “hot” temperature (20 to 80°C) with a liquid flow rate of 10 L/min. The precision of the liquid temperature maintenance in the Bath is ±0.1°C. Furthermore, the measured data were recorded by the Agilent 34970A data acquisition system, which was subsequently processed. To measure a working vapor pressure inside the LTCE during the experiments, a PSA-C01 pressure meter, and an NI-9203 were used. A temperature field along the LTCE was registered by thermocouples placed on a surface of an evaporator and condenser envelops (Fig. 1). The measurement errors were determined in accordance with the methodology proposed in [32]. The precision of the heat flow measurements was ±0.5%; temperature uncertainty was about ±1.25 °C. To minimize heat transfer with the environment, the system was reliably insulated, thus enabling a correct assessment of the thermal performance of the LTCE. LTCE samples were tested using two working fluids, R245fa and R600. In these experiments, a heat load applied in an evaporator starting from 10 W was increased up to 30, 40, 50, 60, 70, 80, 90, 100, and 120 W and then was decreased back. No hysteresis of LTCE thermal resistance via heat load decreasing was observed.

The thermal resistances of an evaporator $R_e$, a condenser $R_c$, and total $R_t$ for the LTCE are calculated as follows:

$$R_e = \frac{(T_e - T_v)}{Q},$$

$$R_c = \frac{(T_v - T_c)}{Q},$$

$$R_t = \frac{(T_e - T_c)}{Q},$$

where $T_e$ and $T_c$ are temperatures of an evaporator and a condenser, $R_t$ is a total thermal resistance of LTCE.

4. Results and discussion

In the present research, a cycle of experiments was conducted to study and analyze some LTCE parameters, including the thermosyphon geometry, liquid filling ratio, vapor and liquid line lengths, and heat load. It is known that a functioning of a closed system in which combined process of evaporation/boiling and condensation occur accompanied by a mobility of an interface between vapor and liquid, which is in principle impossible without temperature and pressure pulsations. The same phenomena are typical for LTCE. A difference may lie in an organization of mentioned processes and the values of pulsations. If a process of heat and mass transfer in LTCE is organized optimally, using evaporation in a porous structure as the main heat transfer mode, the amplitude of pulsations will be very small and it is of little practical importance.

4.1. Results

4.1.1. Copper-R245fa LTCE #1.

The geometric parameters of Copper-R245fa LTCE thermosyphon, sample #1 are presented in the table 1. The start-up and the temperature evolution of LTCE #1 via a time for different heat input $Q$ are presented in Figure 7.a. The temperature curves are shown for an evaporator and a condenser, working fluid in vapor and liquid pipes, and inside a condenser (heat sink). The obtained results show that LTCE (copper-R245fa) has a good dynamic of a start-up. It starts at sufficiently low heat loads (less than 10 W). The LTCE is stable in operation over a wide range of heat input (10–100 W). The total thermal resistance $R_t$ is 0.34 K/W. The evaporator thermal resistance $R_e$ is equal 0.1–0.05 K/W in a heat load range 30–100 W.
Table 1. Dimensions of the LTCE components (sample #1)

| Characteristics | Size, mm |
|----------------|---------|
| Evaporator     | Length 130 |
|                | Diameter/wall thickness 12/1 |
| Condenser      | Length 105 |
|                | Diameter/wall thickness 4/0.5 |
| Vapor line     | Length 90 |
|                | Diameter/wall thickness 4/0.5 |
| Liquid line    | Length 350 |
|                | Diameter/wall thickness 3/0.5 |

The temperature graphs along the LTCE are given in Figure 7.b. The experimental data indicate that the temperature drop along a length of an evaporator is small. When a thermal load of the LTCE evaporator is changing from 30 up to 120 W, a heat transfer capacity of the thermosyphon is high and not deteriorated.

![Figure 7](image_url)

**Figure 7.** (a) Start-up of LTCE, sample #1. $T_e$, $T_v$, $T_c$, and $T_l$ are the temperature of evaporator, vapor, condenser, and liquid respectively. Working fluid – R245fa (b) Temperature distribution along LTCE, sample #1, as a function of heat load in an evaporator. Working fluid – R245fa.

The thermal resistance of an evaporator, condenser and thermosyphon LTCE as a function of temperature of a cooling liquid is shown in Figures 8a and 8b. A heat load is equal 40 W. It should be noted that with increase of the temperature of a coolant liquid in a thermostatic bath the total thermal resistance LTCE decreases, Figure 8.b. This is very important, since the temperature of the working liquid entering the evaporator is increasing and the boiling of the saturated liquid is beginning earlier. For example the air temperature inside a closed space like a data center can be high to compare with a surrounding.

![Figure 8](image_url)

**Figure 8.** (a) Thermal resistances of evaporator $R_e$ and condenser $R_c$ and a total thermal resistance $R_t$ of LTCE #1 as a function of the LTCE heat load (b) Thermal resistances of evaporator $R_e$ and
condenser $R_c$ and a total thermal resistance $R_t$ of LTCE #1 as a function of a temperature of a cooling water, $Q = 40$ W.

4.1.2. Copper-R600 LTCE #2.

The dimensions of the LTCE#2 thermosyphon charged with R600 are the same as those of LTCE#1 (table 1). A temperature evolution of the LTCE #2 components via a time and along the LTCE for different heat input is shown in Figures 9 and 10a. The thermophysical parameters of the LTCE sample #2 with the working fluid R600 are similar to LTCE thermosyphon, sample #1. The thermal resistances of the evaporator, condenser, and thermosyphon as a function of the temperature of the cooling liquid are shown in Figure 10b, depending on the heat load of LTCE.

The thermal resistance of LTCE decreases with the temperature increase of the coolant liquid.

![Figure 9](image)

**Figure 9.** Temperature distribution along LTCE (sample #2) as a function of time and heat flow applied. Working fluid is R600. $T_e$, $T_v$, $T_c$, and $T_l$ are the temperature evolution of an evaporator, a vapor, a condenser, and a liquid, respectively.

![Figure 10](image)

**Figure 10.** (a) Temperature profiles along LTCE (sample #2) as a function of heat load in the evaporator. Working fluid is R600 (b) Thermal resistances of evaporator $R_e$, condenser $R_c$ and the total thermal resistance $R_t$ of LTCE #2 as a function of the LTCE heat load.

The experimental results show that R245fa and R600 LTCE’s have a good dynamics of the start-up. Thermosyphons are easily starting at sufficiently low heat loads (less than 10 W) and are very stable in operation over a wide range of heat loads (10–100 W). The total thermal resistance $R_t$ of the LTCE does not exceed 0.35–0.5 K/W (for evaporator $R_e = 0.1–0.05$ K/W) in the heat load range 30–100 W.

4.2. Discussion
LTCE thermosyphons summarize the advantages of conventional heat pipes, LHPs and LTs. The experimental results show that the modified system of LTCE is able to prevent the unacceptable surface drying phenomena and significantly reduce the evaporator temperature.

According to some authors [16, 21], the start-up at low heat loads is a problem operating stage for conventional LHPs. This problem is not important for the case of LTCE. Even at low heat inputs a easy starting of LTCE takes place. There is good circulation of the working fluid is ensured inside LTCE thermosyphon in the wide interval of heat loads. The porous coating of the evaporator minimizes fluctuations of temperature, pressure and the noise. The application of porous coating in the LTCE evaporator increases the two-phase heat transfer intensity nearly 2–3 times than at a pool boiling heat transfer in a conventional loop thermosyphon with a smooth-wall evaporator.

5. Conclusions
The paper describes a new looped thermosyphon (LTEC) concept, in particular a bayonet-type annular evaporator with a porous coating to facilitate enhanced boiling. The thermosyphon configuration is an evaporator (heat supply zone) with a compensation chamber and a liquid-cooled condenser (heat sink), connected by a vapor line and a liquid (condensate) line, Figure 1. Two experimental thermosyphons LTEC were made of copper tube, the geometric dimensions are given in table 1. Both models of LTCE have the same wick, which is made of copper sintered powder. The working fluids used are R245fa and R600. The LTEC model #1 with R245fa is able to withstand heat loads up to 130 W, providing evaporator heating not higher than 50°C. The LTEC concept is very promising for efficient thermal management of cooling data centers, servers, and other electronic devices operating under high thermal loads. As a result of tests, it was found that the thermal resistance of LTEC decreases with an increase in a supplied heat flux, which is explained by an increase in a circulation rate of a working fluid. Due to passive phase separation, there is no need for active flow control even with very short local increases in heat flow along the evaporator. It is very significant that, unlike a loop heat pipe, the LTEC evaporator is practically unlimited in length. Consequently, a number of cooled elements, such as cryogenic infrared sensors, electronic chips, LEDs, etc., can be attached to one unique evaporator of LTEC. This device has good dynamic characteristics: it starts up at sufficiently low heat loads (less than 10 W), quickly goes into operation and works stably in a wide range of heat loads. In this case, the thermal resistance of the LTEC evaporator is 0.05–0.1 K/W for both tested fluids. The heat flow density for LTEC #2 (L = 130 mm) is equal to q = 48 kW/m². At a heat load of 100 W, the surface temperature of the LTEC evaporator is 105°C for R245fa, and near 100°C for R600.

6. Conclusions

| Symbol | Description |
|--------|-------------|
| c      | specific heat, J/ (kg K) |
| d      | diameter, mm |
| H      | height, mm |
| h      | heat transfer coefficient, W/ (m² K) |
| L      | length, mm |
| m      | mass, kg |
| P      | pressure (Pa) |
| Q      | heat flow, W |
| q      | heat flux, W/m² |
| R      | thermal resistance, K/W |
| T      | temperature, °C |

Subscripts:
- avg – average;
- bg – bubble generation;
- c – condenser, condensation;
- cap – capillary;
Acronyms:
LHP – loop heat pipe,
LT – loop thermosyphon,
LTCE – loop thermosyphon with porous coating of the evaporator

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