UDK 536.248.2

DOI: 10.15222/TKEA2020.3-4.42

Doct. of Tech. Sci. V. Yu. KRAVETS, D. I. HUROV

Ukraine, Kyiv, National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
E-mail: kravetz_kpi@ukr.net

HEAT TRANSFER CHARACTERISTICS OF MINIATURE TWO-PHASE THERMOSYPHONS WITH NANOFLUIDS

This paper presents and analyzes experimental data on the total thermal resistances of two-phase miniature thermosyphons with nanofluids; the geometric parameters of the thermosyphons for all experimental samples are identical: total length 700 mm, internal diameter 5 mm. The following nanofluids used as heat carriers are: aqueous nanofluid based on carbon nanotubes, aqueous nanofluid based on synthetic diamond, and aqueous nanofluid based on amorphous carbon. Much attention is also paid to the influence of the filling ratio on the heat transfer characteristics of the thermosyphons. The influence of filling ratio and types of nanofluid on the performance of miniature closed two-phase thermosyphons is demonstrated.

Keywords: miniature thermosyphons, thermal resistance, filling ratio, nanofluid, heat flux.

The problems associated with maintaining the temperature regime and cooling of semiconductor devices are becoming more urgent and complex every day, which requires an increasingly integrated approach to solving them. This problem becomes particularly urgent with the development of high-power computing; so-called supercomputers need effective "supercooling".

Due to the fact that the packaging density of electronic equipment, which is at the same time a miniaturization criterion, is increasing every day, the cooling systems that have been used for decades have not been able to meet the new requirements for thermal stabilization and maintaining the temperature in a given normalized range.

Two-phase cooling systems have proven themselves to be highly efficient and fairly cheap, while also being quite reliable. The operation principle of such systems is based on the evaporation-condensation cycle. Apart from efficiency, one of the main advantages of these cooling systems is that they are passive, which reduces the operating costs relating to the pumping of working fluid. Such systems include heat pipes, thermosyphons, and vapor chambers.

This work is devoted to the study of heat transfer characteristics of thermosyphons (**TS**), because their efficiency-reliability-price ratio is optimal among all the mentioned types. Since there is no capillary-porous structure, the cost and thermal resistance of this device type are much lower than, e.g., for heat pipes. One of the main disadvantages of thermosyphons is that they are not functional against gravity, but many tasks do not require this particular capability.

However, it should be noted that the operation of thermosyphons is limited and depends on a large number of determining factors, such as the filling ratio, the evaporation zone length, the working fluid type, the geometric parameters (system design), etc.

In recent years, increasing interest has arisen in the use of nanofluids as heat carrier for evaporation-condensation systems. A huge number of studies are devoted to the use of nanofluids as heat carrier in thermosyphons. Unfortunately, the existing works are quite limited and often controversial, and moreover, the thermosyphon designs that they deal with can hardly be considered miniature. This study addresses miniature closed two-phase thermosyphons with nanofluid-based coolants.

Literature analysis

Nanoparticles are particles characterized by a small size, which is in the range of 1—100 nm [1]. Nanoparticles have become widely used in various industries because of their unique physical and chemical properties due to their large ratio of the surface area and volume.

Nanofluid (**NF**) is a base fluid (water, oil, ethylene glycol, etc.) with nanoparticles dispersed in it. NFs have better thermophysical parameters, and thus a better heat transfer, compared to the base fluid. However, it is worth noting that one should take into account the influence of many factors when manufacturing specific NFs for every particular purpose. The thermophysical properties of the obtained fluid are influenced by the size, shape and concentration of the nanoparticles, the thermal conductivity of the nanoparticles and the base fluid, the temperature of the base fluid, etc. [2—4].

It was also noted that the use of micron-sized nanoparticles can lead to a decrease in heat transfer as a result of the dispersed phase turbulence suppression [5].

As to using NFs as working fluids for evaporation-condensation systems, despite the increasing number of studies appearing every year, it is impossible to describe clearly the advantages of their use and the quantitative increase in the heat transfer efficiency at the moment.

Thus, some studies note a positive effect of NF-based heat carriers [6—14], while the others highlight their negative effect [15, 16].

The main NFs that have already been studied are: Al_2O_3 — water; CuO — water; Ag — water; FeO — water.

It is also worth emphasizing that most of the thermosyphons described in the above-mentioned publications cannot be considered miniature, but it is the latter that are of particular interest at the moment.

Research techniques

One of the main criteria for the heat transfer characteristics of thermosyphons is thermal resistance, which is defined as:

$$R = \frac{(\bar{t}_{EZ} - \bar{t}_{CZ})}{Q}, \quad (1)$$

where Q is the transferred heat flow;

$\bar{t}_{EZ}$, $\bar{t}_{CZ}$ are the average temperature values of the evaporator and condenser, respectively.

Average temperatures are used because even when the stationary mode has already been established, the temperature of the thermosyphon wall continues to change with time (there are temperature ripples), therefore, the temperature in the evaporation zone (**EZ**) and condensation zone (**CZ**) is determined by their average values for the period of the stationary mode:

$$\bar{t}_{EZ} = \frac{1}{n}\sum_{i=1}^{n} t_i; \quad (2)$$

$$\bar{t}_{CZ} = \frac{1}{n}\sum_{j=1}^{n} t_j. \quad (3)$$

The study of the heat transfer characteristics of the miniature closed two-phase thermosyphons was carried out on an experimental stand similar to that given in [17, 18] (**Fig. 1**).

Heat was supplied to the evaporation zone of the thermosyphon by an electric heater, which was wound onto the thermosyphon body over a heat-resistant dielectric film with a thickness of 0.1 mm. For the manufacture of the heater, a nichrome wire with a diameter of 0.3 mm was used. Heat from the condenser was removed by water running through a pipe-in-pipe condenser and monitored using a flow meter *8* (Fig. 1). Cooling water flow rate was kept constant and varied from $1.75\cdot10^{-3}$ to $7.85\cdot10^{-3}$ kg/s.

The temperature in the main zones of thermosyphons was determined using copper-constantan thermocouples with an electrode diameter of 0.16 mm. Hot junctions of thermocouples were soldered to the thermosyphon body. The heat flux of the thermosyphon was changed using a laboratory transformer and monitored in the evaporation zone using a wattmeter *4*. To reduce heat loss to the environment, the thermosyphon was completely insulated with basalt fiber.

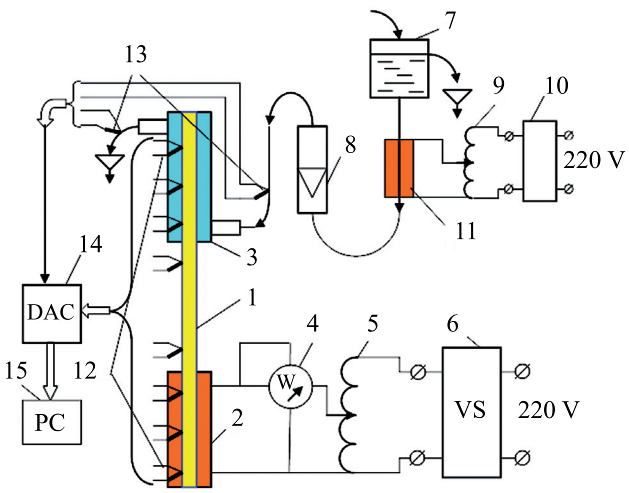

Fig. 1. Schematic drawing of the experimental setup:
1 — miniature thermosyphon; *2* — evaporation zone heater; *3* — condenser; *4* — wattmeter; *5*, *9* — voltage regulator (laboratory transformer); *6*, *10* — voltage stabilizer; *7* — pressure tank; *8* — flow meter; *11* — heater for cooling water; *12*, *13* — copper-constantan thermocouples; *14* — analog-to-digital converter; *15* — personal computer

The heater *2* was powered by a voltage regulator *5*, which was connected via a voltage stabilizer *6* to the mains (220 V, 50 Hz). The control of the supplied electric power was carried out using a wattmeter *4* (D529). The cooling water temperature was controlled with a heater *11* using a voltage regulator *9*. The temperature of the cooling water at the inlet and outlet of the condenser was monitored using thermocouples *13*. Signals from all thermocouples *12* were fed to an analog-to-digital converter *14* and then to a personal computer *15*.

We studied three samples of thermosyphons with an inner diameter of 5 mm and a length of 700 mm, filled with different NFs (**Table**). To study the effect of the fill ratio (***FR***), which characterizes the ratio of the volume of the working fluid to the total volume of the evaporation zone, a multi-section heater was used. As a result, it was possible to change the *FR* in a wide range from

Properties of the nanofluids

TS	Heat carrier: aqueous NF based on	Mass fraction of NP, %	Average diameter of NPs, nm	Surface tension, mN/m
TS1	carbon nanotube	0,1	410—590	71,4
TS2	synthetic diamond	0,3	50—300	70,5
TS3	amorphous carbon	0,31	100—150	69,8

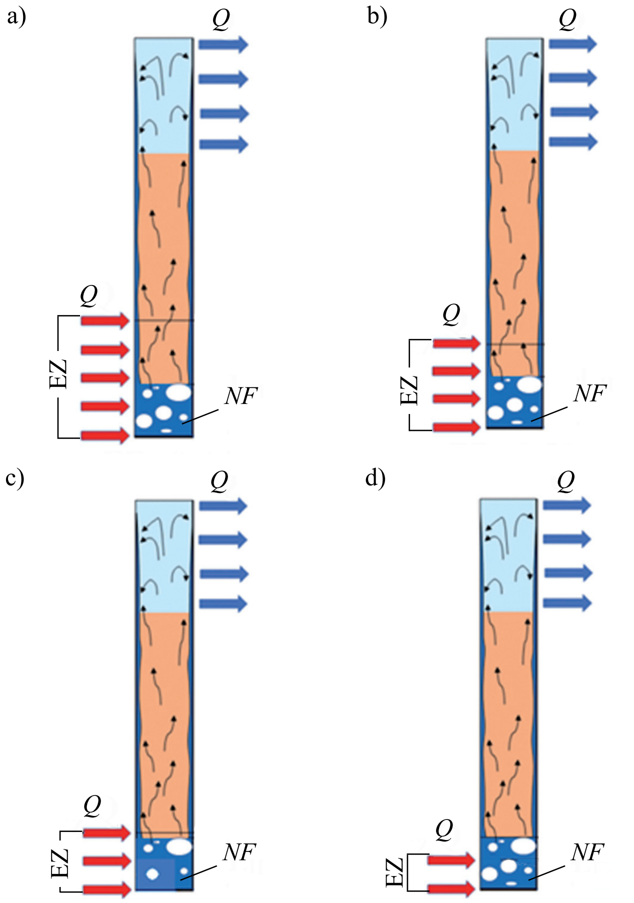

Fig. 2. Schematic representation of the amount of heat carrier relative to the evaporation zone volume at different filling ratio values:
a — *FR* = 0.44; *b* — *FR* = 0.59; *c* — *FR* = 0.87; *d* — *FR* = 1.66

0.4 to 1.7 (**Fig. 2**). The Table provides information on the nanofluids used as coolants.

Research results

The study of the thermal resistance of miniature thermosyphons with different working fluids showed that their heat transfer characteristics are significantly higher than of those with water as a heat carrier. The effect of filling ratio on thermal resistance is shown in **Fig. 3**.

Fig. 3, *a* shows that for carbon-based thermosyphon (TS1), the maximum transferred amount of heat corresponds to *FR* = 0.44; the maximum transmitted heat flux is 180 W. The minimum recorded thermal resistance is 0.18 K / W (*FR* = 0.44). Moreover, an increase in *FR* leads to a decrease in the maximum heat flux and an increase in thermal resistance.

Fig. 3, *b* shows that the heat transfer characteristics of the thermosyphon with working fluid based on synthetic diamond (TS2) are slightly lower than those for TS1. The minimum thermal resistance values for different filling ratios of TS1 and TS2 are similar; however, the maximum heat fluxes are somewhat lower. Thus, at *FR* = 0.44, the maximum heat flux decreases to about 120 W. However, at *FR* > 0.44, the thermosyphon TS2 has the maximum heat flux slightly higher than does TS1.

It should be noted that the minimum thermal resistances of TS2 and TS1 are close in their values to those obtained in [6, 7]. However, the concentration and type of nanopowders in water were slightly different.

Significantly lower are the values for the miniature thermosyphon TS3 with working fluid based on amorphous carbon (Fig. 3, *c*). The maximum heat flux for each *FR* value decreased by about 1.5 times, and the thermal resistance increased, its minimum value of 0.2 K/W being fixed at *FR* = 0.44 (Fig. 3, *c*).

To generalize the experimental data presented above, as well as to determine the effect of *FR* on the heat

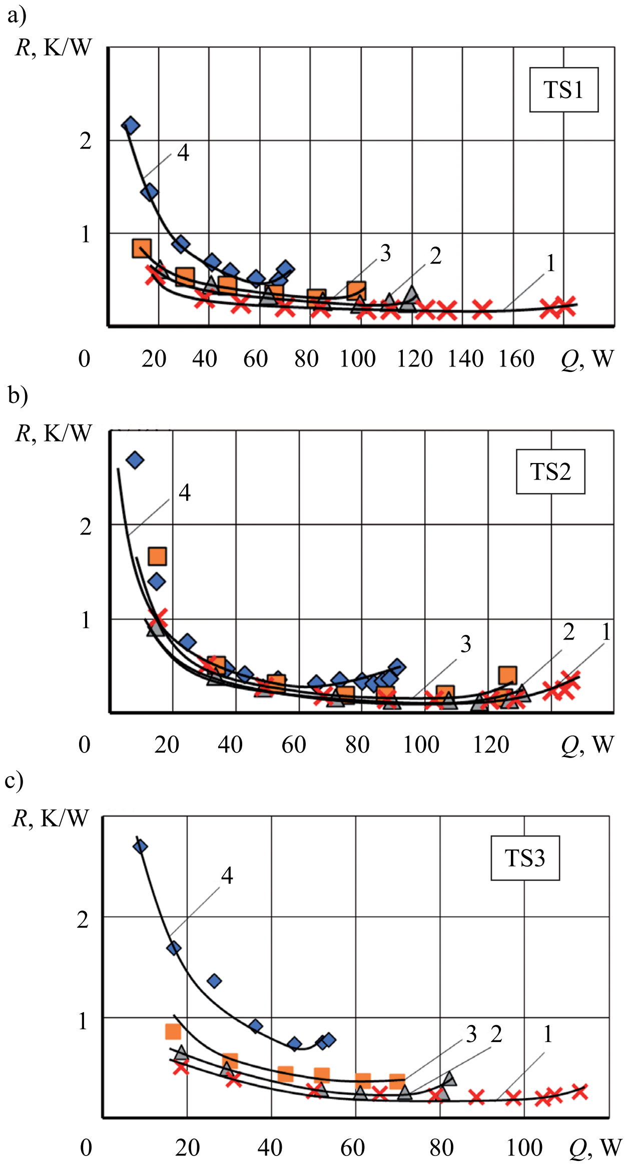

Fig. 3. Dependence of the thermal resistance *R* on the heat flux for thermosyphons with working nanofluids based on carbon nanotube (*a*), synthetic diamond (*b*), and amorphous carbon (*c*) at different filling ratio values:
1 — *FR* = 0.44; *2* — *FR* = 0.59; *3* — *FR* = 0.87; *4* — *FR* = 1.66

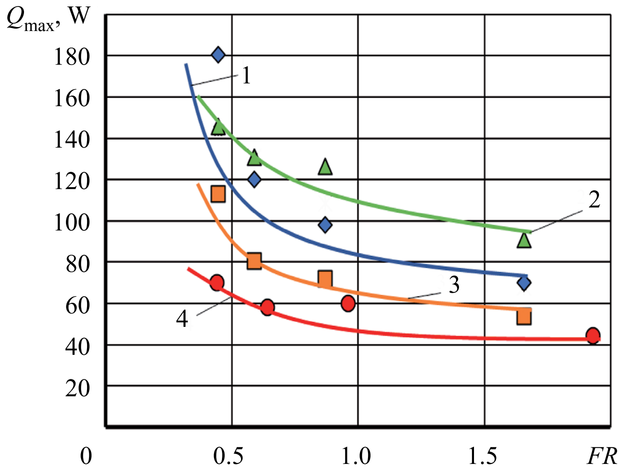

Fig. 4. Dependence of the maximum transferred heat flux Q_{max} on the filling ratio for thermosyphons with working nanofluids based on:

1 — carbon nanotube (TS1); *2* — synthetic diamond (TS2); *3* — amorphous carbon (TS3); *4* — water (TS4)

transfer characteristics of thermosyphons, the results of experimental data are presented in the form of the dependence of *FR* on the maximum transferred heat flux (**Fig. 4**). Also, for the possibility of comparative analysis, a thermosyphon was manufactured with an identical design and water as a heat carrier (TS4).

Fig. 4 shows that the best heat transfer characteristics were demonstrated by the thermosyphon TS2. TS1 also showed good functionality. It was the latter that transmitted the maximum heat flux (FR = 0.44), which amounted to 180 W.

As was mentioned above, the lowest heat transfer characteristics among the thermosyphons with nanofluids was demonstrated by TS3. However, even this thermosyphon transfers the heat flux much more effectively than the one with water (TS4).

For all tested thermosyphons, the following dependence is traced: the maximum heat flux increases with decreasing *FR* (increasing the length of the evaporation zone). This is due to the fact that the liquid column located above the evaporation zone creates additional hydraulic resistance for the movement of the vapor phase from the evaporation zone to the condensation zone.

Conclusions

Thus, the studies of miniature thermosyphons with aqueous nanofluids based on carbon nanotubes, synthetic diamond and amorphous carbon showed that the heat transfer characteristics of the thermosyphons with nanofluids significantly exceed those of thermosyphons filled with ordinary fluids (water).

The experimental results show that using nanofluides as heat carriers in miniature thermosyphons is promising, however it is evident that other types of nanofluids also need to be tested as heat carriers (type of nanofluid, concentration, size of nanoparticles, etc.), and life tests need to be carried out.

REFERENCES

1. Tawfik M. M. Experimental studies of nanofluid thermal conductivity enhancement and applications: A review. *Renewable and Sustainable Energy Reviews*, 2017, vol. 75, pp. 1239–1253. https://doi.org/10.1016/j.rser.2016.11.111

2. Chandrasekar M., Suresh S., Senthilkumar T. Mechanisms proposed through experimental investigations on thermophysical properties and forced convective heat transfer characteristics of various nanofluids. A review. *Renewable and Sustainable Energy Reviews*, 2012, vol. 16, pp. 3917–3938. https://doi.org/10.1016/j.rser.2012.03.013

3. Ghadimi A., Saidur R., Metselaar H. A review of nanofluid stability properties and characterization in stationary conditions.*Int. J. Heat Mass Transfer,* 2011, vol. 54, pp. 4051–4068. https://doi.org/10.1016/j.ijheatmasstransfer.2011.04.014

4. Mahbubul I.M. *Preparation, Characterization, Properties and Application of Nanofluid*. Norwich, New York, William Andrew, 2019, 350 p.

5. Terekhov V.I., Kalinina S.V., Lemanov V.V. [The mechanism of heat transfer in nanofluids: current state of the problem (review). Part 1. Synthesis and properties of nanofluids]. *Teplofizika i aeromekhanika*, 2010, vol.17, no. 2, pp. 173–188. (Rus)

6. Liu Z. H., Yang X. F., Guo G. L. Effect of nanoparticles in nanofluid on thermal performance in a miniature thermosyphon. *Journal of Applied Physics*, 2007, vol. 102, pp. 1–9. https://doi.org/10.1063/1.2748348

7. Liu Z. H., Yang X. F., Guo G. L. Influence of carbon nanotube suspension on the thermal performance of a miniature thermosyphon. *Int. J. Heat Mass Transfer*, 2010, vol. 53, pp. 1914–1920. https://doi.org/10.1016/j.ijheatmasstransfer.2009.12.065

8. Naphon P., Assadamongkol P., Borirak T. Experimental investigation of titanium nanofluids on the heat pipe thermal efficiency. *INT COMMUN HEAT MASS*, 2008, vol. 35, pp. 1316–1319. https://doi.org/10.1016/j.icheatmasstransfer.2008.07.010

9. Naphon P., Thongkum D., Assadamongkol P. Heat pipe efficiency enhancement with refrigerant–nanoparticles mixtures. *Energy Conversion and Management*, 2009, vol. 50, pp. 772–776. https://doi.org/10.1016/j.enconman.2008.09.045

10. Noie S.H., Heris S. Z., Kahani M., Nowee S.M. Heat transfer enhancement using Al_2O_3/water nanofluid in a two-phase closed thermosyphon. *Int. J. of Heat and Fluid Flow*, 2009, vol. 30, pp. 700–705.

11. Parametthanuwat T., Rittidech S., Pattiya A. A. Correlation to predict heat-transfer rates of a two-phase closed thermosyphon (TPCT) using silver nanofluid at normal operating conditions. *International Journal of Heat and Mass Transfer*, 2010, vol. 53, pp. 4960–4965. https://doi.org/10.1016/j.ijheatfluidflow.2009.03.001

12. Paramatthanuwat T., Boothaisong S., Rittidech S., Booddachan K. Heat transfer characteristics of a two-phase closed thermosyphon using de ionized water mixed with silver nano. *Heat Mass Transfer*, 2010, vol. 46, pp. 281–285. https://doi.org/10.1007/s00231-009-0565-y

13. Huminic G., Huminic A., Morjan I., Dumitrache F. Experimental study of the thermal performance of thermosyphon heat pipe using iron oxide nanoparticles. *Int. J. Heat Mass Transfer*, 2011, vol. 54, pp. 656–661. https://doi.org/10.1016/j.ijheatmasstransfer.2010.09.005

14. Huminic G., Huminic A. Heat transfer characteristics of a two-phase closed thermosyphons using nanofluids. *Experimental Thermal and Fluid Science*, 2011, vol. 35, pp. 550–557. https://doi.org/10.1016/j.expthermflusci.2010.12.009

15. Xue H. S., Fan J. R., Hu Y. C., Hong R. H., Cen K. F. The interface effect of carbon nanotube suspension on the thermal performance of a two-phase closed thermosyphon. *Journal of Applied Physics*, 2006, vol. 100, pp. 1–6. https://doi.org/10.1063/1.2357705

16. Khandekar S., Joshi Y. M., Mehta B. Thermal performance of closed two-phase thermosyphon using nanofluids. *International Journal of Thermal Sciences*, 2008, vol. 47, pp. 659–667. https://doi.org/10.1016/j.ijthermalsci.2007.06.005

17. Kravets V. Yu., Nekrashevich Ya. V., Goncharova A. P. [Investigation of thermal resistance of miniature heat pipes]. *Eastern-European Journal of Enterprise Technologies,* 2011, vol. 1, no. 9, iss. 49, pp. 55-60. (Ukr)

18. Kravets V.Yu. [Heat exchange in miniature evaporation-condensation cooling systems] *Ph.D. thesis abstract*, NTUU “Igor Sikorsky Kyiv Polytechnic Institute”, Kyiv, 2016, 41 p. (Ukr)

Received 30.05 2020

DOI: 10.15222/TKEA2020.3-4.42
УДК 536.248.2

В. Ю. КРАВЕЦЬ, Д. І. ГУРОВ

Україна, Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
E-mail: kravetz_kpi@ukr.net

ТЕПЛОПЕРЕДАВАЛЬНІ ХАРАКТЕРИСТИКИ ДВОФАЗНИХ МІНІАТЮРНИХ ТЕРМОСИФОНІВ З НАНОРІДИНАМИ

У зв'язку з постійним збільшенням щільності упаковки електронного обладнання, яка одночасно є і критерієм мініатюризації, стають все більш нагальними і складними проблеми, пов'язані з підтриманням температурного режиму і охолодженням напівпровідникових пристроїв. Системи охолодження, які використовувалися впродовж десятиліть, вже не можуть задовольнити нові вимоги до термостабілізації і підтримки температури в заданому діапазоні, що потребує все більш комплексного підходу до їхнього вирішення. Крім цього, системи охолодження електронного устаткування зазвичай проектуються під конкретне технічне рішення, і в таких випадках відсутня можливість змінювати геометричні параметри (дизайн системи) в широкому діапазоні. З цієї причини для підвищення ефективності роботи систем охолодження мало не єдино можливим варіантом є поліпшення теплофізичних властивостей теплоносія. Саме з такою метою проводиться заміна звичайного теплоносія (вода, етанол, метанол і ін.) на нанорідину.

У даній роботі експериментально досліджені теплопередавальні характеристики, такі як термічний опір та максимальний тепловий потік, двофазних мініатюрних термосифонів при використанні нанорідини як теплоносія. Дослідження проводилися з трьома видами нанорідини на основі води: з вуглецевими нанотрубками, наночастками синтетичного алмазу і аморфного вуглецю. Загальна довжина термосифона становила 700 мм, внутрішній діаметр 5 мм. Було показано, що теплопередавальні характеристики термосифонів з нанорідиною значно кращі за показники термосифонів, заправлених водою. Досліджено також вплив коефіцієнта заповнення на теплопередавальні характеристики термосифонів.

Отримані результати показали перспективність використання нанорідини як теплоносія для мініатюрних термосифонів.

Ключові слова: мініатюрний термосифон, термічний опір, коефіцієнт заповнення, нанорідина, тепловий потік.

DOI: 10.15222/TKEA2020.3-4.42
УДК 536.248.2

В. Ю. КРАВЕЦ, Д. И. ГУРОВ

Украина, Национальный технический университет Украины
«Киевский политехнический институт имени Игоря Сикорского»
E-mail: kravetz_kpi@ukr.net

ТЕПЛОПЕРЕДАЮЩИЕ ХАРАКТЕРИСТИКИ ДВУХФАЗНЫХ МИНИАТЮРНЫХ ТЕРМОСИФОНОВ С НАНОЖИДКОСТЯМИ

В настоящей работе экспериментально исследованы теплопередающие характеристики, такие как термическое сопротивление и максимальный передаваемый тепловой поток, двухфазных миниатюрных термосифонов при исследовании наножидкости качестве теплоносителя. Исследования проводились с тремя видами наножидкости на основе воды: с углеродными нанотрубками, наночастицами синтетического алмаза и аморфного углерода. Общая длина термосифона составляла 700 мм, внутренний диаметр 5 мм. Было показано, что теплопередающие характеристики термосифонов с наножидкостями значительно превышают показатели термосифонов, заправленных водой. Исследовано также влияние коэффициента заполнения на теплопередающие характеристики термосифонов. Полученные результаты показали перспективность использования наножидкости в качестве теплоносителя для миниатюрных термосифонов.

Ключевые слова: миниатюрный термосифон, термическое сопротивление, коэффициент заполнения, наножидкость, тепловой потокг.

Опис статті для цитування:
Кравець В. Ю., Гуров Д. І. Теплопередавальні характеристики двофазних мініатюрних термосифонів з нанорідинами. Технология и конструирование в электронной аппаратуре, 2020, № 3–4, с. 42–46. http://dx.doi.org/10.15222/TKEA2020.3-4.42

Cite the article as:
Kravets V. Yu., Hurov D. I. Heat transfer characteristics of miniature two-phase thermosyphons with nanofluids. Tekhnologiya i Konstruirovanie v Elektronnoi Apparature, 2020, no. 3–4, pp. 42–46. http://dx.doi.org/10.15222/TKEA2020.3-4.42