Heat Transfer Enhancement in Heat Pipes and Thermosyphons Using Nanotechnologies (nano-coating, nano liquids and nano composites as the HP envelope).

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Abstract. A new trend in the heat pipes and thermosyphons successful application is related with nanotechnologies. Nano liquids, nano coatings and nano composites invention open a new niche in the heat pipe and thermosyphon design and use. The aim of this work is to present a short review of some experimental results in the field of heat pipes and thermosyphons tests, using nano liquids and nano coating on the heat loaded zones. Nano fluids are considered as the vacant working liquids for the transparent flat mini heat exchangers heated by laser beam, or solar radiation. The combination of nano fluid and small channels constitutes an innovating method providing effectiveness, compactness and low thermal resistance. Thin porous nano coating in coaxial mini channels, or mini grooves of the heat pipe evaporator plays a role of additional centers for stable vapor generation, which do not require high superheating of the surface to obtain the heat transfer enhancement. The porous nano coating (thickness 25-100 μm) on the surface of mini grooves allows reducing its thermal resistance (2-3 times) and increasing the working fluid capillary pressure and permeability at the same time. Polymer composites reinforced by nano wires and nano particles are considered as promising alternative to metals. The new design of loop polymer based thermosyphon was suggested, designed and tested. The thermosyphon envelope consists of polyamide composite with nano carbon filaments and nano diamond particles to increase its effective thermal conductivity up to 11 W/m ^{0}C, which is more than 40 times higher to compare with pure polymer thermal conductivity. It was found that a flat grooved evaporator thermal resistance *Rev* of polymer thermosyphon is the same order of merit as a classical aluminum smooth grooved heat pipe evaporator. In certain applications polymers composites reinforced by carbon nano wires and nano particles can successfully replace the metal envelope of heat pipes and thermosypons.

Introduction

Considering the rapid increase in energy demand worldwide, intensifying heat transfer processes and reducing energy losses due to ineffective use now have become increasingly important task, Wen, D., Ding, Y. 2005. Heat pipes are very flexible systems with regards to their effective thermal control of different heat loaded devices. A new stream in the modern heat pipe technology is related with nano fluid application. Recent advances in nano technology have allowed the development of a new nano fluids (NF), to describe liquid suspensions containing nano particles (NP) with thermal conductivity orders of magnitudes higher than the base liquids, and with sizes significantly smaller than 100 nm, Vassallo, P., Kumar, R., Amico, S. 2004; Bang, I.C, Chang, S.H., 2005. It has been found that both thermal conductivity and viscosity increase with the concentration of nano particles, whereas when the temperature increases the viscosity diminishes and the thermal conductivity rises. Colloidal suspensions of nano-sized particles in a fluid, have recently gained popularity as cooling fluids mainly due to their enhanced heat transfer capabilities. However, there are controversies in the literature for the reported properties of nano fluids and their applicability, especially since there is no fundamental understanding that explains these enhancements. A better understanding of these fluids and how they interact with a solid boundary may be achieved by a detailed near-wall fluid flow study at nanoscale. NFs are very stable due to the small size and volume fraction of NPs needed for heat transfer enhancement. When the NPs are properly dispersed, NFs can offer numerous benefits besides the anomalously high effective thermal conductivity, such as improved heat transfer and stability, microchannel cooling without clogging, the possibility of miniaturizing systems scaling, or reduction in pumping power, among others. Thus, NFs have a wide range of industrial engineering, and medical applications in fields ranging from transportation, micromechanics, heating, ventilating and air conditioning systems, biomolecules trapping, or enhanced drug delivery. The nano coating of the heat pipe evaporators and nano particles based polymer composites design are also considered as a mean to increase its effective thermal conductivity. Some new polymer based nano composites with effective thermal conductivity close to stainless steel are attractive materials for heat pipes fabrication Nano structures and nano materials are getting more and more commonly used in cosmetics, aerospace, communication and computer electronics. The generation of engineered nano structures represents a major breakthrough in material science and nano technology, You M., Kim J.H, Kim K.H., 2003; Das S.K, Putra N., Roetzel, W., 2003.

Nano liquids for heat pipes

In some cases it is interesting to make the mini-channels heat exchanger and heat pipes envelope from transparent material (glass, plastic) and to heat them by radiation, Fig.1.

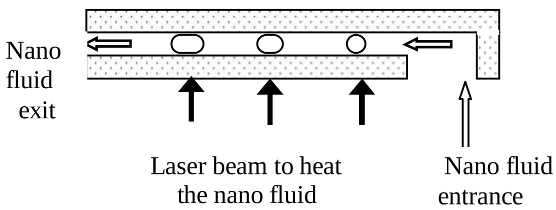


Figure 1. Schematic of the flat mini evaporator with transparent walls heated by impulse laser beam.

Bubbles generation phenomena in mini volumes filled with nano fluid and the impulse arrived as the consequence of bubbles departure are the reason of NFs circulation in the mini heat pipe loop, Fig. 2. This impulse is working as two-phase mini pump, which initiate the fluid circulation inside the mini channel. The bubbles are considered also as a motive force to organize the fluid circulation in pulsating heat pipes and loop thermosyphons. Such types of two-phase cooling system, for example, are welcome and could have a good perspective for space applications in the system of the satellite thermal control. Transparent evaporators made from glass or plastic have a real practical interest for mini/micro fuel cells thermal control, photo electronic components cooling. High temperature heat transfer devices are also interesting to be used in power stations as transparent (glass) pulsating heat pipe heat exchangers in the air pre-heater for furnaces and boilers. One of the major interesting topics is the investigation of the influence of metal oxide NPs (Al_2O_3 nanoparticles) immersed in the fluid (water) on the local bubbles generation and two-phase heat transfer intensification to compare with pure water.

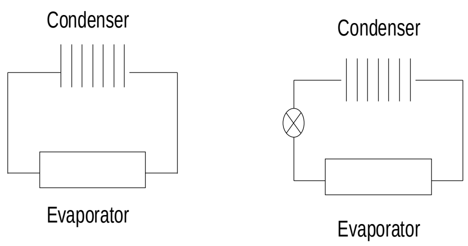


Figure 2. Schematic of two-phase loop with nano fluid (without mechanical pump – left and with mechanical pump - right).

As it was previously shown by D. Lapotko (Lapotko, D., Lukianova, E. 2005; Lapotko,2006) the heat flow generated by light-absorbing nano particles (gold NPs) initiates more intense bubble generation when short laser pulses are used as primary sources of thermal energy, Fig. 3. The temporal scale of photothermal conversion of the energy is limited by the duration of laser pulse and provides good thermal confinement of the heat release in NPs. The main role of such energy absorbing NPs is to generate the heat in NFs volume. The limitation of this method for vapor generation is in delivery of the energy into the point of interest: it should be optically transparent to allow optical radiation to reach for the NPs. NPs are considered as additional centers of nucleation due to increased surface of liquid/solid interaction. Are NPs in such a case stimulates the appearance of earlier threshold of vapor generation? The second aim is to validate this hypothesis and evaluate the influence of “passive” NPs (Al_2 O_3 particles as non absorbing energy media), as the element of heterogeneity in the fluid on the decrease of the energy threshold of bubble generation. Such NPs are considering now as additional centers of nucleation due to increased surface of liquid/solid interaction, Fig. 4.

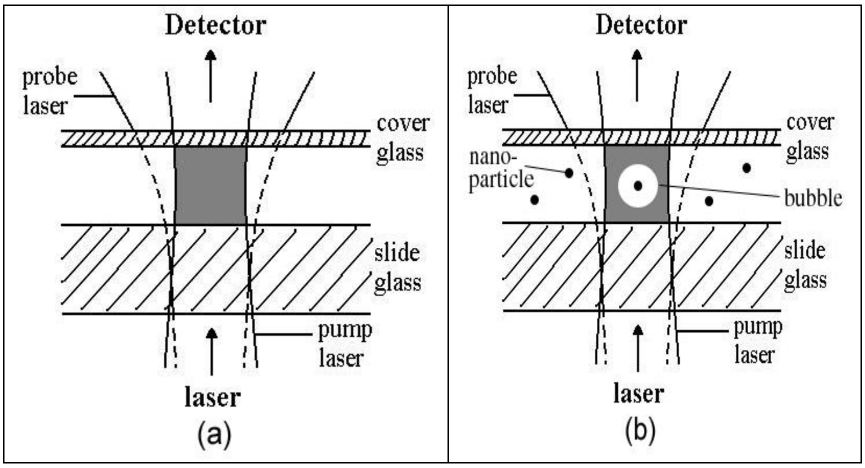


Figure 3. Visualization of the bubble generation by short laser pulse (532 nm, 10 ns) in mini channel of the flat evaporator with nano fluid (water + Al2O3 NPs) .(a) - control pure water;
(b) – nano fluid; D_{Al2O3} particle < 220 nm.

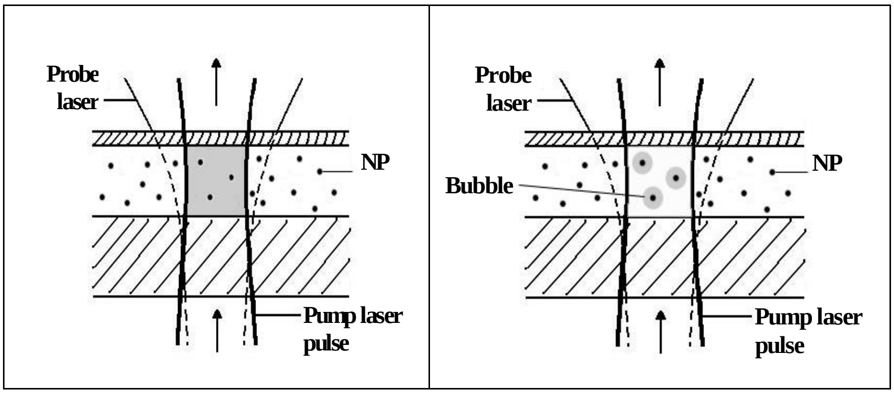


Figure 4. Experimental model: laser-induced heating of the volume of liquids with non-absorbing nano particles Al_2O_3 (left); generation of laser-induced bubbles around gold light-absorbing nano particles (right); single laser pulse: 532 nm, 10 ns.

For all studied cases the bubble–specific photo-thermal signals (Fig. 3 - Fig. 5) - PT–responses and PT–images - were detected and evaluated. Bubble-specific PT – response has negative symmetrical profile; its front describes bubble expansion and the tail describes bubble collapse. The length of bubble-related signal response indicates bubble life-time (Figure 5 (left)). In the homogeneous media bubbles emerge in all area of the pump laser beam.

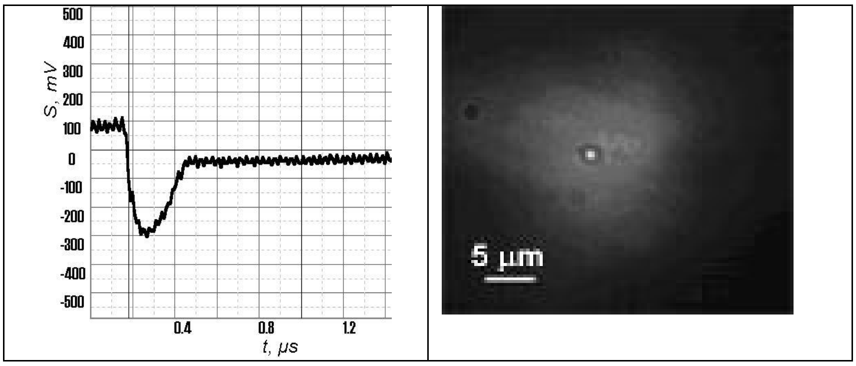
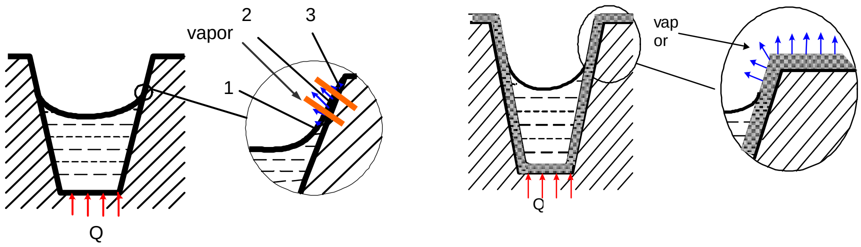


Figure 5. Photo-thermal signals obtained from individual bubble, which was generated in transparent micro-evaporator: PT-response with bubble-specific shape (left) and PT-image (right). Y axis is for the output of the photodetector (mV).

The diameter of the bubbles is much smaller than that for heated volume (cell or laser beam, Figure 5 (right)). Regardless of the medium the bubble generation process had statistical nature with the bubble generation probability *PRB* from 0 to 1. The energy threshold of bubble generation for light absorbing gold particles is less to compare with Al_2O_3 particles and the pure water. Convective heat transfer in mini channels using nano fluid is treated as heterogeneous mixtures with weak solutal diffusivity and possible Soret separation.

Nano coatings in heat pipes

A number of studies on evaporation phenomena in grooves of heat pipes have been carried out over the last decade, Holm, F.W., and Goplen , S.P. 1979; Suman, B., et al.,2005; Mirzamoghadam, A., and Catton, I.,1988. Most investigators have focused their attention on the liquid evaporation on menisci formed in smooth grooves with extended thin film, as shown in Fig. 6(a) , Stephan, P.C. , and Busse, C.A. 1992; Ma, H.B. and Peterson, G.P. 1996. It is known that the heat transfer intensity on evaporation in thin liquid films greatly exceeds the heat transfer intensity of the pool boiling. Though capillary grooves possess indisputable advantages, they present certain restrictions in evaporation and boiling of liquid which are related to the special features of heat transfer in the grooves. Intensive heat transfer in the grooves occurs on the thin film region that extends from the intrinsic meniscus. However, the extended thin film in the grooves with different sections constitutes only a small portion of the total surface of the grooves.

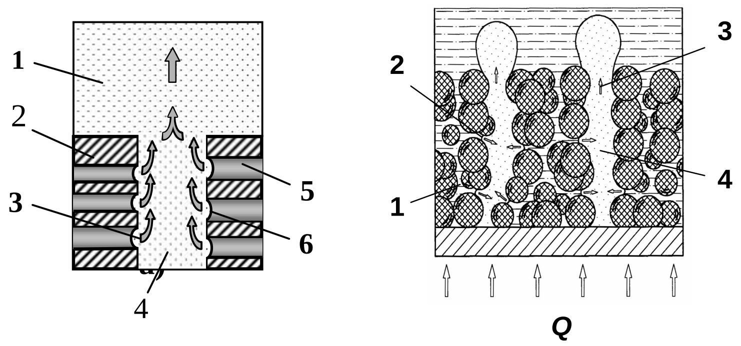


a) b)

Figure 6. Evaporation phenomena in trapezoidal grooves: (a) smooth; (b) with porous layer. 1-liquid meniscus, 2 – hin film – zone of extensive heat transfer with evaporation, 3 –dry zone of groove

A large fraction of the groove surface in the grooved heat pipe evaporator (GHP) is covered by the thick liquid film, or the intrinsic meniscus, where the local heat transfer coefficient is particularly low due to the small thermal conductivity of the liquid or dry part of the groove, where only natural or mixed vapor convection exists between the solid surface and vapor phase. Compared to the heat transfer with liquid–vapor phase changes, the convection heat transfer coefficient in the dry area of the groove surface is insignificant and can be safely neglected. As the heat flux increases, the meniscus in the groove recedes and the dry area, a region of pronouncedly low heat transfer performance, increases as well. In 1981 an innovative method was proposed, (Vasiliev, L., Grakovich, L., Khrustalev D., 1981), Fig. 6b, to enhance the evaporative heat transfer in grooves of GHP. The surface of trapezoidal grooves (copper GHP) of the HP evaporator was covered by a thin porous layer of copper sintered powder to ensure an extended surface of evaporation with high heat transfer intensity. Evaporative heat transfer occurs on the meniscus inside the porous coating of the groove (on its bottom and the edge simultaneously). The latter not only improves capillary forces action but also considerably extends the surface of the evaporation accompanied with high heat transfer in comparison with the smooth groove. Capillary forces distribute the liquid inside the porous volume of the wick. The surface of the groove edge beyond the zone of the main meniscus turns to be wetted uniformly and the area of effective evaporation is increased manifold. Nano coating of the heat loaded surface have a grand potential to increase the wettability and heat transfer intensity in small size heat transfer devices such as mini heat pipes and miniature heat exchangers. To stimulate the bubbles generation an advanced technology of particles deposition on extended surfaces of heat transfer was studied in the past, Mitrovic, J. 2006; Vasiliev, L. et al. 2004; Vasiliev, L., Lapotko, D. ,Lukianova, E., et al. 2007. Micro heat pipe effect inside the porous structure + two-phase forced convection in the annular mini channel were considered thermodynamically as an efficient mean to improve parameters of mini evaporator. Such evaporator is used as an effective cooling device for micro and optoelectronic components, Xie, X.,et al.,2003; Vasiliev, L., et al. 2006. Investigation of boiling and evaporation heat transfer in mini-grooves inside the single horizontal tube (smooth and with porous coating) is a good tool to analyze the cooling efficiency of heat pipe. Due to its excellent performance, the lack of impact on the environment (zero ODP and GWP < 3) and its physical properties ammonia - a long-term alternative refrigerant was used in compact heat exchangers and heat pipes. To prove the suggested hypotheses the thermal behavior of Grooved Heat Pipes (GHPs) and Grooved Heat Pipes with porous layer (GHPPL) was tested. To guarantee identical boundary conditions GHP and GHPPL samples were tested simultaneously on the same experimental bench in parallel at a temperature range between -30°C and 70°C, typical for the electronic components application. The set of experiments was performed with copper sintered powder and Al_2O_3 porous coating on copper and aluminum pipes. After the tests it was observed that the evaporator thermal resistance ($R_{e,v}$) of GHPPL was low in comparison with $R_{e,v}$ typical for smooth GHPs. Thermal resistance of GHPPL is 1.3 to 1.4 times lower (between 0.021 and 0.018 W/K) to compare with GHP (between 0.025 and 0.035 W/K). A detailed analytical model was developed (Wang, J., Catton, I. 2011) in order to predict the evaporation heat transfer intensity in a triangular groove. The trapezoid fins disposed between triangular grooves were covered by a thin porous layer. It was shown that the heat transfer in such grooves is three to six times higher than in smooth grooves. As a result, in the new advance design of the GHPPL the significant intensification of heat transfer was obtained.

So, the application of NCs technology is encompassed on improving the cooling capability of GHPPLs. Porous Nano Coating (NC) of GHP evaporators formed from micro- and nanoparticles enhance heat transfer not only in the thin liquid film, Fig.7a, but also in the liquid pool and flooded surfaces, Fig.7b. Thin porous NC plays the role of additional centers for stable vapor generation, which do not require high superheating of the surface. The porous NC (thickness 25-100 µm) on the surface of mini-grooves of the GHP allows reducing its thermal resistance and increasing the working fluid capillary pressure and permeability at the same time.



a) **b**)

Figure 7: Model of heat transfer on the edge (a) and bottom (b) of the GHP mini groove with porous coating.
a). upper part of the groove edge: 1 – vapor, 2 – solid part of the wick, 3,6 – vapor stream, 4 – macropore free of liquid, 5 – micropore with capillary liquid flow;
b). bottom part of the groove (liquid pool): 1 – micropore, 2 – interface meniscus of evaporation, 3 – vapor bubble, 4 – vapor stream;

Unlike the heat transfer with boiling on the smooth surface the liquid evaporation/boiling on the porous coating (for example, like aluminum oxide NCs) is characterized by the constant sources of nucleation, Fig.6 - Fig. 7. It is so due to the limited number of evaporation menisci available inside the porous wick. In porous coatings the liquid/vapor interface consists of menisci, which are situated inside the macropores and numerous menisci disposed between macro and micropores. The menisci of the evaporation disposed on macropore are typical for low heat flux, when the wick is completely saturated with liquid. For such low heat flux the heat transfer is realized by conduction through the wick. The menisci of the evaporation available in mini pores are typical for high heat flow, when the menisci in macropores recede and become open for the vapor flow. For such a case

many nucleation sites are becoming the centers of the vapor generation inside the macropore (micro menisci are developing on the interface between macro and micropores). Following the experimental data, the upper part of the groove initiates more intense heat transfer compared to the bottom part of the groove saturated with the liquid, Vasiliev L.L. et al. 2012.
The heat flux q going through the wall of the GHP can be written as:

$$q = \frac{T_w - T_{sat}}{\frac{\delta_{wick}}{k_{eff}} + \frac{1}{h_e}}, \qquad (1)$$

where $T_w - T_{sat} = \Delta T_t$ and is determined as:

$$\Delta T_t = \frac{2\sigma T_{sat}}{h_{lv}\rho_v}\left(\frac{1}{r_v} - \frac{1}{r}\right) \qquad (2)$$

The effective thermal conductivity of porous system has been a source of interest over the last two centuries. As for now, numerous experimental materials have been devised and a large number of formulae have been put forward to calculate the effective thermal conductivity of porous systems, (Luikov, A.V. et al., 1968). The method of generalized conductivities for the determination of effective thermal conductivity was used in GHP wick analysis. Here, one assumes the complex of Al_20_3 particles in the elementary cell on the GHP evaporator to be symmetric and considers only quarters of two particles contacting each other.
Table 1. Experimental values of the GHP evaporator heat transfer coefficients as a function of heat flow value

T_{sat} = -10°C	Heat flow,W	40	50	70	80	100	150	170
	h_{smooth}, W/(м^{2}K)	6500	6500	6350	6100	6000	5900	5500
	h_{porous}, W/(м^{2}K)	6000	6250	7000	7300	7600	7000	6400
T_{sat} = 40°C	Heat flow,W	40	50	70	80	100	150	-
	h_{smooth}, W/(м^{2}K)	6600	6700	7100	7300	7700	7100	-
	h_{porous}, W/(м^{2}K)	12000	12300	13000	12900	12200	8200	-
								-
T_{sat} = 70°C	Heat flow,W	40	50	70	80	100	120	140
	h_{smooth}, W/(м^{2}K)	-	8500	8500	8400	8200	8000	7800
	h_{porous}, W/(м^{2}K)	-	13000	13000	13100	12900	11100	9500

The schematic of an elementary cell of a capillary porous material and its thermal resistance network is shown on Fig. 8 (**a** and **b**).

Let V be the total volume of an elementary cell; V_1, the volume of solid phase of the elementary cell; V_2 the volume of the vapor phase (macropore). The liquid phase is disposed between two solid particles 1 (in micropore), Fig.8 **(a)** and Fig.8 **(b).** Following Luikov, A.V. et al., 1968, $\Delta/B = X$ and $H/b = X/(0.5 - X)$. Finally, the wick porosity is considered as $\prod = f(H/b)$.

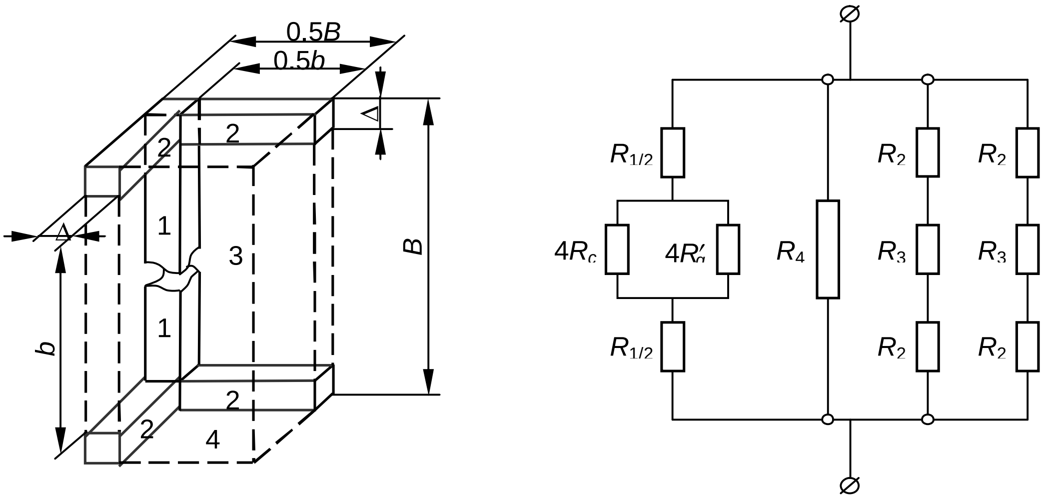
The effective thermal conductivity k_{eff} of the wick is calculated as:

$$\frac{k_{eff}}{k_s} = \frac{1}{\frac{1}{(H/B)^2} + A} + v_g(1-B)^2 + \frac{2}{1 + s/b + \frac{1}{v_g\, s/B}}, \qquad (3)$$

where

$$A = \frac{1}{\frac{k_c}{k_s} + \frac{v'_g}{4}\left(\frac{s}{B}\right)^2 \cdot 10^3}, \quad B = b + s, \quad s = 2\Delta \qquad (4)$$

This complex number A characterizes the thermal resistance of the contact between two Al_2O_3 particles. The term of equation (3) v_g - is the ratio of thermal conductivity of the liquid (ammonia) to solid (Al_2O_3). $v_g = k_l / k_s$; k_c – thermal conductivity of the thermal contact between the particles of Al_2O_3 in vacuum. The thermal conductivity of the porous particles Al_2O_3 k_s is equal to 2.1 W/mK.



(a) (b)

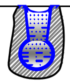
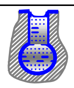
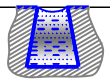
Figure 8. (a) One quarter of the porous coating elementary cell, and (b) diagram of its thermal resistances.

The calculated data of the effective thermal conductivity of the porous deposit saturated with liquid (ammonia), or vapor are presented in Table 2.

Table 2. Calculated values of k_{eff} of the Al_2O_3 porous coating (thickness δ = 50 µm), completely saturated with liquid or vapor.

Temperature, ^{0}C	-10	30	40
k_{eff}, (liquid), W/(mK)	1.14	1.09	1.07
k_{eff}, (vapor), W/(mK)	0.646	0.656	0.659

Table 3: Characteristics of the GHP with different capillary grooves (smooth GHPs and GHPPL with porous coating)

Structure designation	Groove shape	Groove depth, mm	Edge width at the crest, mm	Porous coating thickness, µm
S-1		2	0.54	
S-1-1		2	0.54	50
S-2		2	1	
S-2-1		2	1	50
S-3		1.3	0.36	
S-3-1		1.3	0.36	50

The parameters of different GHPs [S1-(S1-1), S2-(S2-1), and S3-(S3-1)] as a function of the temperature were investigated for constant heat load (Vasiliev L.L. et al.,2012). GHPs with smooth grooves are S-1, S-2 and S-3. GHPPLs with porous coating are S1-1, S2-1, S3-1. The difference of the heat transfer intensity between them is 1.3-1.6 times, Fig.10-12.

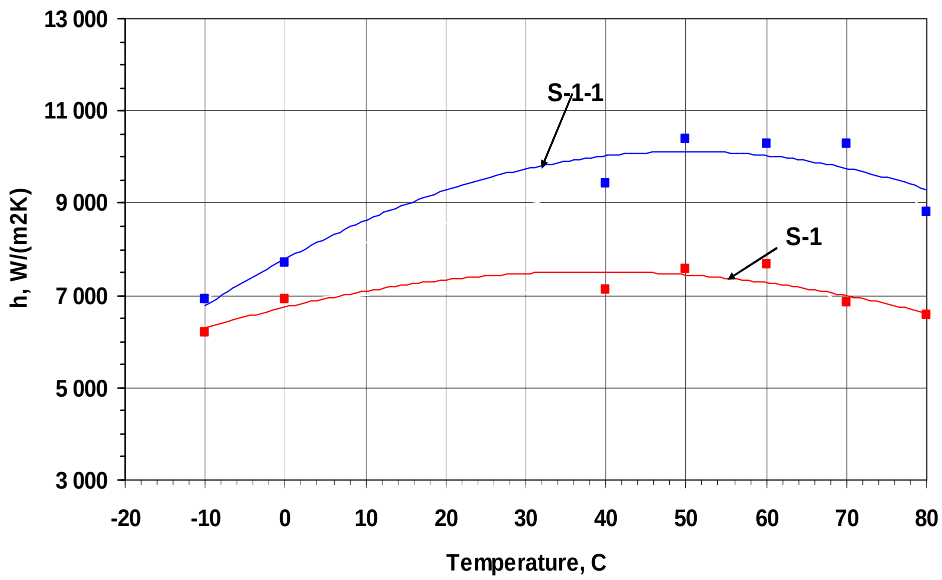


Figure 10. Heat transfer intensity in the evaporators S1 and S1-1 (ammonia) as a function of the temperature of saturated vapor

An appreciable increase in the heat transfer intensity was noted for all GHPPL with porous coating to compare with GHPs with smooth grooves. The evaporator S2-1 has the highest heat transfer intensity, Fig.11.The S2-1 portion of the total area occupied by the crests of edges is the largest and equal to about 0.6. For S1-1 it is equal 0.43 and for S3-1 is equal 0.33. These data are in good agreement with those data published in D.K. Edwards, I. Catton, et al, 1973

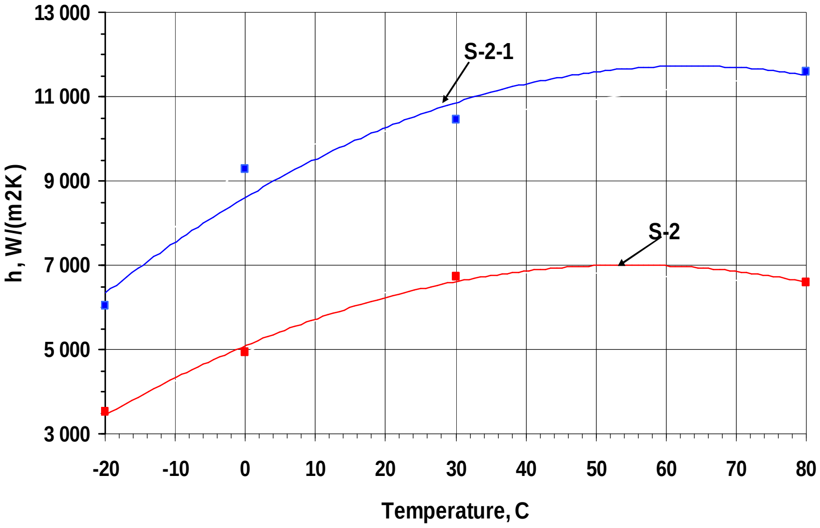


Figure 11. Heat transfer intensity in the evaporators S2 and S2-1 (ammonia) as the function of the saturation vapor temperature

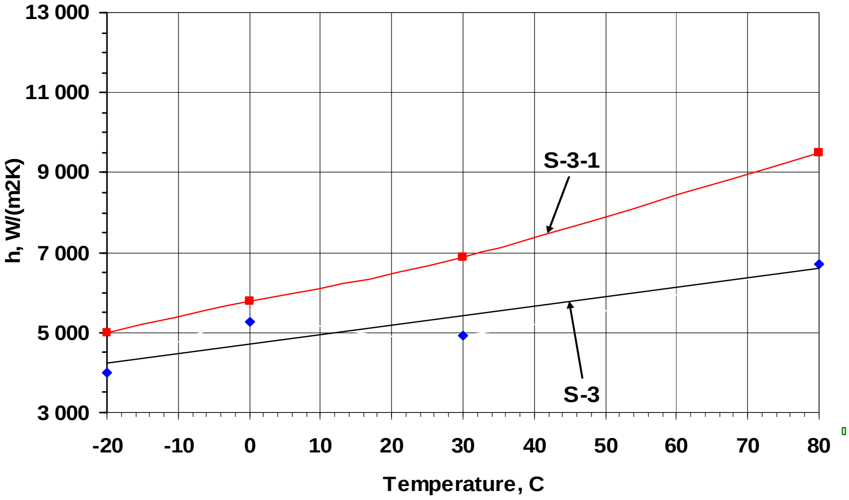


Figure 12. Heat transfer intensity in the evaporators S3 and S3-1 (ammonia) as function of the saturation vapor temperature

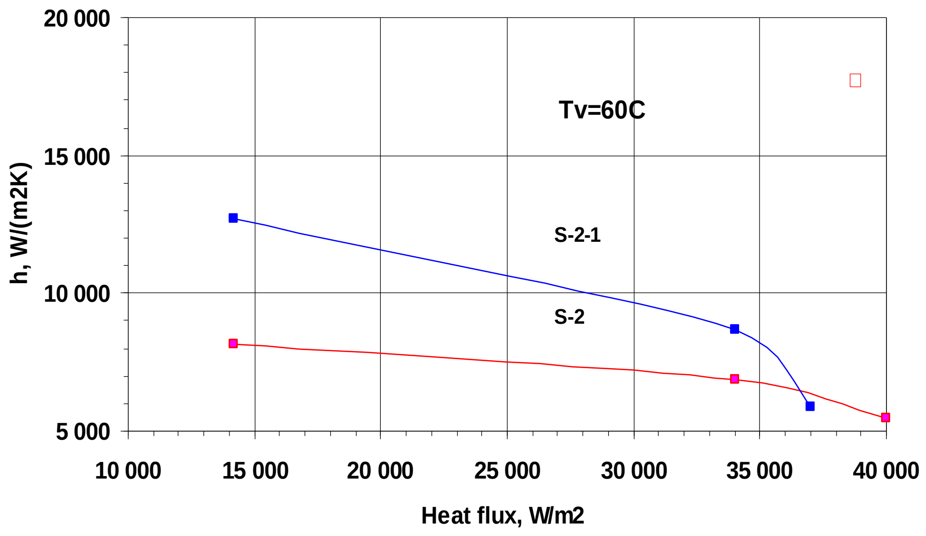


Figure 13. Heat transfer coefficients as a function of heat load in S2 and S2-1. Tv = 60 0 C.

The value of the surface of the GHPPL edge, Fig.14, is important to know the input of the evaporation from the nano porous coating to the vapor channel of the GHPPL.

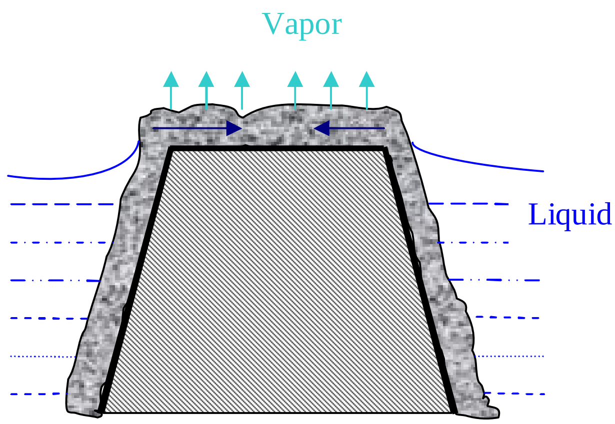


Figure 14: Schematic of the liquid evaporation at the edge of GHP with porous coating

Heat flux removed from the porous layer of certain thickness and length can be determined, using formula:

$$q=\frac{\dfrac{2\sigma\cos\theta}{R_p}-\rho_l gL\sin\varphi}{\left(\dfrac{\mu_l}{\rho_l KA_w}+\dfrac{1}{n_{\max}}\dfrac{8\mu_v}{\rho_v r_v^4}\dfrac{\delta_v}{L}\right)\dfrac{LA_e}{h_{fg}}} \qquad (5)$$

Capillary transport of liquid in thin coatings with micro porous structure can become an appreciable factor that limits the heat removal value. A maximum curvature of the meniscus is determined by the dimensions of the nano particles. For a GHPPL fin with a rather wide edge or in the case of liquid meniscus deepening inside the mini channel the capillary potential of the coating may turn to be insufficient. In this case, a portion of the edge surface can be dried and the effect of the porous coating is decreasing.

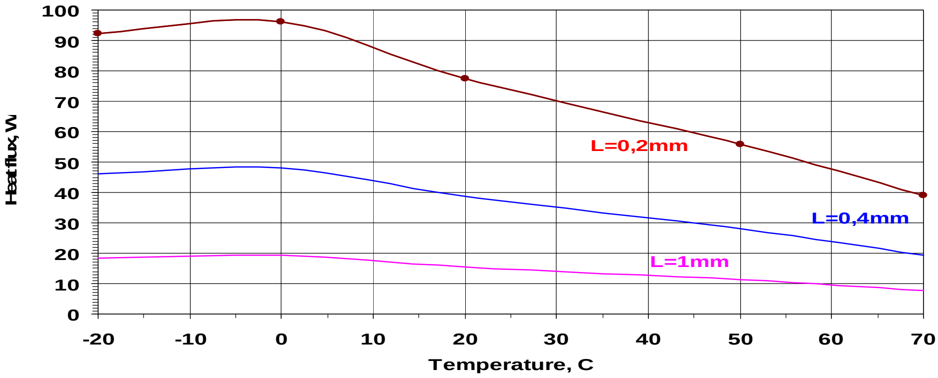


Figure 15. Heat flow removed from one edge of the capillary groove with porous coating as a function of temperature. *L* is the edge width, mm; temperature of ammonia vapor -20°C.

Fig. 15 shows the estimated maximum of the heat flux that can be removed from one crest of the groove edge, when the groove is wetted completely. The heat flux value depends on the liquid temperature. It is assumed that the main meniscus of the liquid lies at the groove base. The capillary structure used in the experiments is shown in Fig. 16. It was made from the aluminum oxide micro and nano particles.

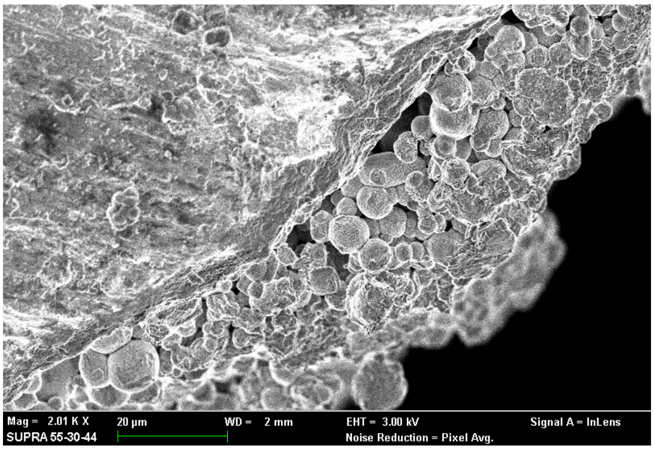


Figure 16. Aluminum oxide porous coating of GHPPL mini groove

Visual analysis and experimental validation of the heat transfer intensity using nano-porous technology (GHPPL) testify the heat transfer enhancement (2.5 to 3 times) compared to the heat transfer occurring on the same GHP with smooth grooves. Micro and Nano porous coating of mini-fins completely modifies the hydrodynamics of two-phase flow in mini grooves. A micro-scale effect is essential inside a porous body, and a mini-scale effect is available in the groove. A porous coating with open pores can be considered as a medium in which a large number of “micro heat pipes” with zones of evaporation and condensation are available, Fig.6-7. Mini/micro porous coating on the GHPPL remarkably enhances heat transfer, H.B. Ma, G.P. Peterson, 1997; A. Mirzamoghadam, I. Catton , 1988. It means that the heat flux increasing may occur with a slight increase of the wall temperature.

Polymer composites reinforced by nano wires and nano particles

Polymer-metal composites, Carlberg B, Ye LL, Liu J, 2012, are becoming an attractive subject due to their unique surface morphology. They can be made on the base of polymeric films metalized from one or both sides with a noble metal (gold or platinum), Kim KJ, Shahinpoor M., 2003; Slepička P, Fidler T, Vasina A, Švorčik V, 2012. Considerable efforts have been devoted to the design and fabrication of controlled organic/inorganic composites with novel properties, including optical, electrical, chemical, biological, and mechanical properties, Bledzki AK, Gassa, 1999; Stankovich S, Dikin DA, et al. 2006. In these hybrid systems, phase separation occurs naturally because they are composed of two materials with totally different chemical characteristics, Lipatov YS, Nesterov AE, et al. 2002. Besides the polymer-metal composites the carbon fibre reinforced carbon composites, epoxy and phenolformaldehyde composites reinforced by glass and carbon wires, polyamide composite materials with nano carbon filaments and nano diamond particles are also the subject of interest in the designing of the polymer loop thermosyphons and heat pipes. The envelope of such heat pipes have the effective thermal conductivity 10-40 times more to compare with the pure polymer material. The evaporator and condenser flat interface of such thermosyphons and heat pipes are interesting to be used for the heat-generating elements cooling and heat sink heating. Actually some polymer heat transfer equipment are used in different devices, Guan-Wei Wu, Sih-Li Chen, Wen-Pin Shih, 2012; Masataka Mochizuki, Aliakbar Akbarzadeh and Thang Nguyen,2013; L. L. Vasiliev and L. L. Vasiliev Jr.,2013. In this work a loop thermosyphon with flat interface is considered. The schematic of this flexible thermosyphon is shown on Fig.17. Its envelope is made of polyamide composite with nano carbon filaments and nano diamond particles to increase its effective thermal conductivity. The effective thermal conductivity of composite is equal to 11 W/m ^{0}C. The width and length of the thermosyphon (evaporator and condenser) is 30 mm and 250 mm, respectively. Its thickness is 10 mm. There are two flexible vapor and liquid lines made from pure polyamide used to join the evaporator and condenser. The grooved capillary structure of thermosyphon is made as longitudinal mini channels, allowing the condensed liquid to wet uniformly the heat transfer surface.

Figure 17. Flat loop thermosyphon made from polymer composite
(Polyamide reinforced by carbon nine filaments and nano diamond particles)

The working fluid of the thermosyphon is iso-buthan. The temperature distribution along the evaporator, adiabatic zone and condenser of the thermosyphon for different heat flow is shown on Fig.18. Thermal resistances of evaporator and condenser as a function of heat input and vapor temperature are shown in Fig.19 and 20. Three zones of temperature distribution could be observed in the evaporator, transport zone (vapor line) and condenser. The temperature difference T_w-T_{sat} between the external wall of the evaporator, $T_{w,}$ and the saturated temperature of the adiabatic zone, T_{sat}, was measured by four thermocouples. Saturation conditions were maintained by regulation of temperature and fluid flow through the condenser.

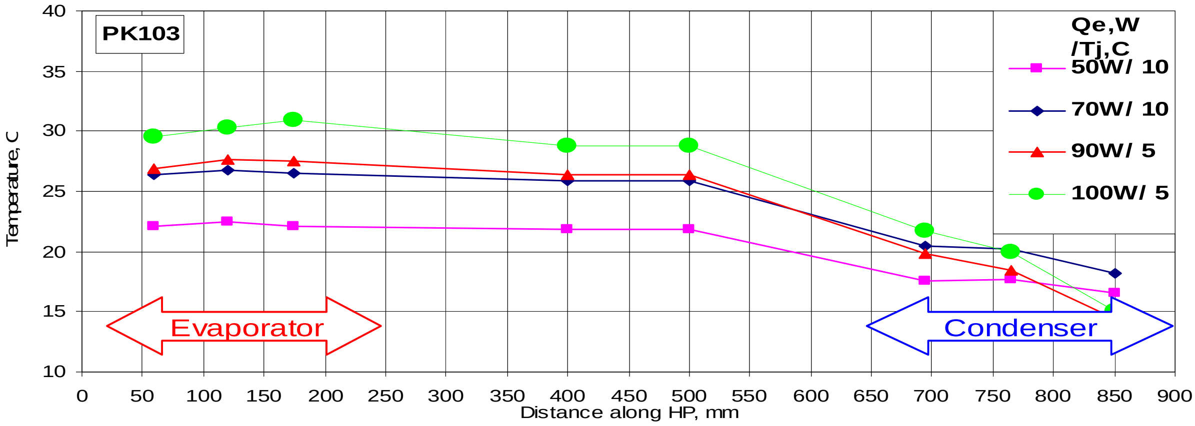


Figure 18. Temperature distribution along the evaporator, transport zone and condenser of the thermosyphon as the function of heat input.

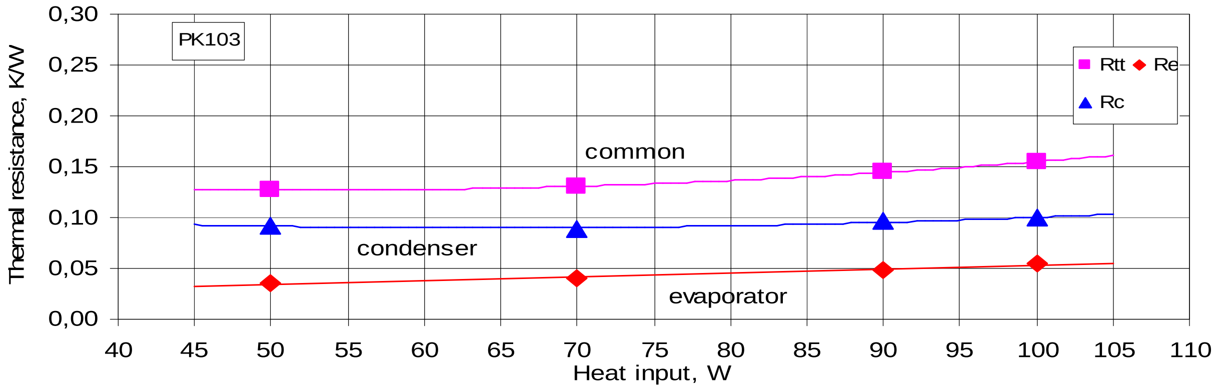


Fig. 19 Thermal resistance of evaporator (R_e), condenser (R_c) and total thermosyphon (R_{tt}) as a function of heat input.

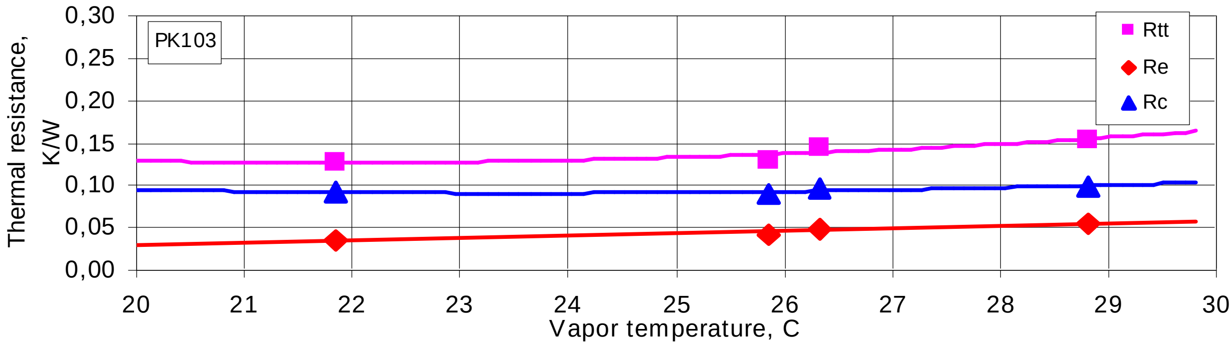


Fig. 20 Thermal resistance of evaporator (R_e), condenser (R_c) and total thermosyphon (R_{tt}) as a function of the vapor temperature in the adiabatic zone (vapor pipe).

6. CONCLUSIONS

1. Recent advances in nanotechnology have allowed development of a new nano fluids and nano coatings, intensifying heat transfer processes and reducing energy losses. Nano fluids and nano

coatings have been used as the means to increase the heat transfer intensity in original designs of heat pipes and thermosyphons evaporators.

2. Comparative studies of the heat transfer coefficients of the evaporators with different types of capillary grooves were conducted. The regimes of both evaporation and boiling of the working fluid (ammonia) were provided in the set of experiments with the evaporators having smooth capillary grooves and capillary grooves with nano porous coating of walls with a thickness of 20-100 μm. Within the entire studied range of temperatures and heat loads the heat transfer coefficients of all types of evaporators with the nano porous coating are 1.3-1.8 times higher than of similar evaporators with a smooth surface of capillary grooves (0.015-0.02 K/W for GHP with nano porous layer and 0.025-0.035 K/W for classical one).

3. New type of horizontal polymer flat loop thermosyphon with nano technology application was suggested, designed and tested. It was found that the evaporator thermal resistance R_{ev} of polymer thermosyphon is similar to that of classical aluminum heat pipe.

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