

Two-phase nanofluid-based thermal management systems for LED cooling

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Abstract. This research focuses on two-phase thermal control systems, namely loop thermosyphons (LTS) filled with nanofluids, and their use as LED cooling devices. The behavior of the fluid in the thermosyphons and the mechanisms explaining the possible impact of nanoparticles on thermal properties of the working fluid as well as the processes in the LTS are addressed. Nanoparticle distribution in the nanofluid, methods of preparation of nanofluids and nanofluid degradation processes (aging) are studied. The results are obtained from a set of experiments on thermosyphon characteristics depending on the thermophysical properties of the working fluid, filling volume, geometry and materials of radiators. The impact of nanofluids on heat-transfer process occurring inside thermosyphon is also studied. Results indicate strong influence of nanoparticles on the thermal properties of the thermosyphons, with up to 20% increase of the heat transfer coefficient. Additionally, a method of calculating the hydrodynamic limit of the LTS is proposed, which allows for estimation of the maximum heat flux that can be transferred by means of the LTS. Possible ways for further improvement of the model are proposed. The nanofluids are shown to be effective means of enhancing two-phase systems of thermal management.

1. Introduction

Two-phase heat transfer systems are widely used in different technical devices, especially in spacecraft thermal control systems, as well as in electronic devices such as microprocessors, semiconductor power electronics, modern powerful laser sources, optoelectronic devices, light-emitting diode (LED) lighting [1-3], etc.

Recent findings indicate that a new type of liquids with addition of metal or metal oxide nanoparticles may enhance thermal characteristics of two-phase systems. Over the last 12 years, extensive studies of nanofluids have been conducted containing both positive and negative results of the use of nanoparticles in heat transfer systems. Effect of nanoparticles on the system parameters is characterized by change of thermal resistance, critical heat flux, heat transfer coefficient, thermal conductivity, intensification of boiling and changes in the operating mode of the system. Some studies demonstrate viscosity increase, reduction of flow resistance, and change of wetting angle along with changes in flow mode between laminar and turbulent [4-9].

However, the conducted studies primarily concern conventional thermosyphons or focus on defining thermal properties of nanofluids, thus leaving LTS outside the scope of research.

Considering the above, we have set the following objectives for our study:

1. Examine nanofluids as a working fluid for thermal-management devices; compare the obtained results with the performance of clear working fluids;



2. Study nanoparticle distributions;
3. Develop a thermal control system based on loop thermosyphons for LEDs with a flat cylindrical evaporator and front heat input;
4. Optimize working fluid volume, come up with recommendations for working fluid choice and devise a filling procedure for nanofluids (omitted from this short version);
5. Compute the maximum heat flux based on the hydrodynamic limit using MathCad.

2. Experimental apparatus

In order to determine the change in thermal properties of the system, in this work we utilize temperature measurement by thermocouples at specific locations throughout the thermosyphon. Using thin, lightweight copper-constantan thermocouples allows for placing them at otherwise hard-to-reach locations of the thermosyphon. Temperature recording has been conducted as follows: After applying voltage and measuring power, the data acquisition system began to take temperature over a period of time. Then, when the temperature stabilized, the experimental run continued for one hour, with the temperature still being recorded every second by the DAC (Owen TRM-148). Finally, after the experiment was finished, the measured temperatures were averaged and standard deviation was calculated. For all experimental runs, the total error was less than ± 0.2 °C.

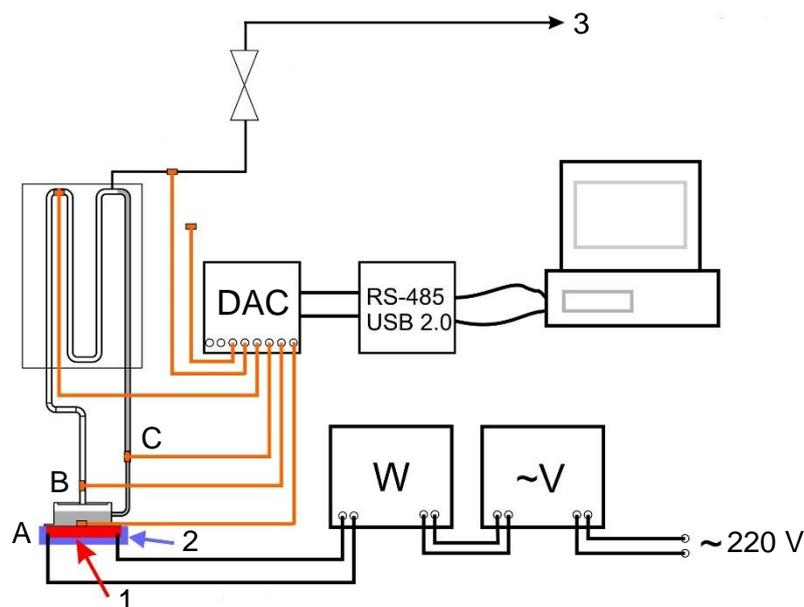


Figure 1. Conceptual scheme of experimental setup for temperature measurements at specific locations of the thermosyphon. 1 – heater, 2 – thermal isolation, 3 – filling/evacuation; A, B, C – thermocouple locations; DAC – data-acquisition system.

Figure 1 illustrates the schematic experimental setup and location of thermocouples. Experimental study assumes obtaining temperatures at specific points on a loop thermosyphon depending on the nominal load of LEDs or heat load, both measured in Watts. The heat load is intended to simulate the actual LED heat flux. The following locations on the thermosyphon have been selected: A – temperature of the heater or diodes, located between the evaporator and the heater T_h ; B – vapor temperature at the top point of the evaporator T_v ; C – liquid temperature by the condenser pipes at the evaporator's entrance T_l .

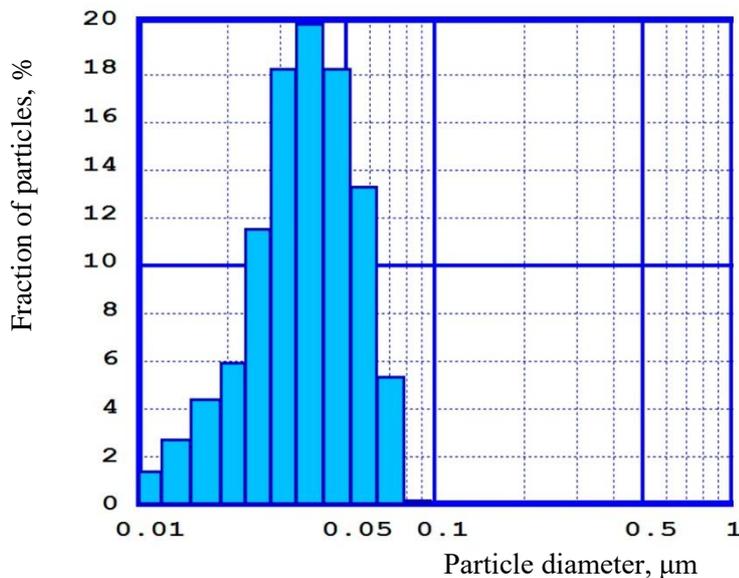


Figure 2. Particle size distribution in nanofluid.
Mean size is 36 nm.

Preparation of nanofluid included the following 3-step procedure. First, laser-ablated highly dispersed powder of Fe_2O_3 was added to bi-distilled water in a cylinder. The resulting mixture was placed into an ultrasonic dispergator for 10-15 minutes. During dispergation, in order to cool down the mixture and prevent boiling, the cylinder was wrapped with pipes flowing cold water, since boiling causes nanoparticles to exit the liquid and condense elsewhere in the environment. Total ultrasonic power was 5kW. Finally, in order to assess the quality of the prepared nanofluid, the mixture was placed into the laser-based particle size analyzer SHIMADZU SALD-7101, which measured the particle size

distribution. The measurement results are presented in figure 2. The Fe_2O_3 nanoparticle powder has been selected for its non-reactive nature and affinity to the materials used in the system. This procedure was repeated for each solution. Prepared solutions had the following mass concentrations: $w = 2.0\%$, 1.5% , 1.0% , 0.8% , 0.3% .

3. Results and discussion

3.1. Calculation of maximum heat flux of the thermosyphon

The calculation of the hydrodynamic limit was based on the necessary working condition that causes the circulation of working fluid in thermosyphon. This condition can be written as the inequality $\Delta P_g = (\rho_l - \rho_v)gH \geq \Delta P_v + P_l$, where ρ_l – density of liquid phase; ρ_v – density of vapor phase; H – the height difference between the evaporator and the condenser (gravity force that actually returns the liquid to the evaporator); ΔP_v and P_l are the pressure drop in liquid phase and vapor phase, respectively.

Using Hagen-Poiseuille equation for laminar flow of vapor and Fanning equation for turbulent flow and considering formulas for local and integral pressure drop coefficients (left out), the final equation will be:

$$Q(H) = \begin{cases} \frac{-(E + D) + \sqrt{(E + D)^2 + 4(O + P) \cdot [(\rho_l - \rho_v) \cdot g \cdot H \cdot 0,75]}}{2 \cdot (O + P)} & \text{at } Re \leq 2100 \\ \frac{-(C + D) + \sqrt{(C + D)^2 + 4(O + P) \cdot [(\rho_l - \rho_v) \cdot g \cdot H \cdot 0,75]}}{2 \cdot (O + P)} & \text{at } Re > 2100, \end{cases}$$

where

$$D = 128 \frac{\eta_l(T_l)}{\rho_l(T_l)} \cdot \frac{L_v}{\pi d_l^4} \cdot \frac{1}{H_{ev}(T_v)}, P = 0,0175 \lambda_k \cdot \delta \cdot \frac{R_0}{d_v} \cdot \frac{1}{2 \cdot H_{ev}^2 \cdot \rho \cdot S^2}, O = \zeta_{loc} \cdot \frac{1}{2 \cdot H_{ev}^2 \cdot \rho \cdot S^2},$$

$$E = 128 \frac{\eta_v(T_v)}{\rho_v(T_v)} \cdot \frac{L_v}{\pi d_v^4} \cdot \frac{1}{H_{ev}(T_v)} \text{ and } C = 0,6328 \cdot Re^{0,75} \cdot \frac{\eta_v(T_v)}{\rho_v(T_v)} \cdot \frac{L_v}{\pi d_v^4} \cdot \frac{1}{H_{ev}(T_v)}.$$

The equation above includes physical properties of liquid and vapor phases, namely viscosity, density, heat capacity, and enthalpies of condensation and vaporization. Therefore, knowing the listed properties, it's possible to obtain functional dependency Q from H for laminar and turbulent flow respectively. Figure 3 presents the graph plotted for a set of commonly used working fluids as a function $Q(H)$. As apparent from the graph, the selected model adequately describes the processes of heat and mass transfer in thermosyphon even though the model doesn't take into account boiling process and leaves out certain details of heat transfer mechanisms that occur at liquid-vapor phase boundaries.

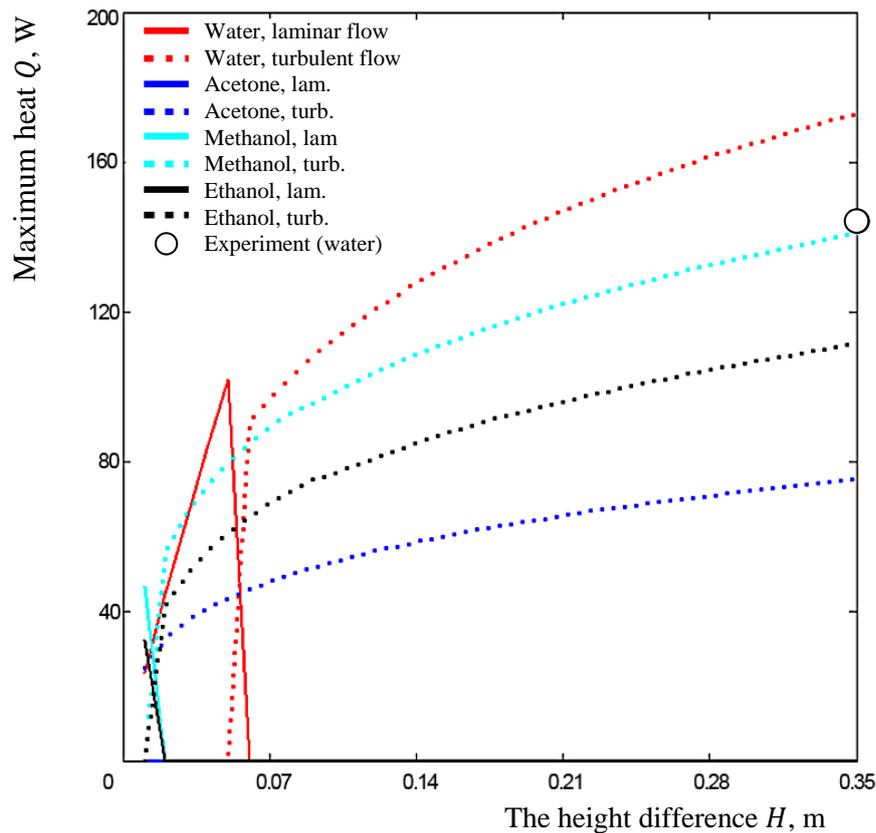


Figure 3. Maximum heat Q that can be transferred by LTS as a function of the height difference H between the evaporator and the condenser for a set of commonly used working fluids.

Possibly, employing the finite-element (FEM) method alongside the finite-volume method (FVM), depending on modeling situation, can significantly improve the consistency of the model with the experimental results.

3.2. Two-phase thermosyphons with nanofluids

To determine the influence of nanofluid on the process occurring in the thermosyphon, we have calculated the heat transfer coefficient using the equation $\alpha = Q / S / (T_h - T_v)$, where Q – the applied heat; S – the surface area of heat input $19.2 \cdot 10^{-4} \text{ m}^2$; T_h and T_v are the heater and vapor temperatures at the locations A and B (Fig.1), respectively.

The experimental results show that there's a substantial increase of the heat transfer coefficient (see Figure 4). For concentration $w=2.0\%$ the increase is as high as 20%, taking into account that thermosyphon itself is a very effective system. A possible explanation of how the nanoparticles may cause the heat transfer coefficient increase is presented in Figure 5.

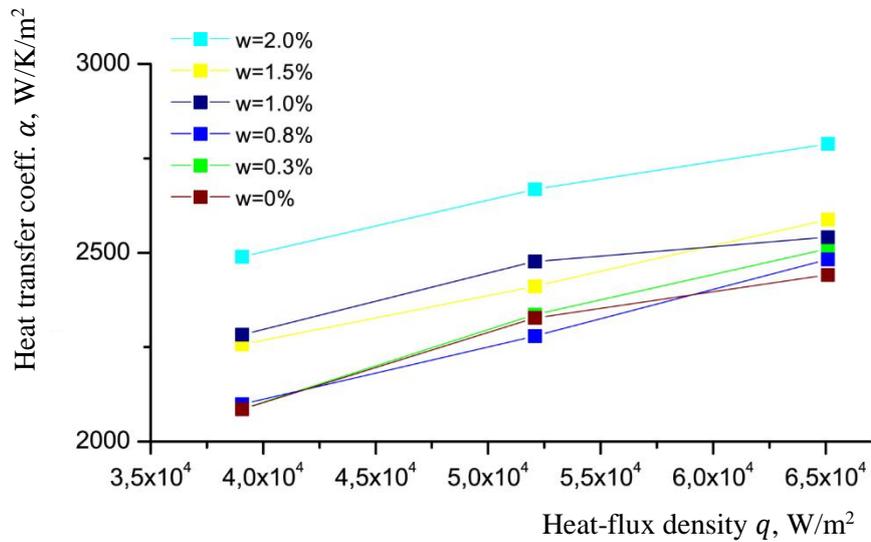


Figure 4. Nanofluid's influence on the heat transfer coefficient α for different mass concentration w of nanoparticles.

Nanosystems are subject to processes of degradation due to high values of free energy, which can be reduced via an agglomeration process. Some of the studies have shown a degradation over time (aging) process caused by aggregation of nanoparticles in the solution and their settling. To estimate the possible negative impact of these processes, the experiments were repeated the next day and in one week. No difference between the one-week and one-day results has been observed, so the final results include only

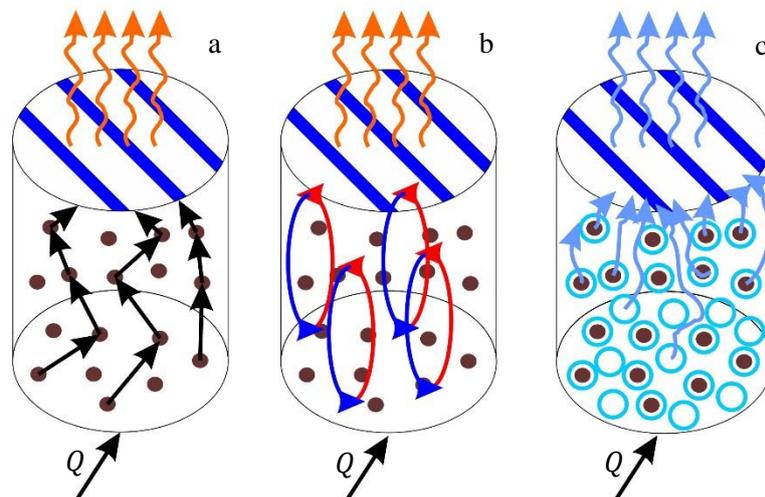


Figure 5. Possible explanation of the heat transfer increase. a – nanoparticles have greater heat conductivity than liquid, and heat is conducted via Brownian motion of the particles; b – nanoparticles' influence on Rayleigh–Benard cells formation; c – nucleate boiling (particles act as nucleation centers); Q is the applied heat.

the one-day degradation dependency.

Figure 6 presents the process of the nanofluid degradation over time. Indeed, obtained results show that nanofluids are subject to steady decrease in thermal conductivity, most probably due the process of aggregation and settling of nanoparticles.

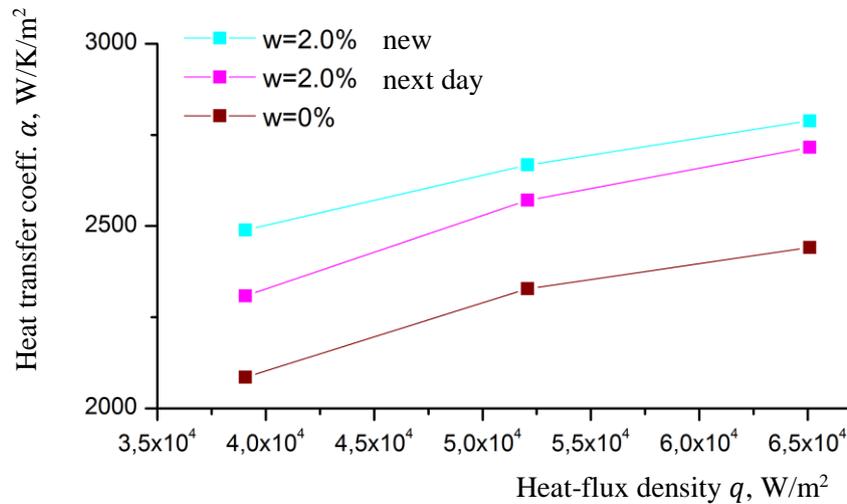


Figure 6. The process of the nanofluid degradation (aging of nanofluid) over time; w is mass concentration of nanoparticles.

To address this problem, an introduction of surface-active agents is proposed. Alternatively, a non-stop operation mode is recommended for such systems. These measures can effectively prevent nanoparticles from segmentation, thereby stabilizing the thermal system.

4. Conclusion

1. New thermal management devices have been proposed, tested and proved to be effective for LED cooling.
2. In this study, we have proposed a model for calculating maximal heat flux based on the thermal properties of working fluids and height difference between the evaporator and the condenser. This model has shown good consistency with experimental data. Possible ways of improvement of the model have also been discussed.
3. The experimental study of the nanoparticles' effect on the processes occurring in the thermosyphon has also been conducted. The obtained results indicate that nanofluids show great promise as a working fluid in two-phase systems, effectively increasing the heat transfer coefficient for up to 20%. Particularly the study of stability of nanofluids has revealed that in time nanoparticles tend to agglomerate and settle down, which can be prevented by introducing surface-active substances. However, further studies of these process need to be conducted. Additionally, the mechanism of nanoparticles improving the thermal properties of the base liquid is yet to be explained. The study of nanoparticles of different substances also merits attention. Metallic particles promise greater thermal conductivity than oxides, though the former are prone to oxidation, which may result in a substantially lowered thermal properties. These studies have not yet been conducted.

5. References

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