Research Article **Open Access**

Utilization of Passive Thermal Control Technologies for Electronics Cooling: A Brief Review

Riehl RR*

GamaTech Thermal Solutions, R Córdoba, 34 São José dos Campos, SP Brazil

Abstract

Technologies that have been used for space missions have gained attention on several other applications especially for military and surveillance systems. The increase on processing speeds and needs for communications where high data rates are present have resulted in higher heat dissipation rates that require proper consideration. Depending on the project, severe limitations are presented in systems operating in ground missions, which require the use of technologies only considered before in satellites. Therefore, heat pipes and their related technologies together with the enhancement promoted by the use of nanofluids as alternative working fluids, have gained attention and have been applied on several systems with reliable results. Such applications have allowed the design of more compact systems enhancing their capabilities of heat dissipation, keeping the systems' temperatures within the required limits established by the projects' requirements. From heat pipes applied on radars and military communication systems to loop heat pipes being considered for several other ground applications, the use of those technologies have opened new horizons for thermal issues solutions. Since the heat dissipation rates have increased dramatically over the last years, nanofluids also requires important consideration to be made before defining them as a contribution. Based on potential applications, the objective of this work is to present a brief review on passive thermal control systems technologies that can be applied to current ground systems, considering their potential contribution on the enhancement of heat dissipation rates but also pointing some of the limitations on applying them.

Introduction

The continuous development of electronics systems for communication able to transfer high data rates has guided new designs to face an important issue for their correct operation: thermal limitations. New designs of printed circuit boards (PCBs) have considered the use of high density processing speeds microchips, being accommodated in very compact boards with numerous other components that, along with the main one, present high heat dissipation rates.

One might consider that a few watts or even tenths of watts being dissipated by a given component might not signify something to be considered upon performing a thermal analysis. However, when taking into account the heat dissipation density (heat dissipation rate per surface area), concerns related to system's thermal and mechanical designs began to be an important issue. To be able to solve this thermal limitation, several solutions can be considered as many are available currently, from liquid cooling, high speed fans, etc. However, at some point, the so-called ordinary solutions are not able to perform the required heat dissipation and new solutions have to be applied.

The thermal design needs first to consider how efficient the heat transfer process from the source to the environment is where the heat will be dissipated. The correct selection of thermal interface materials plays the major role on this process. With the same degree of importance, the heat dissipation surface and its material are also important variables to be considered, focusing on designing the correct interface that will reject the heat to the environment as efficient as possible. However, even with the correct design of the heat rejection surface with high efficiency, one can face some serious issues related to the concentration of heat in one specific region which is usually close to the components that present the highest heat density. Spreading the heat is the most adequate and applied solution (given the fact of the existence of the so-called heat spreaders), in such a way that the majority of the available area can be used to dissipate the heat to the environment. In this case, different materials with higher thermal conductivities can be applied, but also the use of high performance thermal devices such as heat pipes (and their related technologies) can be considered on the overall design.

Heat pipes (HPs), pulsating heat pipes (PHPs) and loop heat pipes (LHPs) have been applied to many thermal management designs due to the fact that new equipment are requiring more efficient ways to dissipate the heat. Since those technologies have been successfully applied for space missions where the operational conditions are extremely severe, ground applications have found them to be very important devices to be considered on the heat dissipation issues faced on new projects [1-4].

To better address the application and considerations that need to be made regarding these technologies on current thermal management designs, a brief review is presented in order to show the advantages and also some issues that require attention from designers. Contributions from different authors are presented based on each technology applied, with the objective to better understand how they can be useful. More Important, the technological approach is also presented, where the objective it to have a better sense of the advantages and disadvantages concerning each technology.

Heat Pipes

Heat pipes are a well-known technology among thermal systems

---

*Corresponding author: Riehl RR, GamaTech Thermal Solutions, R Córdoba, 34 São José dos Campos, SP Brazil, Tel: +55 12 3206-4305; E-mail: roger.riehl@gtts.com.br

designs and by many are considered already a "commodity". There are several heat pipes manufacturers worldwide, each one presenting their own designs, shapes, selection of working fluids and qualification/quality degrees. Applications vary from satellites and spacecrafts to computer's cooling [5], but heat pipes have gained attention for other applications as well, especially those related to military and surveillance systems [3,6]. Figure 1 presents the most classical configuration of a heat pipe.

Heat pipes are composed of three sections: evaporator (heat source), adiabatic and condenser (heat sink) and can be manufactured in many shapes (cylindrical, flat, straight, curved, etc.). In some applications, the adiabatic section does not exist and the heat pipe can operate with little temperature differences from the heat source to the sink. They are manufactured with a housing (usually metallic), a working fluid and may contain a wick structure that can be a screen mesh wrapped around its inner diameter or be sintered. Other wick structures used in heat pipes are internal axial grooves extruded with the housing. Depending on the project, the selection of the housing, wick structure and working fluid will be made to give the maximum heat transport capability for the heat pipe, also considering the chemical interaction between all those parts during the life time of this device in order to avoid the generation of non-condensable gases (NCGs) that can be harmful to the device's operation.

A comprehensive review about the heat pipe technology has been presented by Chan et al. [6], describing the development, constructive and phenomena involved on heat pipes operation, varying from regular to thermosyphon heat pipes, as well as variable conductance heat pipes, miniature and pulsating heat pipes, as well as loop heat pipes. In this publication, the technological approach is given to this device showing their construction components and important conclusions obtained from several authors during the years. However, depending on the application, heat pipes design require several different considerations regarding the thermal couplings, materials compatibility and costs, this latest especially considered upon analyzing the economic impact on the final project and its price to the final client.

The continuous development of heat pipe technology has given to this passive thermal control device great interest for new applications where it has not been considered before. It is well known that heat pipes are reliable two -phase passive thermal control devices and their applications have spread out for many fields, from aerospace to computer cooling as well as industrial. Special attention should be given to heat pipes that operate at mid-level temperatures (up to 200°C), which have found several applications in both aerospace and industrial areas [3].

Figure 1: Schematics of a classical heat pipe [6].

(a) Accelerated life tests rig   (b) Acceptance tests

Figure 2: Miniature heat pipes.

(a) Before final integration   (b) After final integration

Figure 3: Miniature heat pipes embedded in the structure.
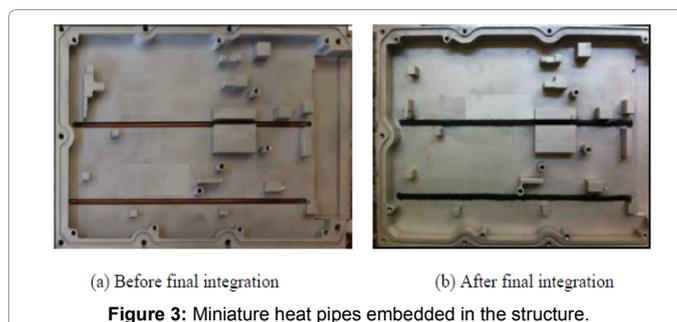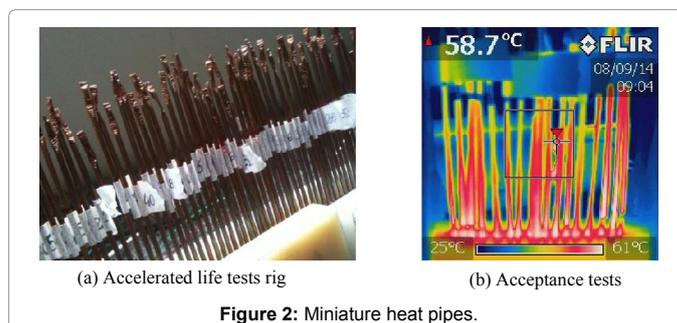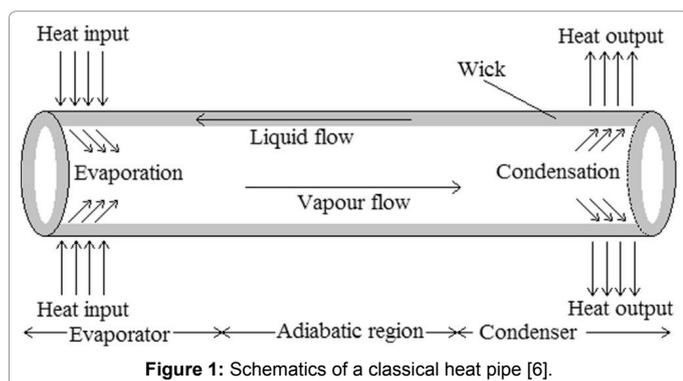
New applications are constantly being suggested for heat pipes which have called attention from many sensitive fields such as military and surveillance. This is especially important to consider because of new developments of electronic systems devoted to military applications, regarding data and communication hardware. Previous investigations have addressed this issue, where the potential of applying heat pipes and also pulsating heat pipes have been demonstrated [1-4]. Concerns related to any new heat pipe development are clearly regarding the chemical compatibility between the housing and working fluid, as well as maximum heat transport and life time for a given application [5,7]. Recently, Designs for communication and surveillance devices have showed the application of heat pipes as a device to assist on the heat dissipation issues found in that equipment. The entire technological procedure towards the achievement of a reliable thermal management and heat transport device had to be applied, considering material and working fluid chemical compatibility, life time expectancy and integrated operation. On a specific application, which is an in-house development, miniature copper (oxygen free and high conductivity) heat pipes with outer diameter of 3 mm and 175 mm in length have been designed to perform the heat transport of up to 12 W using methanol as working fluid, presenting a #200 screen mesh wick. The main objective of these heat pipes was to spread the heat generated over the heat dissipation area in order to enhance the process. Figure 2 presents the photographs of the heat pipes conceived for this application along with their infrared image during acceptance tests [8].

Figure 3 shows the heat pipes being integrated in the structure where they will perform the heat transport. Such an application was related to the thermal management of a PCB with highly concentrated heat density, based on the concept of low inertia thermal design, where the heat shall be promptly removed from the source and dissipated to the environment. Figures 3a and 3b show the heat pipe integration before and after the application of a high thermal conductivity epoxy, respectively.

One should notice a very important feature applied on this specific design, which are the so-called "contact towers" presented on this structure. They are at the matching position of the most important

electronic components and were used to promptly drive the heat generated to the heat pipe, which is responsible for spreading it on the rejection surface that will then transfer the heat to the environment. For such an application, the contacts between the electronic components and their designated contact towers were done using a high thermal conductivity interface material (also called interfiller) to enhance the heat transfer process and avoid conduction issues.

Figure 4 presents the heat pipes being tested for verification, where the heat source was simulated by a skin heater controlled by a DC power supply delivering 12 W of power on each heat pipe. On this simulated test, it is clear the operation of the heat pipe presenting a startup right after heat is applied. After a few minutes, steady-state is reached as seen by the thermal images, showing that the heat pipes are transporting the heat along their axis while keeping the heat source with a slight increase on its temperature when compared to the initial condition. Such a thermal behavior was expected from the heat pipes as they have performed according to their designs.

When operating in thermal cycles test (TCT), the heat pipes presented a reliable operation as expected, since their application will require such responses especially during transient periods. Figure 5 presents the results during a TCT for the entire structure with the embedded heat pipes operating with a dedicated PCB and their electronics components at full charge. On the following figures, temperatures were read using Omega type K thermocouples with error
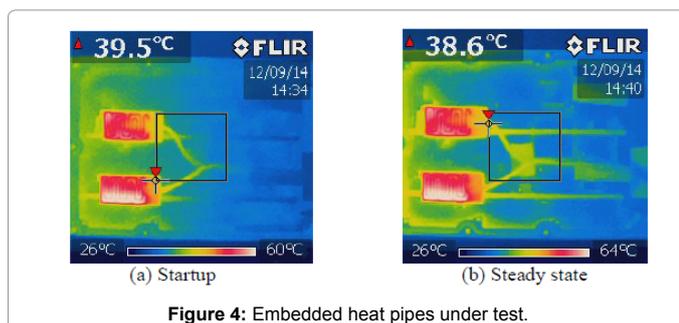

Figure 4: Embedded heat pipes under test.

Figure 5: TCT for the embedded heat pipes in the structure.

Figure 6: Pulsating heat pipe configurations [6].

of ±0.2 ℃ at 100 ℃. On Figure 5a, TC-1 is the thermocouple located at the heat pipe's condenser, TC- 5 is located at the adiabatic section and TC -4 is located at the evaporation section for the heat pipe at the superior part of the structure; on Figure 5c, TC-6 is the thermocouple located at the heat pipe's condenser, TC-8 is located at the adiabatic section and TC-3 is located at the evaporation section for the heat pipe at the inferior part of the structure.

The test results show that, after progressing from a lower to a higher level temperature, the heat pipes present a fast start up and also a fast tendency to reach the steady state, with very small temperature differences between the heat sources and sink. Thermal conductances (evaporator to condenser) reached the maximum values of 10.6 W/℃ and 4.4 W/℃ for the superior and inferior heat pipes, respectively, as they were operating at different heat transport levels (12 W and 8 W, respectively). For this specific project and application, the equipment would not be able to operate without the presence of the heat pipes, since the simulated results were showing highly concentrated heat that would certainly shut down the electronic components due to excessive temperature.

Therefore, it is clear the great contribution of the heat pipes on the improvement of the equipment's heat dissipation, which results on confidence during its operation for the purpose that they have been designed for.

Pulsating Heat Pipes

Pulsating heat pipes (PHPs), also known as Oscillating Heat Pipes (OHP), consist of a simple meandering tube bent with several curves forming several parallel channels, without the presence of a wick structure. The channels are formed from capillary tubing and a working fluid is responsible for acquiring the heat from a source and dissipating it in a sink. This kind of device can be considered a special type of heat pipe and was introduced by Akachi [9]. Pulsating heat pipes can present three configurations: closed loop, where the endings are connected Figure 6a; closed loop with a check valve, which is used to regulate the fluid flow and its direction Figure 6b; open loop, where the endings are not connected Figure 6c. For the first 2 configurations, there is circulation of the working fluid and this can be regulated especially with the use of the check valve. On the last configuration, the dynamics involving the plug/slug movement is rather chaotic and difficult to simulate, but it presents reliable operation and it is able to promote the thermal control once its design and manufacturing procedures are well controlled.

Pulsating heat pipes can be applied in several thermal control problems, such as microelectronics, but recently has gained interest in applications such as those for aerospace and surveillance systems used on the ground. Since PHPs operate by means of slug/plug dynamics [10], several investigations have been performed in order to improve their efficiency, also focusing on working fluids with the presence of solid nanoparticles, which can act on the improvement of this dynamics as well as on the thermal conductivity of the fluid [11]. Pulsating heat pipes have been under investigation in the last years with great development regarding the phenomenon involved in their operation, but further investigations are still required. Delil [12] has presented a survey on pulsating/oscillating devices suitable to be used in space and microgravity environments where important contributions to understand such devices were given. Lin et al. [13] presents an experimental investigation on an open loop PHP, where the maximum heat transport capability was investigated, showing the great perspective of using PHP as a thermal control device. The
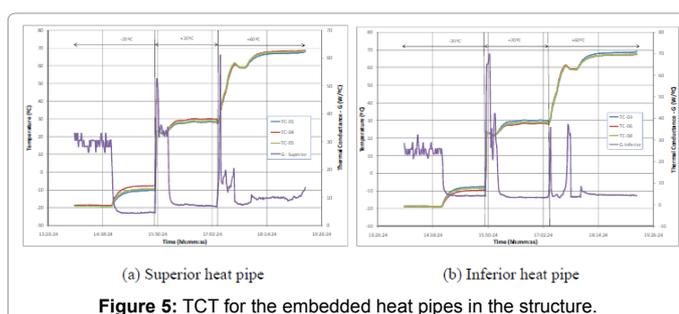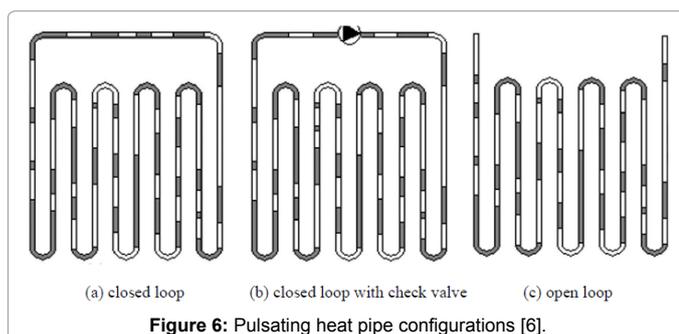
first investigations regarding the operation of PHPs were important to guide future studies and applications, focusing on the use of this technology where a temperature difference greater than those observed on regular heat pipes, between the heat source and sink, was not an issue as this is a characteristic of this device. The operational limits of closed loop PHPs have been investigated by Yang et al. [14], indicating that this type of thermal control device can operate at any orientation, even though a loss on its performance can be expected. Recently, Supirattanakul et al. [15] have presented an investigation where a PHP was used on the performance enhancement of air conditioning systems, showing promising results for such application. Investigations regarding the pressure losses presented in closed loops PHPs were performed [16], where it shows that this parameter is the limitation for some applications. Other important investigations regarding the use of PHPs were performed focusing on their improvement upon using the so-called nanofluids [17], as well as the application with magnetic fields when ferrofluid working fluid was used [18] and the analysis of the startup on the PHP overall performance [19]. Previously used on the thermal control of aerospace systems, passive two-phase thermal control systems have gained interest of the aeronautics and defense industry, being applied for cooling of avionics and aircraft actuators [20,21]. The use of regular heat pipes and PHPs have been widely used for the thermal control of electronics, and since the amount of heat to be dissipated increases at each new project, such devices will become even more popular in the near future for several terrestrial applications [22,23]. The PHPs give several degrees of freedom to thermal systems designers as they can be shaped in any configuration possible, as long as the plug/slug dynamics can be sustained to promote the heat transport. High density heat management equipment have required such passive thermal control device, which has been used to remove
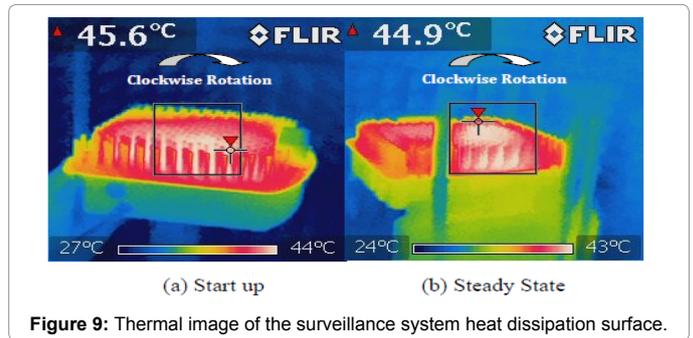

Figure 7: PHP application for PCB temperature control.
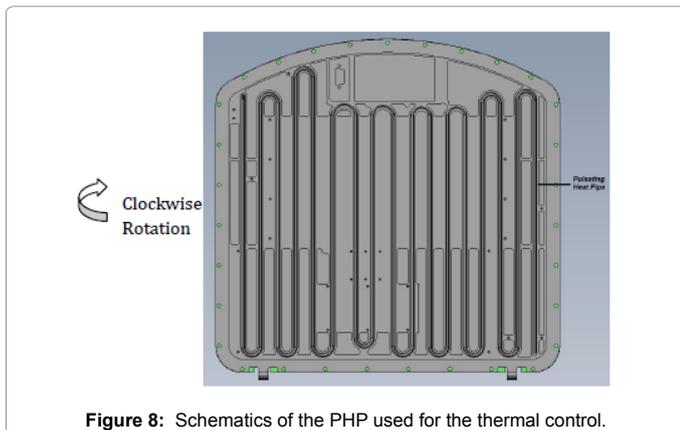
Figure 8: Schematics of the PHP used for the thermal control.

Figure 9: Thermal image of the surveillance system heat dissipation surface.

Figure 10: High power thermal management with PHPs.

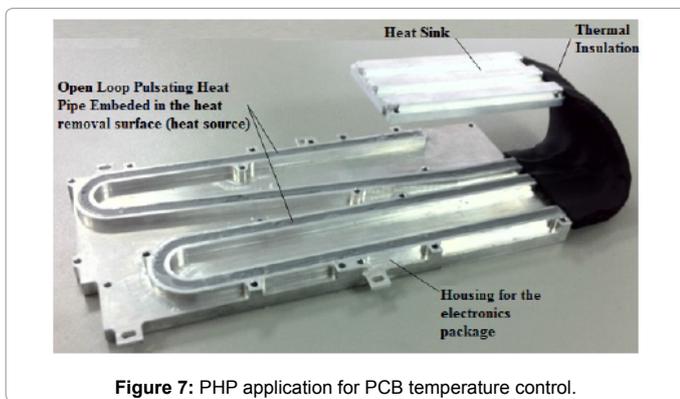the heat and transport it to the environment to be rejected. Figure 7 presents a configuration for a PHP applied on the thermal control of a high density heat management PCB, which was able to control the electronic components' temperatures within the limits established by the project's requirements [24].

Surveillance systems have showed potential applications for PHPs due to their particular configuration on their PCBs and construction, as most of them are far away from possible heat sinks and the use of other passive thermal control systems would result on the increase of costs. Since the PHPs configured as open loop can operate at adverse gravity orientation, they can be applied for this specific thermal management task given the correct design and control of their manufacturing processes [24].

Another application for a surveillance system using the thermal control promoted by PHPs is presented by Figure 8. In this case, a PHP was embedded in the heat dissipation structure in order to collect the heat from the several components located in the electronic setup and spread it throughout the available area, in order to enhance the heat dissipation process. With the device in operation at its full thermal capacity it was clear that the PHP was performing as expected, collecting and spreading the heat throughout the heat dissipation area as it can be verified in Figure 9, where a comparison made with the device at the start up and later at steady state can be observed.

Another case can be verified when PHPs have been applied to the thermal control of high heat density electronic components, as presented by Figure 10. On this configuration, several PHPs have been used to promote the thermal management of highly concentrated heat

on electronic components, keeping them at the required temperature. The operation of the PHPs can be observed on Figure 11.

From the presented results, it can be observed that PHPs can perform a reliable thermal control when their design is done according to the application needed, as well as the correct control of the manufacturing processes deeds to be done.

Loop Heat Pipes

Loop heat pipes (LHPs) are basically composed of the following parts: capillary evaporator, compensation chamber (or two-phase reservoir), vapor and liquid lines, and the condenser. They are considered reliable two-phase thermal control devices, able to transport large amounts of heat over long distances. This is possible due to the fact that its capillary evaporator is able to generate substantial capillary pumping pressure to drive the working fluid from the heat source to the heat sink because of the small pore size present on its primary wick, which can overcome the loop's overall pressure drop, while controlling the heat source's temperature. Since its capillary evaporator is the most important component, the LHP can be designed to operate either at gravity assistance or adverse condition as long as enough pumping pressure is generated. Usually, the capillary evaporator is built with the following components: housing, primary wick with fine pore sizes (usually below 1 m), secondary wick (usually made from screen mesh) that connects the evaporator liquid core to its compensation chamber, vapor and liquid seals, a bayonet to deliver the working fluid (most of the times with some degrees of subcooling) to the evaporator liquid core and, in some case, a pressure control regulator that it is used to set the LHP operation temperature [2,24].

Heat pipes and LHPs are embedded in the honeycomb panels [25] or directly attached to an electronic module dissipating heat that needs to be rejected via a space radiator or condenser [26]. Due to the reliability and the fine temperature control capability provided by LHPs, their applications have also gained a growing interest for terrestrial applications, especially for defense and military use.

Loop heat pipes are known to be reliable two-phase thermal control devices, operating by means of capillary pressure generated in a capillary evaporator, which is in direct thermal contact with the heat source. A working fluid in its saturated condition evaporates in the primary wick in the evaporator and the vapor flows towards the condenser where it loses its latent heat, returning to the liquid phase. Thus, liquid flows back to the evaporator where the cycle restarts. Coupled to the evaporator there is the compensation chamber, which is responsible for setting the operation temperature of the entire loop as well as delivering or draining the working fluid when the LHP requires more or less liquid, which is directly dependent on the power applied to the evaporator. Many authors have reported the development of LHPs with different configurations on the transport lines as well as in regard to their porous (wick) structure [27-29]. Depending on the requirement, a pressure regulation valve can be installed on the LHP at its vapor line, which automatically controls the heat source temperature independent of the heat power applied to the evaporator [30-32].

Since the need to have a fine control on the operation temperature of LHPs has become a major objective for designers, the conception of a thermal control valve located at the evaporator's vapor outlet appeared to be a potential solution. Firstly conceived by Goncharov et al. [30], the so called 3-way pressure regulator device is a bellows valve which receives the vapor coming from the evaporator and, by the action of an inert gas (not mixed to the working fluid) adjusts the stem opening to allow more or less flow depending on its temperature set point. At the valve's outlet, vapor can be guided directly to the LHP's condenser or be diverted to the compensation chamber, thus regulating the operation temperature with great precision. However, further improvement was promoted on this device to present a 2-way configuration [31], where the outlet to the compensation chamber was eliminated. Figure 12 shows the pressure regulator valve for the 3-way and 2-way configurations.

The pressure regulator valve presents fine control on the operation temperature of the LHP (set by its compensation chamber temperature), even when the condenser/radiator is operating at low temperature and the evaporator has low power applied to it, maintaining the evaporator's temperature and avoiding the use of electric heaters [32]. Since the volume of inert gas is loaded to the chamber to control the LHP's temperature, leakages from/to the working fluid are potentially possible. Another important issue is related to accumulation of powder coming from the evaporator as a result of material displacement from the primary wick (especially sintered metal wicks) during the LHP's operation, which may cause the stem to be locked at a given position that could compromise the LHP operation and its temperature control. One should notice that, given the high precision needed to manufacture the pressure regulator valve components, its cost impact on the LHP must be carefully considered as well. Another method to control the operation temperature of LHP has been proposed by Jong et al. [33] as presented by Figure 13. This method consists of pressurizing the compensation chamber with an inert gas (Helium) and using an external pressure control. Such method showed good results and temperature control resolution of 0.06ºC and can be considered a promising methodology, with the advantage of not presenting a complex mechanical interface to control the pressure as seen on both 3-way and 2-way valves.

When more than one heat source needs to be controlled by an LHP based system, most likely the option of using several LHPs will be
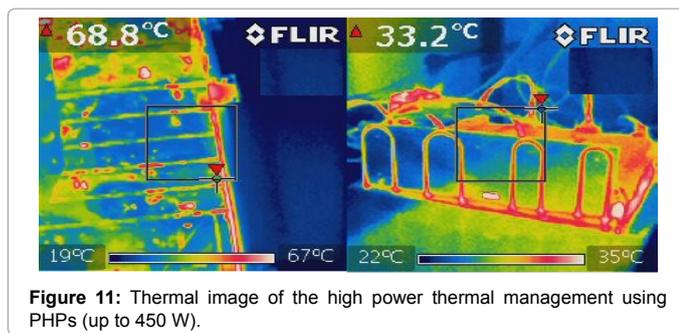

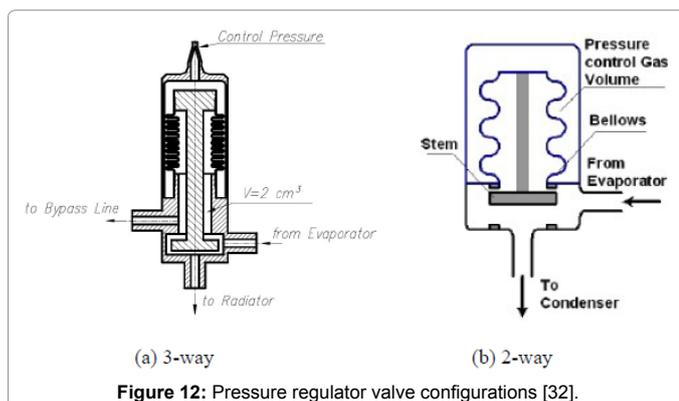**Figure 11:** Thermal image of the high power thermal management using PHPs (up to 450 W).

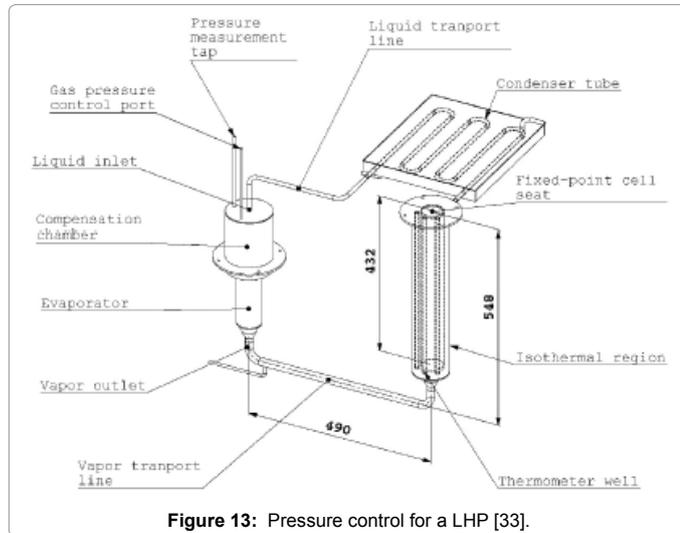**Figure 12:** Pressure regulator valve configurations [32].

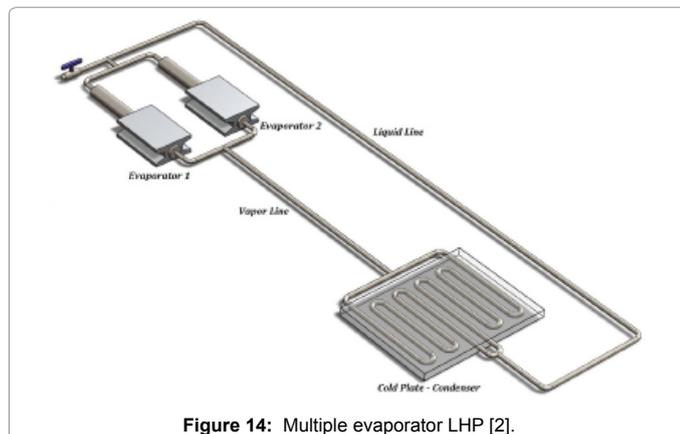**Figure 13:** Pressure control for a LHP [33].

Figure 14: Multiple evaporator LHP [2].

preferred. This is due to the difficulties associated with the availability of the multiple evaporator designs sharing the same condenser and transport lines, which are called multiple evaporator LHP and a representation of this configuration is shown by Figure 14.

One of the first reports on this subject reveals the difficulty on operating multiple evaporators LHPs. In this work, it was reported that the evaporator with higher heat load will set the entire loop's operation temperature, while the others will seek the equilibrium under this condition [34], which was further verified during investigation of several types of LHPs developed for aerospace applications [35]. The interaction between multiple parallel evaporators has been reported as a complex operation, even though they might present a reliable operation if some steps could be taken prior to their startup [36-38]. Such conditions were applied on a previous investigation with a simple configuration of a multiple evaporator LHP, which proved to be efficient on its startup and operation [2,39].

Applications of Nanofluids

Nanofluid application is a recent area of investigation with promising results for thermal control systems. Basically, a nanofluid is composed of a base fluid (such as water, methanol, ethanol, etc.) and metallic nanoparticles with sizes below 40 nm mixed, which can be copper, nickel, alumina, and they are held in suspension in the base fluid. Mixing techniques have been developed to guarantee

no sedimentation of the metallic nanoparticles, which could have a negative impact on the overall heat and mass transport.

The main effect caused by the addition of metallic nanoparticles is to improve the thermal conductivity of the fluid. By adding 5% of the working fluid's mass with nanoparticles, the liquid thermal conductivity can be increased by up to 20% [40]. Some researchers have already presented important contributions using nanofluids usually composed of water and copper nanoparticles with sizes around 25 nm [40,41], which all represent the recent advances on this new and innovating technology. The investigations performed so far have pointed to the potential in using nanofluids in several thermal control applications with great improvement on the heat transfer coefficient, especially when liquid single-phase thermal control has been used. It is important to mention that investigations performed so far utilizes regular pumping devices to transport the nanofluid throughout the loop. However, very little is known about nanofluids application in devices such as heat pipes and loop heat pipes (LHPs) that require the generation of capillary forces to drive the working fluid [42]. In this last case, the capillary evaporator presents a porous wick structure with fine pores and the interaction with the nanofluid needs to be better investigated. Considering that the fluid's viscosity will also be affected by the addition of solid nanoparticles in the base fluid, the overall pressure drop can potentially increase and limit the operation of capillary pumped systems.

Few works have been presented related to nanofluids application in LHPs so far, but show the potential of this line of research in the future. Mishkinis et al. [43] presented the analysis of a LHP operating with gold nanoparticles, which did not show any major improvement. Riehl [42] also presented an investigation on nanofluids applied to LHPs, which showed that since nanoparticles are carried with the working fluid, more flow restrictions are imposed to the device, also resulting on a higher pressure drop across the wick structure.

As pulsating heat pipes (PHPs) operate by means of slug/plug dynamics [44], the presence of solid nanoparticles can act as nucleation sites necessary to improve the nucleation boiling as well as improving the thermal conductivity of the fluid [44]. The base fluid and the solid nanoparticles, with sizes below 40 nm in diameter should be as pure as possible. They require to be chemically compatible to be used with heat pipes, PHPs and LHPs in order to avoid any kind of chemical reaction and non-condensable gases generation that could compromise the enhancement on the thermal conductivity. Investigations have already presented the increase on the liquid thermal conductivity of the nanofluid when compared with the pure substance by as much as 20% (depending on the nanoparticle material), when a mass fraction of up to 5% of nanoparticles were added [39, 45-48].

One of the most important parameters for a reliable nanofluid is stabilization of nanoparticles in the base fluid, which is related to the homogenization of nanoparticles. In this case, the nanofluid shall keep its nanoparticles stable in the base fluid without presenting sedimentation and/or nanoparticle aggregation as time passes. When nanofluids are kept stable during their lifetime, the thermal conductivity and thermal enhancement ratios are kept stable as well.

For a reliable and stable nanofluid, one should observe the following important characteristics:

1.   Nanoparticles dispersion, which means nanoparticles evenly dispersed in the base fluid;

2.   Surface charge, which requires the control of the zeta potential.

In the literature, it is possible to identify the three most common methods to obtain a reliable stabilization and avoid clogging and sedimentation of nanoparticles [49,50]:

1) Addition of surfactant or activator;

2) Modification of nanoparticle surface chemistry, it means surface charge changes;

3) Ultra sonication for nanoparticles in agglomeration process.

Some authors have applied all the three methods on their studies, while there are some authors using only the combination of two. However, there are some authors applying only one of the methods. As there is no standard guideline for application of one, two or even the three nanofluid stabilization methods, each author decides which method or all three methods that will better satisfy their experiments conditions [51,52]. Such considerations require further investigations as it is not possible to clearly state which method is more effective among all three. Also, when comparisons are made among thermal enhancement levels obtained from different experiments, it is recommended to verify which method was used in nanofluid preparation for an improved investigation. However, due to the lack of standard guidelines and more data, some authors do not mention their nanofluid preparation methods, which indeed make a proper comparison impossible.

Even though several issues require proper addressing in order to better evaluate the potential improvements when using nanofluid, some investigations have already been made on the analysis of the impact of nanofluids on the performance of heat pipes and LHPs [8,50,53-60]. From the results, it is clear that the use of nanofluids cause a gain on the performance of heat pipes and LHPs especially when considering that they can lower the heat source temperature significantly. The direct enhancement is related to the heat transfer coefficient upon using nanofluids. However, the increase on the fluid's viscosity causes an increase on the pressure drop that requires attention by the designer [50]. There are however, several variables that need to be properly investigated and their effects on the nanofluid impact as a potential working fluid to enhance the thermal control require further evaluation. The available models that have been presented to predict the nanofluid effects on the thermal management process have divergent results, either for those applied to predict the thermal conductivity or viscosity [61]. Great contributions have been made by the investigations of several nanofluids, such as water-copper, water-alumina and ferrofluidic [62-64]. Most importantly, upon applying nanofluids to heat pipes, there is a significant improvement on their thermal behavior as presented by several investigations [56,57,60], where it was verified that the heat pipe could operate with lower temperatures at the heat source when compared to the operation with the base fluid only.

Conclusions

From this brief review, the conclusions that can be taken show that even with the domain of the technology involving heat pipes and loop heat pipes, great contributions to the enhancement of their thermal behavior and applications can be done. The following are the most important considerations to be made.

Heat pipes, as considered by many thermal specialists as a "commodity", can be potentially applied on the thermal control of PCBs and structures, especially those related to military, surveillance and industrial areas. They have proved their capability on promoting

the thermal management of new electronic devices with remarkable results and should continue to be applied on new thermal systems designs, in order to meet the temperature requirements for new projects; Loop heat pipes, despite their outstanding capability on promoting the thermal management of large quantities of heat and dissipating it over long distances, a fine control on their operational temperature is usually required. Methods using pressure regulator valves (3-way and 2-way) have been tested with remarkable results on the temperature control resolution, however, technological issues still require attention especially those involving leak control and locked stem due to accumulation of powder released from the primary wick (in case of sintered metallic wicks). Another method using a pressure control located at the compensation chamber seems to be a promising technology, but still lacks from long term operation results to verify its reliability.

The application of PHPs for the thermal management of high power electronic devices has presented to be a promising technology, which enables high heat rejection with considerably low costs. Future projects where a more flexible solution is needed for the thermal control of electronics devices shall consider the presented results. Variations on the thermal designs can be applied for the use of PHPs for several setups where the thermal control becomes necessary, in order to promote their heat dissipation according to the projects' requirements. More flexibility on the design of such applications can be reached with the proposed solution, along with more compact equipment also resulting in less weighted devices, presenting reliable operation due to the use of well-known aerospace thermal control solutions.

Nanofluids can also be considered a promising solution to enhance the thermal control capability of several systems, as it has proved to increase the thermal conductivity of the working fluid by adding metallic nanoparticles to a base fluid, especially those using heat pipes and LHPs.

However, considerations must be done upon using nanofluids especially related to the increase on the overall pressure drop that could compromise the operation of capillary pumped systems. Also, reliable methodologies for mixing the nanoparticles in the base fluid are still required, where the most important parameter would be not adding any other substance to the nanofluid to avoid chemical incompatibilities. On the same way, more reliable models to predict the thermal and viscosity influences of the working fluid by adding the nanoparticles need to be developing to assist future projects.

The application of heat pipes and LHPs technologies on the thermal control of PCBs and, structures and other systems that require a more elaborate thermal represents a potential solution for new designs that require high heat density management. However, the thermal design should consider not only the use of such technologies as a miracle solution, but must visualize them as additive solutions for the entire thermal problem.

References

1. Riehl RR, Cachuté L (2013) Thermal control of surveillance systems using pulsating heat pipe and heat pipes. 11th International Energy Conversion Engineering Conference, San Jose, CA, USA.

2. Riehl RR (2013) Thermal performance and development of a dual evaporator loop heat pipe heat pipe science and technology. International Journal 4:105-117.

3. Silva D, Riehl RR (2014) Development of heat pipes operating at mid-level temperature range applied for industry defense and aerospace. 12th International Energy Conversion Engineering Conference, Cleveland, OH, USA.

4. Riehl RR (2015) Passive thermal management of surveillance systems using

pulsating heat pipes IX Minsk. International Seminar on Heat Pipes, Heat Pumps, Refrigerators, Power Sources. Minsk, Belarus.

5. Reay DA, Kew PA (2006) Heat pipes-theory design and applications (5thedn). Elsevier's Science & Technology.

6. Chan CW, Siqueiros E, Ling-Chin J, Royapoor M, Roskilly AP (2015) Heat utilization technologies: A critical review of heat pipes. Renewable and Sustainable Energy Reviews 50: 615-627.

7. Faghri A (1995) Heat pipe science and technology. Taylor and Francis.

8. Riehl RR (2016) Development of copper-methanol heat pipes: Thermal Performance Evaluation for Electronics Cooling Heat Powered Cycles Conference, Nottingham, UK.

9. Akachi H, Polasek F, Stulc P (1996) Pulsating heat pipes. Proceedings of the 5th International Heat Pipe Symposium Melbourne, Australia. 208-217.

10. Tong BY, Wong TN, Ooi KT (2001) Closed-loop pulsating heat pipe. Applied Thermal Engineering 21: 1845-1862.

11. Yu W, Choi SUS (2003) The role of Interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated Maxwell model. J Nanoparticle Research 5:167-171.

12. Delil AAM (2001) Pulsating and oscillating heat transfer devices in acceleration environments from microgravity to super gravity.

13. Lin L, Ponnapan R, Leland J (2001) Experimental investigation of oscillating heat pipes. AIAA J Thermophysics and Heat Transfer 15: 395-400.

14. Yang H, Khandekar S, Groll M (2008) Operational limit of closed loop pulsating heat pipes. Applied Thermal Engineering 28: 49-59.

15. Supirattanakul P, Rittidech S, Bubprachot B (2011) Application of a closed-loop oscillating heat pipe with check valves (CLOHP) on performance enhancement in air conditioning system. Energy and Buildings 43: 1531-1535.

16. Mameli M, Marengo M, Zinna S (2012) Numerical model of a multi-turn closed loop pulsating heat pipe: Effects of the local pressure losses due to meanderings. International J of Heat and Mass Transfer 55: 1036-1047.

17. Riehl RR, Santos N (2012) Water-copper nanofluid application in an open loop pulsating heat pipe. Applied Thermal Engineering 42: 6-10.

18. Liu X, Chen Y, Shi M (2013) Dynamic performance on start-up of closed loop pulsating heat pipes (CLPHPs). International J of Thermal Sciences 65: 224-233.

19. Taslimifar M, Mohammadi M, Afshin H, Saidi MH, Shafii MB (2013) Overall thermal performance of ferro-fluidic open loop pulsating heat pipe: An experimental approach. International J of Thermal Sciences 65: 234-241.

20. Sarno C (2012) Application of Phase change systems in avionics. Proceedings of the 16th International Heat Pipe Conference, Lyon, France.

21. Berder O, Barremaecker L (2012) Two-phase cooling system for aircraft actuators. Proceedings of the 16th International Heat Pipe Conference, Lyon, France.

22. Miyazaki Y, Kawai H, Iwata N, Ogawa H (2012) Operating limit of oscillating heat pipe. Proceedings of the 16th International Heat Pipe Conference, Lyon, France.

23. Ouchi M, Abe Y, Hayashi T, Sato M, Iimura K (2012) Development of high performance and high functionalized heat pipes. Proceedings of the 16th International Heat Pipe Conference, Lyon, France.

24. Riehl RR (2014) Current developments on pulsating heat pipes and dual-evaporators loop heat pipes. 18th Workshop on Thermophysics - Applications in Microgravity - The Aerospace Corporation, El Segundo, CA, USA.

25. Tulin DV, Tulin ID, Serov GP, Shabarchin AF (2011) In-flight experience of heat pipe based thermal control system for geostationary orbiting service module. VIII Minsk International Seminar on Heat Pipes, Heat Pumps, Refrigerators, Power Sources. Minsk, Belarus.

26. Goncharov K (2011) Development and application of space radiators with loop heat pipes. VIII Minsk International Seminar Heat Pipes Heat Pumps Refrigerators Power Sources Minsk Belarus: 12–15.

27. Riehl RR, Santos N (2008) Loop heat pipe performance enhancement using primary wick with circumferential grooves. Applied Thermal Engineering 28: 1745-1755.

28. Nagano H, Ku J (2007) Capillary limit of a multiple-evaporator and multiple-condenser miniature loop heat pipe. J Thermophysics and Heat Transfer 21:694-701.

29. Maydanik YF (2005) Review loop heat pipe. Applied Thermal Engineering 25: 635-657.

30. Goncharov K, Kochetkov A, Buz V (2005) Development of loop heat pipe with pressure regulator International. Two-Phase Thermal Control Technology Workshop. LA, USA.

31. Mishkinis D, Kulakov A, Romera F, Gregori C, Torres A (2011) Thermal control of loop heat pipe with pressure regulating valve. VIII Minsk International Seminar on Heat Pipes, Heat Pumps, Refrigerators, Power Sources. Minsk, Belarus.

32. Hartenstine JR, Anderson WG, Walker KL (2012) Passive control of an LHP with thermal control valve for lunar lander application. Thermal & Fluids Analysis Workshop, Jet Propulsion Laboratory Pasadena. CA, USA.

33. Joung W, Gam KS, Kim YG, Yang I (2015) Hydraulic operating temperature control of a loop heat pipe. International J and Heat and Mass Transfer 86: 796-808.

34. Delil AAM, Maydanik YF, Gerhart C (2003) Development of different novel loop heat pipes within the ISTC-1360 Project. International Conference on Environmental Systems – 33rd ICES Vancouver.

35. Riehl RR (2006) Extensive development of the loop heat pipe technology. International Conference on Environmental Systems – 36th ICES Norfolk Virginia.

36. Ku J, Hoang T (1997) Testing of a capillary pumped loop with multiple parallel starter pumps. International Conference on Environmental Systems – 27th ICES Lake Tahoe NV.

37. Nagano H, Nishigawara M, Kaya T, Riehl RR, Nagai H (2010) Small loop heat pipe with plastic wick for electronics cooling. 2nd International Symposium on Thermal Design and Thermophysical Properties for Electronics and Energy. Tsukuba.

38. Ku J, Birur GC (2001) Testing of a loop heat pipe with two evaporators and two condensers. International Conference on Environmental Systems – 31st ICES Orlando, FL.

39. Okutani S, Nagano H, Okazaki S, Ogawa H, Nagai H (2014) Operating characteristics of multiple evaporators and multiple condensers loop heat pipe with polytetrafluoroethylene wicks. J of Electronics Cooling and Thermal Control 4: 22-32.

40. Koo J, Kleinstreuer C (2006) A new thermal conductivity model for nanofluids. J Nanoparticle Research 6: 577-588.

41. Chein R, Huang G (2005) Analysis of micro channel heat sink performance using nanofluids. Applied Thermal Engineering 25: 3104-3114.

42. Riehl RR (2007) Performance evaluation when using nanofluids in loop heat pipe and pulsating heat pipe in: Proceedings of the 37th International Conference on Environmental Systems (ICES) Chicago, IL, USA.

43. Mishkinis D, Corbierre MK, Wang G, Nikanpour D (2006) Nanofluids as working media for loop heat pipes in: Proceedings of the 36th International Conference on Environmental Systems (ICES) Norfolk VA USA.

44. Yu W, Choi SUS (2003) The role of Interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated Maxwell model. J Nanoparticle Research 5: 167-171.

45. Xuan Y, Li Q (2000) Heat transfer enhancement of nanofluids. International J Fluid Flow 21: 158-164.

46. Xie H, Wang J, Xi T, Liu Y, Ai F et al. (2002) Thermal conductivity enhancement of suspensions containing nanosized alumina particles. J Applied Physics 91: 4568-4572.

47. Xuan Y, Roetzel W (2000) Conceptions for heat transfer correlation of nanofluids. International J Heat and Mass Transfer 43: 3701-3707.

48. Wen D, Ding Y (2005) Experimental investigation into the pool boiling heat transfer of aqueous based-alumina nanofluids. J Nanoparticle Research 7: 265-274.

49. Riehl RR (2006) Analysis of loop heat pipe behaviour using nanofluid. Heat Powered Cycle International Conference. Newcastle, UK.

50. Zhang Y (2013) Nanofluids research development and applications. (1stedn) Nova Science Inc., New York.

51. Ghadimi A, Saidur R, Metselaar HSC (2011) A Review of nanofluid stability properties and characterization in stationary conditions. International J of Heat and Mass Transfer: 4051-4068.

52. Liu ZH, Zhu QZ (2010) Application of aqueous nanofluids in a horizontal mesh heat pipe. Energy Conversion and management Elsevier: 292-300.

53. Wang PY, Chen XJ, Liu ZH, Liu YP (2012) Application of nanofluid in an inclined mesh wicked heat pipes. Thermochimica Acta Elsevier: 100-108.

54. Kumaresan G, Venkatachalapathy S, Arsivatham LG, Wongwises S (2014) Comparative Study on heat transfer characteristics of sintered and meshes wick heat pipes using CuO nanofluids. International Communications in Heat and Mass Transfer. Elsevier: 208-215.

55. Liu ZH, Li YY, Bao R (2010) Thermal performance of inclined grooved heat pipes using nanofluids. International J of Thermal Sciences Elsevier: 1680-1687.

56. Wang GS, Song B, Liu ZH (2010) Operation characteristics of cylindrical miniature grooved heat pipe using aqueous CuO nanofluids. Experimental Thermal and Fluid Science Elsevier: 1415-1421.

57. Kumaresan G, Venkatachalapathy S (2012) A review on heat transfer enhancement studies of heat pipes using nanofluids. Frontiers in heat pipes.

58. Chien HT, Tsai CI, Chen PH, Chen PY (2003) Improvement on thermal performance of a disk-shaped miniature heat pipe with nanofluid. ICEPT 5th

International Conference on Electronic Packaging Technology - Proceedings.

59. Yang XF, Liu ZH, Zhao J (2008) Heat transfer performance of a horizontal micro-grooved heat pipe using CuO nanofluid. J Micromechanics and Microengineering.

60. Marcelino E, Oliveira D, Riehl RR (2016) A review on thermal performance of CuO-water nanofluids applied to heat pipes and their characteristics. ITherm - The Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems. Las Vegas, NV, USA.

61. Venkatachalapathy S, Kumaresan G, Suresh S (2015) Performance analysis of cylindrical heat pipe using nanofluids -An experimental study. International J Multiphase Flow 72: 188-197.

62. Durga Prasad PV, Gupta AVSSKS, Sreeramulu M, Syam Sundar L, Singh MK et al. (2015) Experimental study of heat transfer and friction factor of Al_2O_3 nanofluid in U-tube heat exchanger with helical tape inserts. Experimental Thermal and Fluid Science 62: 141-150.

63. Ghanbarpour M, Nikkam N, Khodabandeh R, Toprak MS, Muhammed M (2015) Thermal performance of screen mesh heat pipe with Al2O3 nanofluid. Experimental Thermal and Fluid Science 66: 213-220.

64. Taslimifar M, Mohammadi M, Afshin H, Saidi MH, Shafii MB (2013) Overall thermal performance of ferrofluidic open loop pulsating heat pipes: An experimental approach. International J of Thermal Sciences 65: 234-241.