Development of Heat Pipes Operating at Mid-Level Temperature Range Applied for Industry, Defense and Aerospace

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Heat pipes are two-phase heat transfer devices with high thermal capacity, able to transport large quantities of heat with little difference between the temperature of the evaporation and condensation sections, presenting a highly efficient heat transfer process. This technology has found increasing applications in improving the thermal performance and heat dissipation of electronics and other components in aerospace missions (satellites and spacecrafts) and it is widely used today. Also, heat pipes have found applications to improve the efficiency of heat exchangers in many industrial environments. The use of heat pipes in heat exchangers allows the development of more compact and efficient equipments when compared to traditional heat exchangers. For some applications, such as heat recovery in industrial process, the use of the heat pipes on heat exchangers presents to be rather interesting due to an increased efficiency along with more compact equipments. Mid-level temperature heat pipes have found applications both in aerospace and industry, and their development has found interest in those areas. Focusing this scenario, this paper presents and investigation on the operation of heat pipes at designed for medium level temperatures (up to 200 °C) using water as working fluids. Testing results of three different configurations of heat pipes using those working fluids have shown reliable operation when cyclic heat loads are applied, with fast responses. The obtained results show that the heat pipes' configurations investigated are able to reach thermal conductances up to 18 W/°C and could be used in several industrial (for heat recovering systems) and aerospace applications when those levels of temperature are required.

Nomenclature

G_{evap_cond}	=	Thermal conductance (evaporator – condenser) (W/°C)
HP1	=	Heat Pipe 1
HP2	=	Heat Pipe 2
HP3	=	Heat Pipe 3
Q	=	operating power (W)
T_{evap}	=	average evaporator temperature (°C)
T_{adiab}	=	average adiabatic temperature (°C)
T_{cond}	=	average condenser temperature (°C)
T_{evap1}	=	evaporator temperature experimental 1 (°C)
T_{evap2}	=	evaporator temperature experimental 2 (°C)
T_{adiab1}	=	adiabatic temperature experimental l (°C)
T_{adiab2}	=	adiabatic temperature experimental 2 (°C)
T_{cond1}	=	condenser temperature experimental 1 (°C)
T_{cond2}	=	condenser temperature experimental 2 (°C)

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I. Introduction

A very important feature of the heat pipe is the ability to transport large amounts of energy over its length with a small temperature drop, which occurs by means of liquid evaporation at the its evaporator (heat source), vapor flow through its core, vapor condensation at the condenser (heat sink) and liquid return to the evaporator by capillary force. If the heat pipe envelope and its wick have a small heat capacity there is a basic possibility to realize the transient operation of heat pipe in solid sorption machines when there is a necessity to heat and cool the sorbent bed as quickly as possible[1]. Owing to the simplicity of design, and ease of manufacture and maintenance, these devices have found applications in many areas, including solar energy systems, heat recovery systems, air conditioning systems, cooling of energy storage and electronic equipment thermal control, industrial applications and aerospace hardware thermal management.

The heat pipe has been, and currently is being, studied for a wide variety of aplications, covering almost the complete spectrum of temperatures encountered in heat transfer processes. Heat pipes have been applied in many ways since their introduction in 1964. Depending on their intended use, heat pipes can operate over a temperature range from 4 to 3000 K. Heat pipes have been considered as promising means for effective heat transfer in energy transport and storage systems in a medium-high temperature range, such as those found in concentrated solar thermal energy systems. In all cases, their applications can be divided into three main categories: separation of heat source and sink, temperature equalization, and temperature control. Due to their extremely high thermal conductivity, heat pipes can efficiently transport heat from a concentrated source to a remotely mounted sink.[2]

Energy prices are ever higher now, and the interest for energy efficiency is ever greater. The use of heat pipes in energy-efficient systems has not been fully exploited. This is due in part to the perceived high cost of some heat pipes (such as liquid metal heat pipes), a lack of appreciation of their capabilities and limitations, as well as an aversion to risk-taking by industry and potential users.[3]

Due to their high heat transfer capabilities with no external power requirements, heat pipes are being used in heat exchangers for various applications. In the power industry, heat pipe heat exchangers are used as primary air heaters on new and retrofitted boilers. The major advantages of heat pipe heat exchangers compared to conventional heat exchangers are that they are nearly isothermal and can be built with better seals to reduce leakage. Heat pipe heat exchangers can serve as compact waste heat recovery systems which require no power, low pressure drop and are easy to install on existing lines.[2]

Generally speaking, heat pipes are used in applications requiring a continuous heat transfer in single direction, and for steady state conditions or under weak variations of operating conditions. Obviously, heat pipes can work only with a positive temperature difference between its evaporator and condenser parts. Heat transfer is stopped when this gradient becomes zero or is reversed.[4] Heat losses often occur in building air-conditioning systems. Sensible and latent heat is discharged to the surrounding environment unconsciously, therefore the application of heat pipes in such equipments shall be considered for the sake of improving the efficiency on those equipments, reducing the costs of electricity use. Waste energy can be recovered, hence, by the installation of heat transfer equipment for the recovery of some of the wasted heat, such as heat pipes.[5]

Heat pipes are very flexible systems with regard to effective thermal control. They can easily be implemented as heat exchangers inside sorption and vapor-compression heat pumps, refrigerators and other types of heat transfer devices, to ensure the energy saving and environmental protection[1].

Heat exchangers made of heat pipes are one of the most effective devices for heat recovery. The operation of a heat pipe involves phase changes (i.e., condensation and evaporation) and so large amounts of heat can be transferred between the ends of the tube. In practice, the thermal conductance of a heat pipe may be over 500 times than that of the best available thermal conductors[5].

Many applications have indicated the use of heat pipes for aerospace and also there are strong developments for ground applications of heat pipes for surveillance equipments. Such developments have shown remarkable performance during the operation of such equipments[6] as well as their potential use in mid-level temperature ranges (between 100 and 200 ^{o}C) due to the need for high performance thermal control observed in current projects. Also, surveillance systems being designed today are focusing on those temperature levels for better performance, which have been designed and implemented in satellites.

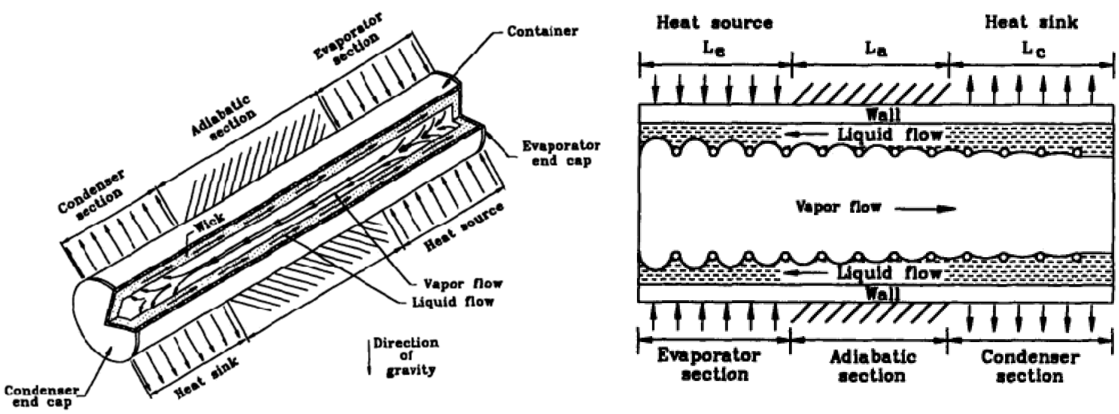
Focusing on the potentiality of using heat pipes for industrial, defense and aerospace applications, this paper presents an experimental study and development regarding the thermal performance of heat pipes using water as the working fluid due to the temperature range at which the heat pipe needs to operate. The main objective is to test and compare the performance of three heat pipes, using stainless steel screen mesh with different characteristics as the wick structure, in order to evaluate the their start-ups behavior, as well as a better understanding of their thermal performances regarding transient and steady-state operation that can be obtained, so their application as thermal management devices can be refined and applied to the current considered thermal control designs.

II. Heat Pipe Invention and Principles of Operations

Of the many different types of systems which transport heat, the heat pipe is one of the most efficient systems known today. The advantage of using a heat pipe over other convencional methods is that large quantities of heat can be transported through a small cross-sectional area over a considerable distance with no additional power input to the system. Furthermore, design and manufacturing simplicity, small end-to-end temperature drops, and the ability to control and transport high heat rates at various temperature levels are unique features of heat pipes.[2]

The principle of the heat pipe was conceived in 1944 by Glauber and in 1962 by Trefethen. However, it was not widely publicized until 1964 when Grover and his colleagues at the Los Alamos Scientific Laboratory independently reinvented the concept. Grover also demonstrated its effectiveness as a high-performance heat transmission device, named it the "heat pipe", and developed its applications.[7]

The operation of a heat pipe is easily understood by using a cylindrical geometry, as shown in Fig. 1(a). The components of a heat pipe are a sealed container, a wick structure, and a small amount of working fluid which is in equilibrium with its own vapor (saturated condition). The length of the heat pipe is divided into three parts: evaporator section, adiabatic section and condensador section. Heat applied to the evaporator section by an external source is conducted through the pipe wall and wick structure, where it vaporizes the working fluid. The resulting vapor pressure drives the vapor through the adiabatic section to the condenser, where the vapor condenses, releasing its latent heat of vaporization to the provided heat sink.[2] Depletion of liquid by evaporation causes the liquid-vapor interface in the evaporator to enter into the wick surface (Fig. 1(b)) and capillary pressure is developed there. This capillary pressure pumps the condensed liquid back to the evaporator to complete the cycle. That is, the heat pipe can continuously transport the latent heat of vaporization from the evaporator section to the condenser without drying out the wick. This process will continue as long as the flow passage for the working fluid is not blocked and a sufficient capillary pressure is maintained.[7]



(a) (b)

Figure 1. (a) Components and principle of operation of a convencional heat pipe; (b) Development of capillary pressure at liquid-vapor interface.[2]

The amount of heat that can be transported as latent heat of vaporization is usually several orders of magnitude larger than that which can be transported as sensible heat in a conventional convective system. The heat pipe can therefore transport a large amount of heat with a small unit size. The temperature drop in a heat pipe is equal to the sum of the temperature drops at the evaporator, vapor passage and condenser. Because of their thin wick structure and small temperature drop for their vapor flow, heat pipes have thermal characteristics with orders of magnitude better than any known solid material.[7]

III. Heat Pipe and Experimental Apparatus

In order to investigate the potential application of heat pipes for the purpose of this work, three heat pipes were designed and manufactured for experimental tests using water as the working fluid, operating at mid-range temperatures. To design the heat pipes, a proprietary computational code was used[8], which has been continuously validated over the last 15 years with many other designs of heat pipes. The heat pipes were built with stainless steel 316L by its wide acceptance and application in industry, defense and aerospace applications and the compatibility with water. The characteristics of all three heat pipes are presented in Table 1.

Each heat pipe was designed using screen mesh as a wick structure. The wick structure has two functions in heat pipe operation: It is both the vehicle and the mechanism through which the working fluid returns from the condenser to the evaporator and it ensures that the working fluid is evenly distributed circumferentially over the entire evaporator surface.[9] The selected wick structure depends on the project and has interesting features, because its purpose is to generate capillary pressure to transport the working fluid from the condenser to the evaporator. In this case, according to the Young-Laplace relation, the smaller the pores size the better because the capillary pressure will be greater. However, it is responsible to increase the pressure drop of fluid across the wick structure, which can be a serious limitation for the heat pipe operation, especially for low permeability wicks.

Table 1. Geometric Characteristics of the Heat Pipes (HP1, HP2 and HP3).

	HP 1	HP 2	HP 3
Evaporador length (m)	0.25		
Adiabatic length (m)	0.9		
Condenser length (m)	0.35		
Total length (m)	1.5		
Working Fluid	Water (deionized)		
Tube material	316L - SS		
Outer diameter (m)	0.0191		
Inner diameter (m)	0.0135		
Screen mesh wick material	316L - SS		
Screen mesh number	400	200	100
Wick layers	3		
Wick Porosity %	63.0	64.0	68.0
Wick Permeability (m^2)	$2x10^{-9}$	$6x10^{-9}$	$4x10^{-8}$
Mean pore radius (m)	$3.18x10^{-5}$	$6.35x10^{-5}$	$1.27x10^{-4}$
Operating temperature range (°C)	22 - 160		
Operating Power (W)	25 - 125		

Heat was applied to each heat pipe to observe, at first, the start-up effect. Once the temperatures for the start-up power have reached stability (presenting variation of ± 1°C during the last 20 minutes), the power was changed according to the testing profile, following the sequence to temperature stabilization. Once all power levels were tested, the power was switched off and waited for temperature equalization with ambient. All tests were performed with the heat pipes at horizontal orientation in order to minimize the gravity effect on their operation.

The experimental test bench consisted of three heat pipes, DC power supplies controller (Agilent N5749A) and a National Instrument SCXI data acquisition system controlled by LabVIEW. Temperatures were measured at various positions at the tubes wall, using six Omega T-type thermocouples (accuracy of ±0.3°C at 100°C) per tube, in two locations of the evaporation, adiabatic and condenser sections. Another thermocouple was used for measuring the ambient temperature. Heat was applied to the heat pipes using an electric resistance wrapped around the evaporation section and connected to the digital DC power supply. The condenser was open to the ambient air, exchanging heat by natural convection. The evaporation and adiabatic sections were insulated with glass wool blanket to minimize the heat loss to the environment. All tests were performed at controlled room conditions, with temperature of 22°C ± 2°C. Thus, oscillations on the ambient temperature were expected due to the air conditioning on/off operation. Figure 2 presents the test bench with the heat pipes used during this investigation. Figure 3 presents the thermocouples' locations on the heat pipes.

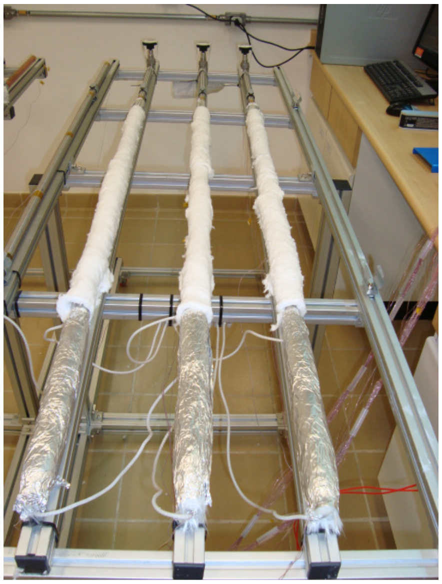


Figure 2. Experimental test bench.

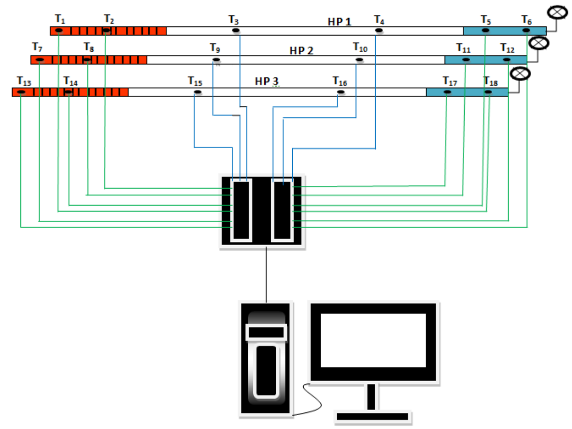


Figure 3. Positions of thermocouples on the heat pipes and data acquisition system.

IV. Results and Discussion

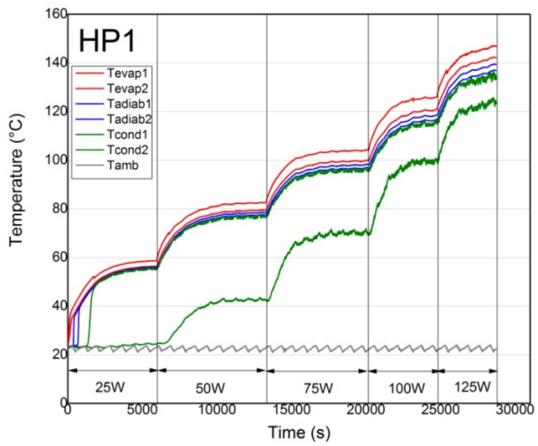
With the conducted tests, it was possible to verify the temperatures along the heat pipes in order to obtain temperature profiles. As might be expected, there was an increase on the temperature at the highest rate of heat transfer to the evaporator, but all three heat pipes presented stable operation, as observed on the following figures. Figure 4 shows the temperature profiles for the heat pipes (HP1, HP2 and HP3), for tests at horizontal orientation for possible evaluation of thermal performance for power levels of 25, 50, 75, 100 and 125 W.

In the results shown in Figure 4, HP2 has a smaller temperature difference in evaporator section, adiabatic and condenser as compared with the HP1 and HP3. The oscillations observed during the start-up can be considered normal when water is used as the working fluid, as the effects regarding the meniscus formation and equilibrium between the evaporation and condensing interfaces must be generated. Once established, the heat pipes operation become more stable with little or none oscillations as the heat applied to the evaporator changes.

With the results of experimental tests, the temperature profiles were obtained for an evaluation of three heat pipes (HP1, HP2 and HP3) performance. A preliminary analysis is made for the startup operation for pipes in horizontal orientation. It can be seen that the HP2 begins its operation in less time when compared to the HP1 and HP3, as the initialization occurs when the last condenser thermocouple senses the presence of the flow of steam. There is a significant difference in relation to the condenser temperature and evaporator temperature when applied adiabatic initial power, but for the completion of the operation to the power of 125 W, the temperatures of the evaporator, adiabatic and condenser are very close for all heat pipes.

For a better analysis, the thermal conductance was calculated for HP1, HP2 and HP3 tubes with the experimental results. It is defined as the ratio of the heat applied (Q) to the device by the temperature difference between the evaporator (T_{evap}) and condenser (T_{cond}), with deviation of ± 1,27% for HP1, ± 2,06% for HP2 and ±1,22% for HP3, being given by the following relationship

$$G_{evap\_cond} = \frac{Q}{T_{evap} - T_{cond}} \tag{1}$$



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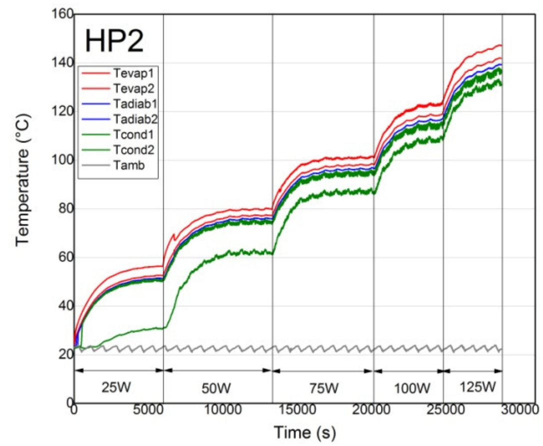

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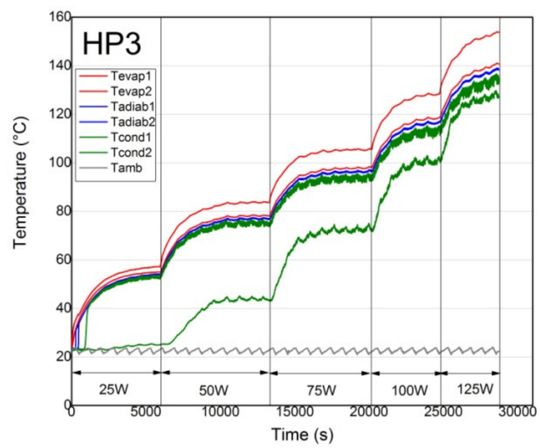
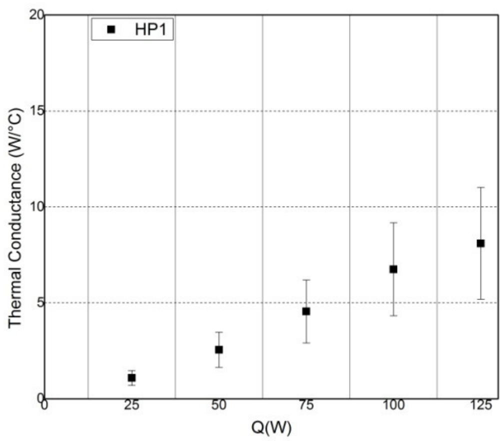


(c)

Figure 4. Temperature profiles for the heat pipes, operating horizontally: (a) HP1, (b) HP2 and (c) HP3.

Figure 5 presents the results of the thermal conductance obtained from Eq. (1) for a better analysis of the heat pipes thermal operation. For best thermal performance, an adjustment to refine the mathematical model[8] used to design the heat pipes was necessary. The adjustment is represented by the error bars for the thermal conductances calculation.

The range obtained for the tests (horizontal orientation) were between 1.0 and 8.2 W/°C for HP1, 1.45 and 14.0 W/°C for the HP2 and 1.0 and 7.7 W/°C for HP3. The adjustment done using the thermal conductances obtained during the experimental tests indicated variations of $\pm$36%, $\pm$25% and $\pm$51% for HP1, HP2 and HP3, respectively. The use the adjustment to refine the model to design the heat pipes aims its use in applications indicated, with important information for integrated simulation of heat pipes with heat exchangers and other aerospace devices. The results obtained for the thermal conductance makes possible to identify that HP2 has higher thermal conductance due to low temperature difference between the evaporator and the condenser, resulting on an improved thermal performance compared with the HP1 and HP3. The highest thermal conductances according to the experimental results for HP2 was 14.0 W/°C and adjusted results of approximately 17.35 W/°C. The best thermal performance verified for HP2 was due to the use of screen mesh #200 as a porous structure as compared with the screen mesh #400 used for HP1 and #100 used for HP3. The use of this screen mesh presented to be the best combination of capillary pressure generation together with smaller pressure drop across HP2 and working fluid selection, which better fits the thermal performance for the heat pipe design according to the thermal behavior expected for this application.



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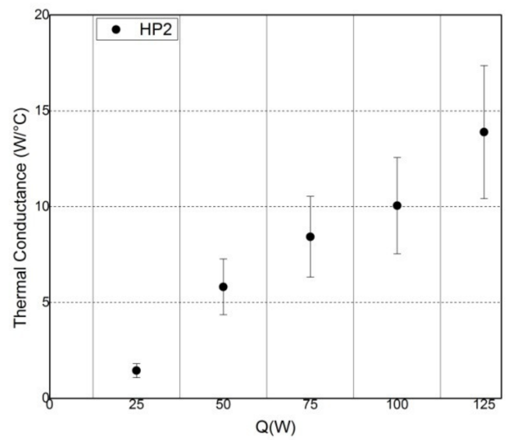

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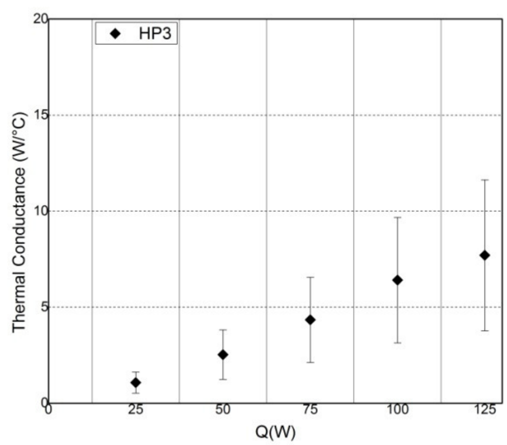

(c)

Figure 5. Thermal conductances: (a) HP1; (b) HP2; (c) HP3.

V. Conclusion

Experimental results heat pipes that use water as the working fluid, with 400, 200 and 100 mesh screen were presented as a porous structure. The results obtained with the experimental results, the adjustment for was calculated. The following conditions were analyzed:

1. Lower thermal conductances for the HP1 and HP3, due to high temperature differences between the evaporator and the condenser;
2. HP1 and HP3 condenser temperatures were below the temperatures observed for the condenser of HP2, obtaining a higher difference between the evaporator and the condenser, resulting on higher thermal conductances when compared to HP2;
3. HP2 presented startups without oscillations of temperatures, getting the temperature of the evaporator, adiabatic and condenser very close during the entire operation of the heat pipe, confirming better performance when analyzing its thermal conductances;
4. The HP2 presents higher thermal conductances when compared to HP1 and HP3 for power levels above 50 W, since temperatures are very close for the evaporator and condenser, confirming the efficiency of the thermal device in transferring heat from one end to another with smaller temperature differences.

For a better assessment of the operation, additional investigations are undergoing to better assess the overall performance of heat pipes, for use in aplications described on this investigation. However, due to their isothermal characteristics and fast response to heat loads variations at different applied loads, the design used for HP2 have been applied on the thermal management for industrial applications as well as defense/surveillance purposes. Future reports will present the results for devices operating fully integrated to their thermal management setup.

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