EXPERIMENTAL INVESTIGATION OF WATER-STAINLESS STEEL HEAT PIPES OPERATING IN POWER CYCLES WITH DIFFERENT INCLINATIONS

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Abstract

Heat pipes have become highly reliable systems and since 1970's and this technology has been widely applied in various areas, such as heat exchangers, spacecraft thermal control and cooling systems for electronic components. This technology has found increasing application in improving the thermal performance 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 heat pipes on heat exchangers presents to be rather interesting due to its direct influence on increasing the efficiency, allowing a more compact design. In order to investigate the potential application of heat pipes for the purpose of this work, three stainless steel 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, which has been continuously validated over the last 15 years with many other designs of heat pipes.

INTRODUCTION

One of the most important subjects ultimately under global discussions have been the energy efficiency and energy optimization or even the proper energy management, therefore thermal energy efficiency augmentation also has been of great interest lately. Indeed the discussions for the augmentation of efficiency in thermal systems has meaningfully increased not only within the aerospace industry but also within the industry in a general manner (Silva et al, 2015).

The use of heat pipes was initially made by aerospace industry due to its high capacity of heat transport through capillary forces in microgravitational fields, but due to increasing of energy costs, industries started looking for energy saving alternatives and energy management solutions for better cost-benefit relations (Faghri, 1995). Therefore, the use of heat pipes represents one of those efficient solutions which industry is looking for. Stainless steel-water heat pipes operating at mid-level temperature range investigated in this paper represent one of the alternatives for several industry applications. A very important feature of the heat pipe is the ability to transport a large amount of energy over its length with a small temperature drop by means of liquid evaporation at the evaporator (heat source), vapour condensation at the condenser (heat sink) and liquid movement in the opposite direction inside a wick by capillary forces.

The operation of a heat pipe is easily understood by using a cylindrical geometry. 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. The length of the heat pipe is divided into three parts: evaporator section, adiabatic section and condenser 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 (Peterson, 1994; Faghri, 1995). The material selection and compatibility between wick and container as well as the working fluid are major factors in the design of heat pipes. Both copper heat pipes and stainless steel heat pipes present to have a good material compatibility level with water. (Reay and Kew, 2006).

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 (Vasiliev, 1995).

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 (Liu et al, 2006).

Focusing on the potentiality of using heat pipes for industrial applications, this paper presents an experimental study and development regarding the thermal performance of heat pipes using water as the working fluid, operating in power cycles, in the following inclination (tilt) angles: 0°, 30°, 60° and 90°. The main objective is to test three heat pipes, using stainless steel screen mesh with different characteristics as the wick structure, in order to evaluate the heat pipes start-ups as well as a better understanding of the thermal performance that can be obtained in order to be used in industry.

HEAT PIPE AND EXPERIMENTAL APPARATUS

Among the most used working fluids applied for heat pipes operating at moderate temperatures, water has been chosen. This choice is due to more favorable properties, such as high latent heat of vaporization, high surface tension, high thermal conductivity, good thermal stability and low viscosity. As water presents itself in the liquid phase at atmospheric conditions, its insertion in the heat pipe is a much simpler process when compared to other fluids. The selection of the working fluid must also be based on thermodynamic considerations, which are concerned with the various limitations to heat flow occurring within the heat pipe (Reay and Kew, 2006). The selection of 316L stainless steel housing for the heat pipes was done due to its potential application on food/pharmaceutical industries where such a material is required. Even though 316L SS and water are not fully compatible as non-condensable gases (NCGs) might be generated over the heat pipes lifetime, this is the most indicated combination and continuous evaluation on NCG has been done.

For this investigation, heat pipes were built basically using 3 layers of 316L stainless steel screen mesh, with geometric characteristics shown by Table 1, operating in power cycles. Additional details of their construction cannot be disclosed at this time due to some proprietary information. They were built according to numerical simulations performed with a proprietary computer code (Riehl, 2002), which has been applied to several other projects over the years. Constant validation of this software has been performed and it is considered reliable in face of the results presented.

Table 1 - Geometric characteristics of the heat pipes (HP1, HP2 and HP3).

Geometric Characteristics of the Experimental HP			
	HP 1	HP 2	HP 3
Evaporador/Adiabatic/Condenser/Total length (m)	0.25 / 0.9 / 0.35 / 1.5		
Working Fluid	Water		
Tube material	316L - SS		
Outside diameter (m)	0.01905		
Inside diameter (m)	0.0135		
Screen mesh material	316L - SS		
Screen mesh number	400	200	100
Number of screen mesh layers	3		
Wick Porosity (%)	0.63	0.73	0.68
Wick Permeability (m^2)	$1.25x10^{-11}$	$7.75x10^{-11}$	$2.40x10^{-10}$
Mean pore radius (m)	$3.18x10^{-5}$	$6.35x10^{-5}$	$1.27x10^{-4}$
Operating temperature range (°C)	22 - 160		
Operating Power (W)	25 - 125		

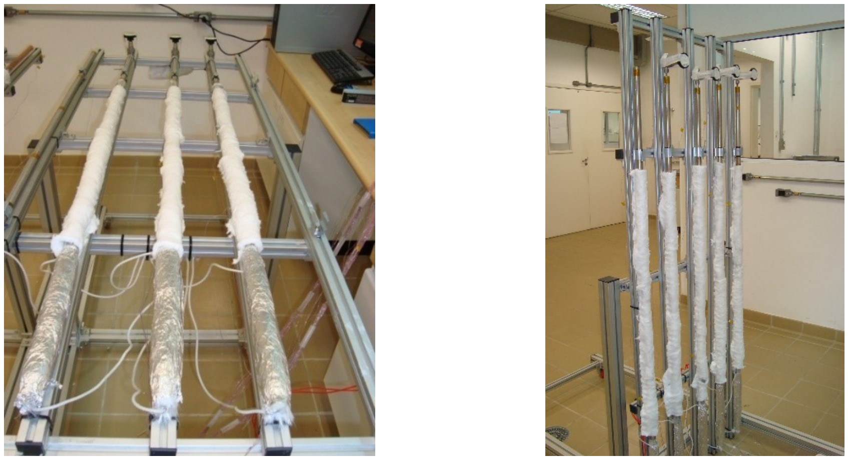

Figure 1 - Heat pipes experimental test rig.

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.

The experimental test bench consisted of three heat pipes, a DC power controller (Agilent N5749A) and a National Instrument SCXI data acquisition system controlled by LabVIEW, as presented by Fig. 2. Temperatures were measured at various positions at the tube 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 issued for measuring the ambient temperature. The condenser was open to the ambient air, exchanging heat by natural convection. 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.

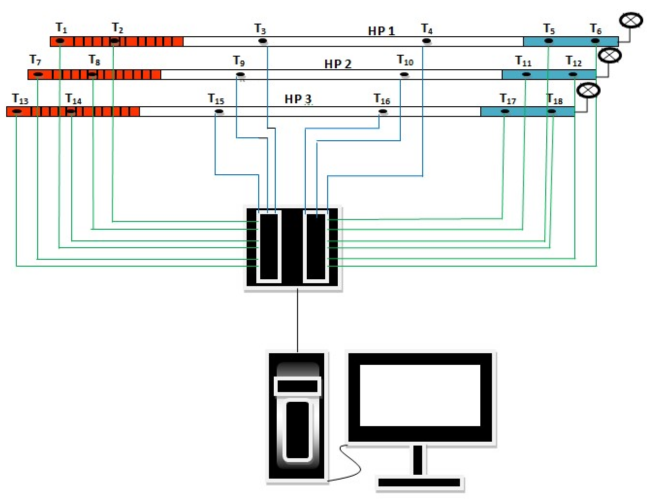

Figure 2. Positions of thermocouples on the heat pipes and data acquisition system.

The laboratory tests were conducted with the following procedures:

1. The test bench with the heat pipes was placed in the following slopes: 0°, 30°, 60° and 90°, adjusted by a digital inclination measurement instrument, in order to avoid any influence of the gravity force;
2. The heat was applied to the evaporator by a controlled electric heater, being used the testing power cycles as presented by Table 2 of 25W, 50W, 75W, 100W and 125W per heat pipe;

Table 2 - Applied power cycles.

Cycle 1	50 W - 100 W - 75 W - 125 W - 25 W
Cycle 2	125 W - 50 W - 100 W - 25 W - 75 W
Cycle 3	100 W - 25 W - 50 W - 75 W - 125 W
Cycle 4	75 W - 125 W - 25 W - 100 W - 50 W
Cycle 5	25 W - 75 W - 125 W - 50 W - 100 W

RESULTS AND DISCUSSION

With the conducted tests, it was possible to verify the temperatures along the heat pipes length in order to obtain their profiles. As expected, there was an increase in the temperature at the highest power applied to the evaporator. However all three heat pipes presented stable operation, as observed on the following figures. Figure 3 presents the temperature profiles for all heat pipes, to evaluate their thermal performances for all power levels. It was possible to verify the temperatures along the heat pipes to obtain the temperature profile for Cycle 2 operating at 0°, Cycle 1 operating at 30°, Cycle 1 operating at 60° and Cycle 4 operating at 90°.

A comparison between the heat pipes has been previously performed for the same conditions, although without power cycles (Silva and Riehl, 2014). The heat pipes presented a significant difference between the temperatures of the evaporator and the condenser, for stainless steel heat pipe, obtaining a highest thermal conductance of 14 W/°C (at 0° angle). The objective with the power cycles investigation was to verify whether the heat pipes present a dry-out tendency in the evaporator, which could affect their performance and operation. Since the heat pipes are under development for several applications, continuous tests have been performed to check their performance over time. This methodology is highly indicated to verify whether the heat pipes present failure or influence of NCGs (non-condensable gases) during their performance. Therefore, upon analyzing previous and current results, similarity on the temperature and heat transfer patterns are expected. Thus, the results presented here are related to several series of tests for the sake of comparing the heat pipes performances and check their life time reliability. In this specific case, the heat pipes have presented similar thermal behavior over the time, as presented by the results.

Figure 3 compares the stainless steel heat pipes (HP1, HP2 and HP3), with different screen mesh numbers (400, 200 and 100 respectively) for different inclinations. It shows a similar behavior for temperatures in the evaporator, condenser and adiabatic sections for both heat pipes. As seen on Figs 3b-c-d, the heat pipes show higher temperatures (evaporator, condenser and adiabatic), when compared with Figure 3a to the critical power of 125W due to the inclination influence on their performances.

For an improved analysis, the thermal conductance (*G*) was calculated for the experimental results, when all heat pipes reached a steady state condition. The thermal conductance was calculated as

$$G = \frac{Q}{T_e - T_c}, \text{ W/°C} \qquad [1]$$

with uncertainties below 10%.

Figure 4 presents the results for the maximum thermal conductance observed for all heat pipes obtained from Eq. (1) for an improved analysis of the heat pipes thermal operation for all power levels. The highest thermal conductance of 19.10 W/°C was observed for HP2 operating on cycle 2, which presents a stainless steel container and wick with mesh number 200, operating at 0°.

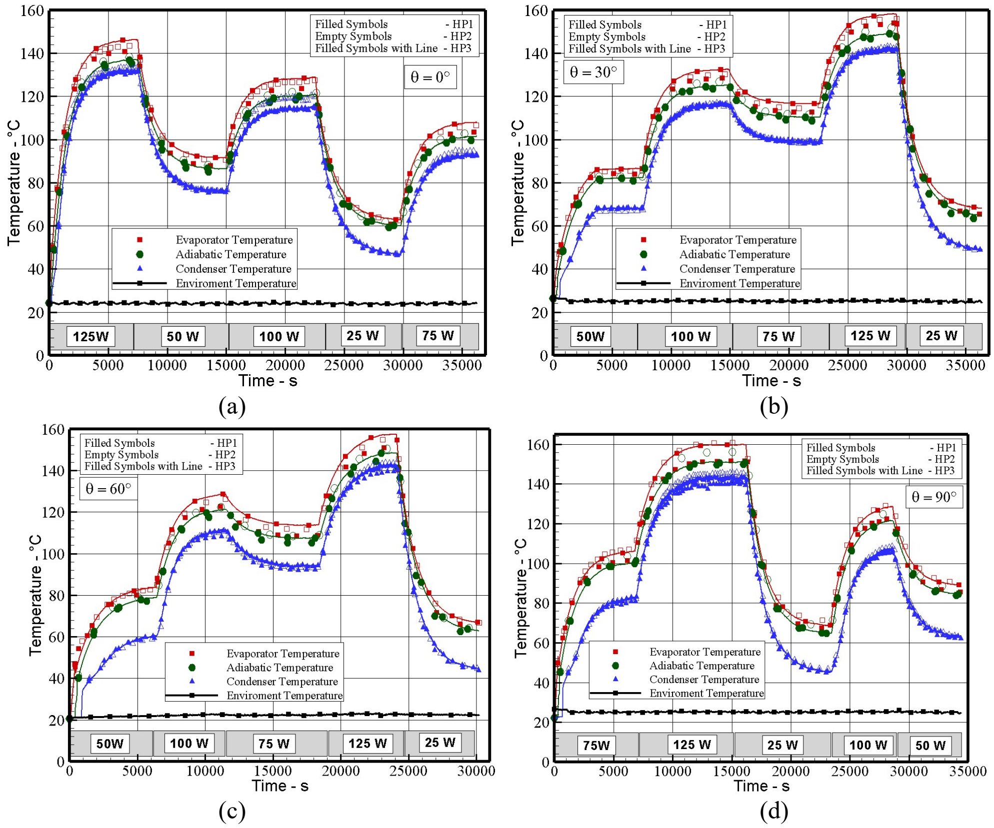

Figure 3 - Temperature profiles for the heat pipes, operating (a) 0°, (b) 30°, (c) 60° and (d) 90° for HP1, HP2 and HP3.

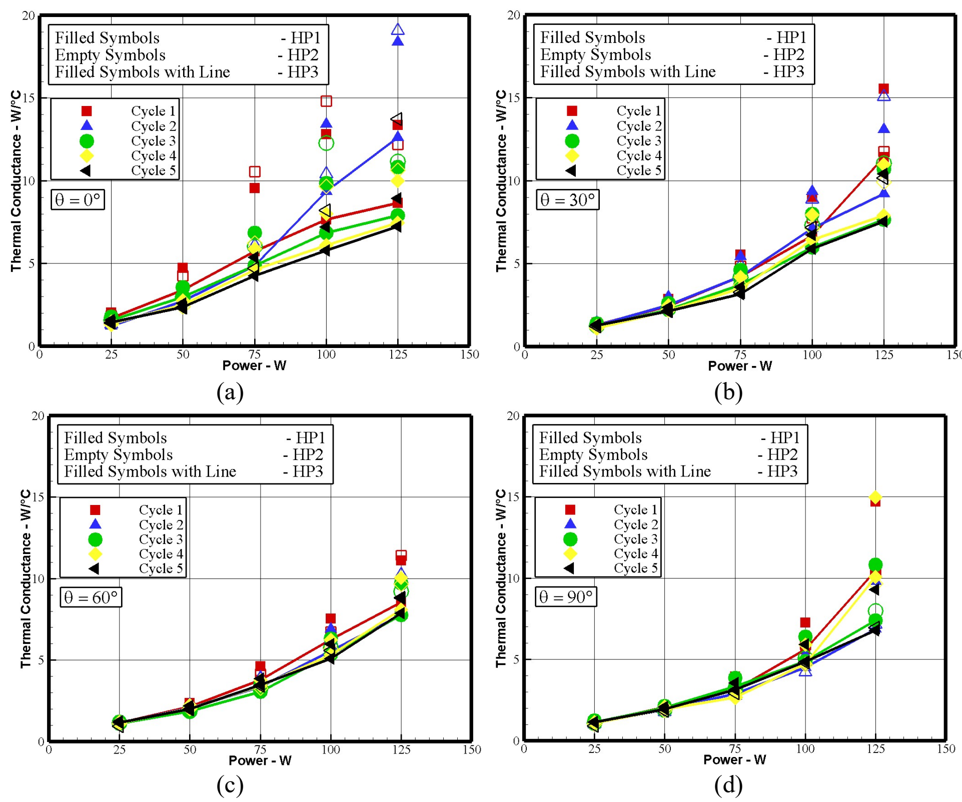

Figure 4- Thermal conductance for the power cycles

The second highest thermal conductance was verified for HP1 in 15.5 W/°C operating at the cycle 1, which presents a stainless steel container and wick with mesh number 400, operating at 30°. Differences on the thermal conductances are basically due to the operating inclination of heat pipes.

CONCLUSION

Experimental results for heat pipes HP1, HP2 and HP3 (stainless steel) operating at mid-level temperatures using water as the working fluid operating with power cycles and different inclinations were carried out. The following conclusions can be derived from this investigation:

1. All four heat pipes presented stable behavior, for both transient and steady-state conditions, when they operated using the power levels of 25, 50, 75, 100 and 125 W. During the experimental tests and analysis of the results, no heat pipe presented dry-out tendencies;

2. Significant differences between the temperatures of the evaporator and condenser were presented by the heat pipes in the inclinations of 30° 60° and 90° when compared with the heat pipes operating horizontally, basically due to gravity influence but also because of lower pumping capacity promoted by the screen mesh 100 using on HP3;

3. Heat Pipes operating at 0° presented startups without oscillations of temperatures, confirming better performance when analyzing the thermal conductance results;

4. Regarding the thermal conductances, the heat pipes demonstrated higher values by using screen mesh number 400 and 200 due to their higher capillary pumping capability.

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