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STUDY OF THE EFFECT OF GRAVITY ON THE PERFORMANCE OF PULSATING HEAT PIPES

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Abstract. *Pulsating heat pipes are a special type of heat pipes that do not need a separate capillary structure for liquid feeding the evaporator. It could be related to a thermosiphon but according to some studies it can work even in the absent of gravity forces. The objective of this paper is to present a study on the influence of gravity in the performance of pulsating heat pipes, as a limiting characteristic for applications of these devices. A updated literature review of the experimental studies is presented showing the conclusions about the influence of gravity in the performance of pulsating heat pipes.*

Keywords: *Pulsating Heat Pipes, Heat Transfer, Experimental Studies, Two - Phase Flow*

1. INTRODUCTION

The development of new technologies for refrigeration is very important for the development of the microelectronics and space industry. The pulsating heat pipes consist of hollow tubes formed by the evaporator, the adiabatic section and the condenser. The first pulsed heat pipe was proposed by Akachi (1996).

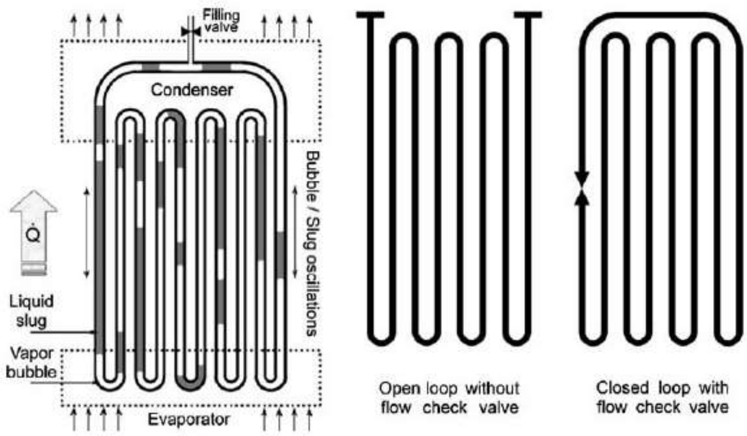

Figure 1. Structure of the pulsating heat pipe and possible configurations, Charoensawan *et al* (2003).

The advantages of using pulsed heat pipe consist in the fact that in these type of devices there is no porous structure so its weight, the space occupied, the amount of material used for manufacturing are minimized.

At possible applications are the cooling of compact computers, cell phones and smartphones, heat pumps, power cells, micro-reactors, space vehicle radiators and satellites.

The understanding of the mechanisms of operation of the pulsating heat pipe is not fully understood, there are some issues that have not yet been resolved and deserve special attention including the effect of gravity and / or inclination on the performance of the pulsating heat pipe.

Charoensawan *et al* (2003) proposes that a given critical number of turns is required for the pulsating heat pipe to operate horizontally this is attributed to an internal disturbance level.

According Zhang and Faghri (2008) the number of turns of the pulsating heat pipe can affect the thermal performance and can negate the effect of gravity if the pulsating heat pipe has few turns it may not operate horizontally but with many turns it can operate in any orientation due to disturbances in each turn. Despite the fact that surface tension forces are dominant, theoretical and experimental investigations show that gravity plays a significant role, with an inclination angle varying from vertical to horizontal, thermal performance can be worsened and in some cases may even cease to operate.

Currently, studies have been carried out to understand and describe the operation of this new refrigeration technology.

In this paper we will present papers that analyzed how the number of turns, pipe diameter and different working fluids relate to the effect of gravity and / or inclination, and how this affects the performance of the pulsating heat pipe.

2. WORK THAT EVALUATED THE EFFECT OF GRAVITY AND / OR INCLINATION IN PERFORMANCE OF PULSANTING HEAT PIPES

Khandekar *et al* (2002) using a glass tube with internal diameter of 2 mm and external of 4.2 mm with water and ethanol as work fluid investigated the influence of the angle of inclination on the performance of the pulsating heat pipe, With angles of 0º, 45º, 90º with 50% filler fraction even if thermal resistance has decreased with the increase of the incoming heat in all cases the operation mode we have single-phase siphon is better than the operation of the pulsating heat pipe , But with a 30% fill fraction was sufficient to reach pulsing mode.

Charoensawan *et al* (2003) their work investigated the effect of the operating orientation of a closed copper pulsed heat pipe with internal diameter of 1.0 mm and 2.0 mm with water, ethanol and R123 with angles ranging from 0º to 90º. Two physical phenomena depend on the orientation of the pulsating heat pipe, the gravity that influences the piston flow and the number of revolutions that influence the dynamics of the perturbations, the conclusions were that a certain critical number of turns is necessary to make the horizontal operation possible, The performance difference between vertical and horizontal operation is attributed to the increase in the level of internal disturbances.

Gu (2004) study the effect of pregnancy on the performance of the pulsating heat pipe using an R114 aluminum tube with gravity ranging from 1- 2.5 g in micro gravity + - 0.02 g on Falcon 20 aircraft flying with parabolic trajectories, the experimental results strongly suggest that The pulsating heat pipes can function satisfactorily under long-term microgravity, under conditions of hypergravity the orientation and positions of the evaporator and the condenser are important both for the operation and the heat transport. The evaporator placed in a lower position would avoid instability and temperature fluctuations because the gravity helps the liquid pistons return to the evaporator and helps the steam bubbles rise to the condenser section.

Wannapakhe *et al* (2009) their work, he used nano silver fluid as a working fluid with concentrations of 0.25, 0.5.0.75 and 1% in a pulsating copper heat pipe with 2.0mm in diameter, in order to investigate the effect of the angle of inclination of the performance Of the device, for an angle equal to 90 º . The heat transfer when the water was used as working fluid was greater than the other inclination angles. The heat transfer rate using nano silver fluids as the working fluid was higher than when water was used, the best value for the heat transfer rate was 8,88 kW / m2 a 90º.

Yuan *et al* (2010) presented a theoretical model for the transfer of heat between liquid pistons and neighboring vapor bubbles was proposed based on the equation of the momentum for the liquid piston and the energy equation for the liquid piston and for the vapor bubbles, the Effect of gravity on the heat transfer coefficient was studied, the results obtained show that the effect of gravity on the difference of pressure, mass and temperature for a vapor bubble is not significant, so the effect of gravity can be considered as A forced vibration system with viscous damping.

Ayel *et al* (2010) with the purpose of presenting the influence of the working fluid and the slope on the performance of the pulsating heat pipe. An experimental set consisting of two tubes made of copper, tube 1 with 1.2 mm diameter and 40 turns, and tube 2 with 2.5 mm diameter and 20 turns were developed. The working fluids used were acetone, ethanol, pentane and water, in the horizontal positions, favorable slope and the adverse slope and variation of the cold source temperature of 20 $°C$ to 80$°C$, and $Tcryo$ is the temperature of a secondary fluid, the results show That thermal resistance generally decreases with increasing heat flow in the evaporator, thermal resistance is reduced by tilting the pulsating heat pipe favorably.

Wei and Zhang (2011) they propose an advanced mathematical model for heat transfer in a pulsating heat pipe where capillary and gravitational forces are included in the momentum equation of a liquid piston, numerical simulation was performed to investigate the effects of surface tension and Of gravity in the oscillatory movement of the tube and in the transfer of heat with different internal diameters and orientations.

Verma *et al* (2013) analyzed the effect of methane and ionized water on the thermal performance of the pulsating heat pipe in terms of thermal resistance and heat transfer coefficient, the optimum methane filling fraction was 40% and for water it was 50%.

Burban *et al* (2013) conducted an experimental study of the performance of open pulsed heat pipes for hybrid vehicles, a 2.5 mm internal diameter copper tube and a 3.2mm external diameter was used, acetone, methanol, water and n-pentane were used as working fluids with 50% filler fraction in three different orientations: horizontal, 45 º with evaporator on top and 45 º with evaporator underneath, thus n-pentane as working fluid is less efficient than acetone and acetone presents better performance when compared to metanol.

The experiments were performed for water and ethanol Jahan *et al* (2013) studied the effect of the angle of inclination and working fluid on the heat transfer and performance characteristics of the closed pulsating heat pipe. In the horizontal direction - angle 90∘ there is practically no movement of the vapor bubbles, suggesting that gravity plays a key role in the performance of the pulsating heat pipe. The best performance was obtained in 75 º, under all circunstancies water presented better performance than the ethanol in the experiment due to its thermophysical properties.

Mameli *et al* (2014) their work analyzed the combined effect between different filling rations and the inclination angle with the obective of understanding the thermal instability in pulsed heat pipes closed. With filling ration of the 50% the thermal resistance decreased by 5 times compared to the empty device. The thermal resistance for the filling ration of 70% is always greater than the thermal resistance for the filling ration of 50%. The lower thermal resistances are obtained for filling ration of 50% both horizontally and vertically. Filling rations of 70% and 90% show worse efficiency. For the filling ration of 90% in horizontal device only works for input power between 60W and 70W.

The thermal response of a pulsating heat pipe was the study focus of the work of Zhihu and Wei (2014), a glass tube with internal diameter of $2mm$ and external of $6mm$ with ammonia as working fluid with 50% Was used, the effects of slope were discussed for four different cases 0 º, 30 º, 60 º and 90 º. For angles of 30 º, 60 º and 90 º decrease of the thermal resistance with 0 º angle occurs a marked increase of the thermal resistance.

An experimental study focusing on the combined effect between different filler fractions and tilt angle was performed in the work Xue and Qu (2014) in their work used ammonia as a working fluid with 50% filler fraction to investigate the effects of variation Of the inclination angle in the performance of the pulsating heat pipes, in this study the thermal resistance decreases as the inclination angle increased.

With the objective of compare the performance of the pulsating heat pipes on the ground in macro and micro gravity, Mangini *et al* (2015) conducted the experiment during the 61st ESA Parabolic Flight Campaign, the flight tests. The experiments presented in Mangini *et al* (2015) reveal that in the horizontal soil the device functions as a pure conductor, in the tests in parabolic flights the device operates in a different way when submitted to microgravity and there is a transition from two-phase siphon to pulsating heat .

To investigate the effect of the magnetic field on nano particles Fe2O3 was added to the kerosene with this Goshayeshi *et al* (2015) performed experiments with different angle of inclination and concluded that addition of nanoparticles reduces the thermal resistance of the tube, the slope of 75 º in the presence Of magnetic field presented lower thermal resistance for Fe2O3 as working fluid and the heat transfer rate increased by 16% and near angles of vertical position impair the performance of the pulsating heat pipe, operating horizontally there was no movement of vapor bubbles , for the inclinations of 60 º to 75 º the pulsating heat pipe operated normally.

Table 1. Experimental work that analyzed the effect of gravity on the performance of pulsating heat pipes.

Author	Internal and external diameter (mm)	Tube Material	Fluid of work	Filling ration	Inclination Gravity	Power Input
Khandekar *et al* (2002)	2, 4.2	Glass	Water and Ethanol	50%	0º, 45º,90º	5 W – 15 W
Charoensawan *et al* (2003)	1, 2	Copper	Water and Ethanol and R123	50%	0º - 90º	0 W – 1.2 W

Wannapakhe *et al* (2009)	2	Copper	Nano silver fluid	-	0º - 90º	0 W – 12 W
Ayel *et al* (2010)	1.2,2.5	Copper	Acetone, Ethanol, Pentane and Water.	--	Vertical e Horizontal	0 W – 4500W
Verma *et al* (2013)	1.45, 2.54	Copper	Water and methanol	50% e 40%	Vertical, horizontal e 45º	-
Burban *et al* (2013)	25 – 3.2	Copper	Acetone, methanol, water and n-pentane	50%	Horizontal, 45º evaporador acima, 45º evaporador em baixo.	-
Jahan *et al* (2013)	2,3	Copper	Water and Ethanol	70%	0º, 15º, 30º,45º,60º ,75º,90º	-
Ayel *et al* (2013)	-	Copper	Water	50%	1.8 g e 0g	50W, 75W,100W, 200W e 300W
Mameli *et al* (2014),	1,1.2	Copper	FC - 72	50%, 70%, 90%	0º, 15º, 30º,45º,60º ,75º,90º	10 W – 100W
Xue and Qu(2014)	2,6	Quartz glass	Ammonia	50%	0º, 30º,60º,90º	40W – 280W
Mangini *et al* (2015)	3,5	Aluminum	FC- 72	50%	Vertical, Horizontal, 0g, 1 g, 1.8g	10 W – 160W
Goshayeshi *et al* (2015)	1.25, 3	Copper	Fe2O3	50%	0º, 15º, 30º,45º,60º ,75º,90º	15 W - 90 W

3. RESULTS OBSERVED IN THE WORK ON THE EFFECT OF GRAVITY IN PULSANTING HEAT PIPES

The experiments studied diameters ranged from 1 mm up to 5 mm various materials were used in the construction of tubes such as aluminum, copper, quartz glass were the materials used. The water, ethanol, pentane, methanol, acetone, Fe2O3 / Kerosene, ammonia and FC - 72 were the working fluids used, the fill fractions used were 50%, 70% and 90%, some works were carried out vertically in the horizontal and also in macro and micro gravity, thus guaranteeing variations in the value of gravity, making it possible to obtain results for the analysis of the performance of the pulsating heat pipes.

1) Ayel *et al* (2010) there was reduction of the thermal resistance with the increase of the entrance heat, in the vertical position for the acetone and the ethanol, the transition from the horizontal to the vertical position occurs abruptly.
2) Ayel *et al* (2013) for the slug flow in microgravity there was drying of the evaporator, for annular flow there was an increase of the heat transfer due to reduction of the thickness of the liquid film in the condenser.
3) Jahan *et al* (2013) when comparing the value of the thermal resistance for different angles of inclination inclinations, it was verified the change in the flow patterns resulting in different levels of performance. The water presents better performance than the ethanol in the experiment in 75º.
4) Mameli *et al* (2014) the heat pipe without working fluid functions as a conductive medium and the thermal resistance was practically constant, when it was filled with working fluid a reduction of the total thermal resistance was achieved by up to five times in relation to the empty device in the case of the filling fraction Equal to 50%. In the vertical it presented good performance for power of inputs equal to80W and 90W, high input heats cause thermal instability and the 70% fill ratio is the least efficient.
5) Xue and Qu (2014) the lower thermal resistance were obtained for the 70% and 80% filler fractions as horizontally operated.
6) Mangini *et al* (2015) concluded what there is a relationship between the thermal resistance and the orientation, there was a decrease in the thermal resistance with the increase of the input power, as was to be expected the parabolic flight tests revealed that the device operates differently when subjected to different levels Of gravity, in micro gravity there is the transition from termofissão to pulsating heat pipe.
7) Ayel *et al* (2015) observed the relationship between the thermal resistance and orientation having lower value in the vertical position and the higher the more stable and efficient input power is the pulsating heat pipe.
8) Goshayeshi *et al* (2015) the inclination of 75º in the presence of magnetic field showed the lowest thermal resistance and the heat transfer rate increased by 16 %, near vertical angles impair the performance of the pulsating heat pipe.

4. CONCLUSIONS

Based on the conclusions of the presented works we can conclude that the pulsating heat pipes are promising and that their performance is closely related to gravity, since different values for thermal resistance, different flow patterns are obtained from the variation of gravity and / or inclination angle of the tube.

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