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Parametric Characterization on the Thermal Performance of a Closed Loop Pulsating Heat Pipe

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ABSTRACT

Recently closed loop pulsating heat pipes have been receiving much attention because of their potential applications in high heat flux micro-electronic systems. They work by self thermal driven oscillation without any mechanical parts. Though they are simple in structure, understanding of the heat transfer mechanism is highly complex having a strong thermo- hydro dynamic coupling governing their performance. In this paper, an experimental study on a closed loop PHP with a single turn has been conducted there by providing vital information regarding parameter dependence on its performance. The PHP is made of brass tube having an internal diameter of 2 mm and outer diameter of 3 mm. The parametric characterization has been done for the variation in internal diameter, fill ratio, working fluid and orientation of the device. The working fluids Acetone, Methanol, Ethanol and Propanol are considered for experimentation with volumetric filling ratios of 50%, 60%, 70% and 80%. Input heat power of 7 to 12 W is varied at the evaporator section. The CLPHP is also verified for its thermal performance at 0^0, 30^0 and 60^0 orientations. The transient and steady state experiments are conducted and operating temperatures are measured using K- type thermocouples. The results highlighted that the thermal performance of a PHP is strongly influenced by change in fill ratios, orientation and heat input. 80% fill ratio yields an effective heat transfer rate for a horizontal mode of operation. Appreciable fluid movement and better heat transfer rate are observed for the 30^0 orientation of PHP operation. Acetone exhibits better heat transport capability compared to other working fluids in all orientations.

Keywords: Electronics cooling; Pulsating heat pipe (PHP); Water cooling; influencing parameters; Experimental study.

NOMENCLATURE

A	surface area (m^2)
Bo	bond number
c	condenser
C_p	specific heat capacity (J/Kgk)
D_{crit}	critical diameter (m)
D_{avg}	average diameter (m)
F_{cap}	capillary force (N)
g	acceleration due to gravity (m/s^2)
h	heat transfer coefficient (W/m^2k)
HCLOHP	Horizontal Closed Loop Oscillating Heat Pipe
I	electric current(A)
ID	inner diameter (m)
l	liquid phase
$\dot{m}$	mass flow rate of cold water (kg/s)
N	no. of vapour bubbles
OD	outer diameter (m)
P_{sat}	saturation pressure (bar)
Q_{cond}	heat removed in condenser (W)
Q_{in}	Input power supplied (W)
R_{th}	overall thermal resistance (k/W)
R	radius (m)
T_c	avg. condenser wall temperature (^0C)
T_{ci}	cold water inlet temperature (^0C)
T_{co}	cold water outlet temperature (^0c)
T_e	avg. evaporator wall temperature (^0C)
U	uncertainty
V	electric voltage (V)
v	vapour phase
σ	surface tension (N/m)
ρ	density (Kg/m^3)
φ	fill ratio
θ_a	advancing contact angle (rad)
θ_r	receding contact angle (rad)

1. INTRODUCTION

Thermal management of high power denser microelectronics is a challenging task for present day designers and researches as there are many shortcomings with the available conventional systems. In the light of increased power levels associated with high heat fluxes, the researchers are motivated to develop novel cooling technology for microelectronic systems. Pulsating heat pipes (PHPS) are the promising two phase passive systems developed by Akachi (1990) in that direction. Due to their simple structure, small size, cost effective and excellent thermal performance, PHPs have drawn a great deal of attention. There are three varieties of PHPS; (i) Open ended systems (ii) Closed loop systems and (iii) Closed loop systems with check valves. Closed loop PHPS are generally preferred over open loop systems due to continuous circulation of the working fluid enhancing the heat transfer majorly in the form of sensible heat rather in the form of latent heat (Shafi 2001, 2002).For a PHP of having capillary dimensions, the inability to give desired results led to the development of CLPHS without the check valves (Akachi 1996, Duminy 1998). Any typical CLPHP also will be first evacuated and then partially filled with a working fluid. For a capillary tube diameter up to its critical value, surface tension forces are predominant over the gravity forces and the working fluid distributes into the train of liquid slugs and vapor plugs. Beyond critical diameter, the flow becomes stratified. The critical diameter which is a design parameter for a PHP is evaluated from the relation (Groll 2003),

$$D_{crit} = 2\sqrt{\frac{\sigma}{(\rho_l - \rho_v)g}} \quad (1)$$

where σ is the surface tension of the working fluid, g is the gravitational acceleration and $\rho_l$and$\rho_v$are the densities of liquid and vapor phases respectively. The thermo-physical properties of working fluids are evaluated based on their saturation temperature

The heat influx increases the pressure of vapor plugs at the evaporator and the heat efflux decreases the pressure at the condenser. The differential pressure between the evaporator and condenser would result in the pulsating flow of liquid slugs trapped between the vapor bubbles. The heat transfer in a PHP during the slug flow of the flow boiling is observed to be in the form of sensible heat and during the annular flow it would take place in the form of latent heat (Shafi 2001, 2002).

Many investigations related to both experimental and numerical studies on PHPs have been reported, as their comprehensive understanding and design is still inconclusive. Experimental works were mainly dealt with flow visualization studies and evaluation of thermal performance under influencing parameters. Numerical studies explained about the flow characterization of slug/plug flows in PHPs.

Gi Hwan Kwon *et al*. (2014) conducted a series of experiments on single turn dual- diameter pulsating heat pipes and investigated its effect on the flow and heat transfer characteristics. The PHPs of various inner diameters were made of glass capillary tubes and charged with Ethanol. Experiments were performed with varying input power and inclination angle and they studied the operational characteristics of PHPs. The results revealed that a circulating flow was promoted by a dual diameter tube even at lower heat input level and reduced the thermal performance of PHP by 45%. Based on the experimental results a numerical model was developed to predict the flow and heat transfer characteristics of PHPs with circulating flow, and proved that the model estimates the experimental data within the error of 15%.The proposed model also showed that the enhancement in thermal performance is maximized at a dimensionless diameter range of $0.25<\Delta D/D_{avg}<0.4$.

The performance of a single loop pulsating heat pipe made of quartz glass tube was carried out by Nandan Shah *et al*. (2014) to understand the influence of process variables on the hydrodynamic characteristics and its performance. In the investigation, parametric measurement is combined with visualization to provide better insight of the thermo-hydrodynamics in a CLPHP. It is noticed that below the minimum start up power, no fluid movement was observed inside the CLPHP. In a horizontal orientation the segregation of vapor and liquid followed by dry out takes place within a short duration from start up. However, at greater orientations the performance of such a loop is greatly affected of gravity and it can operate smoothly only up to an inclination angle of 10^0. For the combination of PHP geometry and working fluid the optimum FR exists within 40-50% and optimum inclination angle exists within 50-70% where the thermal resistance of the loop is minimum.

Thermal performance of a closed loop pulsating heat pipe has been derived by Kammuang *et al*.(2014) in terms of dimensionless numbers. Ethanol, Acetone, R123, R141b and water were chosen as variable working fluids with constant fill ratio of 50%. Thermal performance was derived in terms of Kutateladze number (Ku). It was concluded that when Prandtl number of liquid working fluid (Pr_l) and Karman number (Ka) increases, thermal performance increases. On contrary when bond number (Bo), Jacob number (Ja) and Aspect ratio (L_e/D_i) increases, thermal performance decreases.

Park Yong-ho *et al*.(2012) have explored the pressure characteristics inside a single loop oscillating heat pipe (OHP) made of copper tube having 4.5 mm inner diameter and the loop height of 440mm. Distilled water was used as the working fluid in the OHP with varying fill ratios of 40%,60% and 80%. A Piezo resistive absolute pressure sensor was used to record the pressure data during the experimentation. The investigations demonstrated that a fill ratio of 60% yields highest inside pressure magnitude as well as pressure frequency irrespective of any set of operating conditions apart from the attainment of the lowest flow resistance at this fill ratio.

The hydrodynamics in a PHP were analyzed through visualization studies conducted by Khandekar (2004). The realization of flow visualization studies was done on a single loop PHP developed from copper tubes of 2 mm inner diameter and 3 mm outer diameter forming the evaporator and condenser section and glass tubes of inner diameter 2 mm and outer diameter 4 mm forming the adiabatic section. The evaporator and condenser sections of the PHP were insulated with Armaflex foam and the studies were conducted with a maximum heat input of 80 W. The loop was first evacuated and then the working fluid (ethanol) was partially filled. The temperatures of evaporator, condenser and adiabatic sections were measured using a data logger at a frequency rate of 1 Hz. A constant fill ratio of 60% was maintained throughout the study. The author had seen the slug flow with a low amplitude of oscillations at lower heat input. It was noticed that the slugs/plugs vibrate about a mean position with very little bulk movement. High values of thermal resistance were reported at lower heat inputs. The oscillation amplitude was found to be increased with the increase in the heat input. It was found that there was a clockwise movement for the fluid for some time and then a counter clockwise followed. But it was reported that the flow was in a definite direction for a longer time before it takes a direction reversal at a heat input of 63.3 W. At this heat input, the annular flow was observed in the evaporator section and transition of this flow to slug flow was reported in the condenser section. When the heat input was further increased to 74.4 W, the reversal of flow direction was claimed to be stopped completely and the heating section was characterized with fully developed annular flow while slug flow was seen in the cooling section. It had become very difficult to sustain annular flow, when the fill ratio was increased beyond 70%.

The operating mechanism in an oscillatory capillary tube heat pipe [OCHP] was ascertained by WH Lee *et al*. (1999) through the visualization of flow pattern. For this purpose, the experimental setup was made of brass and an acrylic plate with a looped serpentine flow channel of 4 turns. Tests were conducted with Ethanol as a working fluid in the fill ratio range of 20 to 80% and for the orientations ranging from 30^0 to 90^0. The flow patterns were recorded using high-speed camera (400 frames/sec) have drawn certain conclusions ; Due to the pressure wave created by the contraction and extinction of bubbles simultaneously in the evaporating and condensing sections, working fluid in the PHP oscillated in the axial direction. Circulating flow was not observed by the working fluid and condensed liquid returned to the evaporator section as a stratified flow. Active oscillation of the working fluid was observed at a charging ratio of 40 to 60% and at the inclination angle of 90^0.

The inability of check valves and their reliability to deliver expected results in capillary tubes led to the development of loop heat pipes without check valves (Akachi 1996, Duminy 1998). The diameter of the tubes proposed was 1 mm with open and closed loop structures. The setup used R-142b as the working fluid. The thermal resistance varied in the range of 0.64 to 1.16 K/W for a heat input range of 5 to 90 W in top and the bottom heating modes.

Khandekar*et.al*. (2008) demonstrated the existence of multiple quasi – steady state in a PHP by developing an experimental test rig of a single loop PHP made of copper tubes of inner diameter 2 mm and outer diameter 3 mm. The experiments were conducted for heat inputs of 10 W, 15 W and 20 W with Ethanol as the working fluid at 60% fill ratio and continuous online data were recorded for 12 hours. Three quasi steady states were observed and named as steady state 1, 2 and 3. The flow in steady state-1 was unidirectional with random fluid movement and halt due to which there was an intermittent heat transfer. High thermal resistance was experienced in steady state-1. In steady state-2, a tendency of liquid hold – up was observed in the condenser section which made the evaporator zone become drier and hotter. Extremely poor thermal performance was reported in this steady state. The author demonstrated that the steady state-3 resulted in a unidirectional flow pattern with no halt anywhere leading to least thermal resistance. It was found that the churn flow had taken place in the evaporator and a slug flow in the condenser zones. It was also noticed that continuous heat transfer had taken place in the evaporator and condenser at steady state-3.

Rama Narashimha *et al*.(2012) presented an experimental study on a single turn closed loop PHP. Transient and steady state experiments were carried out for different working fluids, heat input and for different evacuation levels. The authors indicated that at atmospheric condition, the saturation temperature of working fluid is higher compared to evacuated situations. Thus more liquid phase exists in the PHP tube below the heat input range of 15W with a consequent increase in heat transfer. The results of their experiments showed an intermittent motion of the working fluid at lower heat input.

Naik *et al*. (2013) conducted experiments on a single turn closed loop PHP both in the horizontal as well as vertical orientations for different heat loads varying from 9 W to 15 W in steps of 2 W. The PHP performance was tested for a variety working fluids viz. Methanol, Ethanol and Acetone with different fill ratios from 60 to 80 % in steps of 10%. The results revealed that the single loop PHP is found to perform better in the horizontal orientation for all the process variables considered.

Pallavi *et al*.(2013) carried out an experimental study on a single turn vertical closed loop PHP using an azeotropic mixture of water (4.5%wt) and Ethanol (95.5%wt) at a fill ratio of 50%. Experiments were conducted for varying heat inputs of 8 to 96 W in steps of 8 W. Rapid decrease in thermal resistance has been reported with the increase in heat input. No measurable difference of thermal resistance is reported by PHP working with an azeotropic mixture of Ethanol and water when compared the PHP performance with Ethanol as the working fluid.

Zhang *et al*. (2003) clarified that the thermal performance of many PHPS was found to be degraded when the inclination angles were increased and some would not even operate at all. PHPS of sufficiently smaller diameter perform better at low inclination angles.

Based on the best available models (Swanepoel 2000, 2001) a simplified mathematical model for two phase heat transfer under 1-D configuration has been formulated by Xin She yang *et al*. (2014) which could be capable of reproducing the fundamental characteristics of time dependent start up and motion of liquid plugs in the heat pipe. The key parameters and processes that control the main heat transfer processes were analyzed using scaling variations and consequently non-dimensionalisation. An efficient firefly algorithm was used to estimate the key parameters. However, significant difference were still reported between the numerical model and experimental data which can be attributed to incomplete data, unrealistic parameter values, over simplified approximation and unaccounted experimental settings.

The thermal performance of a horizontal closed loop oscillating heat pipe was dimensionally analyzed by Piyanun Charoensawan *et al*. (2007) and formulated the empirical correlation. Various dimensionless groups that were supposed to influence the thermal performance of a HCLOHP such as Prandtl number (Pr_l) of liquid, Karman number (Ka), modified Jacob number (Ja*) etc. were considered. The correlation was developed in the non-dimensional form of the power function by using curve fitting with 98 reliable data sets and the system of equations is solved by the Gauss Elimination method. The standard deviation of this empirical model was observed to be 30%.

Thus the available literature reveals that not many experiments have been reported on single loop PHPs made of materials other than Copper and Aluminum. Moreover, the suitability of different working fluids with new tube materials such as brass has not been verified. The properties like high ease of bending into curved shapes (malleability), corrosive resistance, cheaper cost, compatibility with most of the working fluids and good thermal conductivity provided an extra edge for brass to be chosen as an alternative tube material. Hence in the present work, the thermal behavior of a single loop PHP made of brass is tested under the influence of various working fluids such as Acetone, Methanol, Ethanol and Propanol at different heat inputs, fill ratios and orientations. The ID of the brass tube chosen is 2 mm and the OD is 3 mm.

2. EXPERIMENTATION

A detailed description of the PHP schematic diagram is provided in Fig.1.aand the pictorial view of a single loop brass PHP setup fabricated for heat transfer study is illustrated in Fig.3.

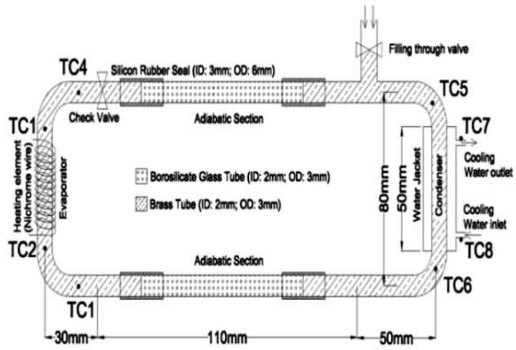

Fig. 1(a). Schematic diagram of the PHP experimental setup.

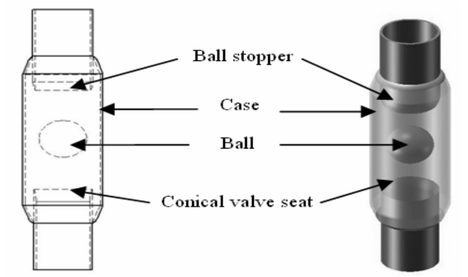

Fig. 1(b). Schematic sketch of a check valve.

2.1 Instrumentation Made with the Set Up

The major components used in the PHP setup are; brass tube, borosilicate glass tube, silicon rubber tube, a non return valve, a tape heater, and a data acquisition system with K- type thermocouples. The glass tube coupled with the U- turns of evaporator and condenser sections is treated as adiabatic section [24].Flow visual effects could be captured through the transparent surface of the glass tube. The glass tube is made of borosilicate which can resist temperature up to 1200^0 C. Brass and glass tube are connected by means of silicon rubber connectors of 2 mm ID and 4 mm OD. They are leak proof and expand at higher temperatures. They are heat resistant and can with stand up to 400^0C.

Although the use of check valve shown in Fig 1.b, could permit an unidirectional flow to be taken place in the PHP with better heat transfer characteristics, it is difficult and expensive to install. Therefore the PHP structures without check valves have become most favorable choice and hence avoided its use even in the present study.

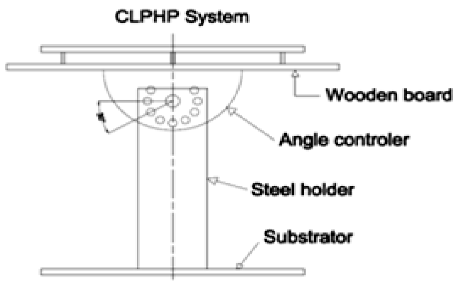

Fig. 2. Schematic diagram of mechanical setup to control inclination.

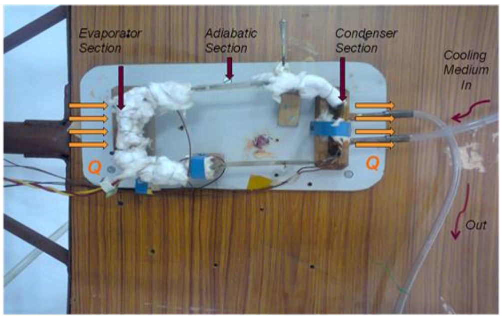

Fig. 3. Pictorial view of the experimental set up.

The tape heater of heating capacity 50 W is winded over the evaporator section which acts as the heat source. The heater element consists of Nichrome wire and the set value of heat input is permitted to flow with controlled supply of voltage and current. Further the heater surface is covered with the insulation of 10mm thick glass wool (k=0.035w/m-k) and exposed to an air film of heat transfer coefficient approximately equal to 5 w/m^2-k. Under these operating conditions, the critical radius of insulation is estimated to be 7 mm which is less than the actual thickness of insulation applied. Due to this reason, the heat loss to the ambient air from the heater surface could be drastically reduced and thus this heat loss is considered to be negligibly small compared to the heat carried away by the working fluid inside the heat pipe. Eight K- type thermocouples four at evaporator section with the remainder in the condenser section are attached for temperature measurement. The thermocouple has a wire diameter of 1 mm and can measure temperature up to 1000^{0}C with a maximum error of ±0.1^{0}C. The temperature data has been acquired using an 8- Channel MCC USB-TC at a frequency of 1 Hz.

The experimentation has been carried out with working fluids viz. Acetone, Methanol, Ethanol and Propanol. Thermo-physical properties of the working fluids are presented in Table.1.During each cycle of operation, a syringe pump was used to inject fluid through a filling valve.

Table 1 Uncertainties of the measured quantities

Quantity	T_e	T_c	V	I	Q
Uncertainty % (±)	6	6	6	7	18.3

2.1 Experimental Procedure

The test facility shown in Fig.2 has been established to characterize the thermal performance of a single loop brass PHP and adopted the following procedure for experimentation.

I. It was ensured that no trace of working fluid used in the previous cycles was available before filling the fresh fluid in the PHP.

II. Working fluid of desired quantity is then filled keeping one end of the non return valve open through the filling valve using a syringe pump. So that the fluid directly enters the evaporator section. Literature studies of Khandekar *et al*. (2004) reveal that true pulsating nature in PHPs could be seen for the fill ratios between 20 to 80% with the 50% fill ratio stated to be the optimum one. Hence in the present work, experiments are conducted for the fill ratios ranging from 50 to 80%.

III. Once the liquid is filled in the PHP, the simultaneous formation of liquid slug and vapor bubbles is ensured due to dominance of capillary forces over gravity forces.

IV. The display unit is ON and required heat input is given through the power supply unit. Heat input of 7 to 12 W is varied in steps of 1 W during the experimentation.

V. Desired quantity of cooling water is circulated to the condenser section from a constant head water bath.

VI. Heat transfer characterization of the PHP is analyzed for the orientations of 0^0, 30^0, 60^0 in the present work. A rotating component shown in Fig. 3 coupled with an angle controller bolt is used to realize the variation of angle from -90^0 to +90^0 in steps of 30^0.

VII. Transient temperature data at different locations of evaporator and condenser is recorded using a data logger. Experiments are continued until a steady state is reached. Due to inherent uncertainties present with the thermocouple-temperature display system, the temperature uncertainty has been found to be ±2% of the full scale.

2.1 Experiment Validation

Using Ohm's law, heat input given at the evaporator is measured. Simultaneously from the flow rate and temperatures of water measured at the condenser section, heat output could be calculated from

$$Q_{cond} = \dot{m} C_p (T_{co} - T_{ci}) \tag{2}$$

Where $\dot{m}$ is the mass flow rate of cooling water, C_p is specific heat and T_{co} and T_{ci} are the temperatures at the outlet and inlet portions of the cooling chamber respectively. The thermal balance analysis at the evaporator and condenser section demonstrated that the maximum heat loss from the evaporator to the condenser is less than 18.3%.

2.1 Uncertainties in Measurements

The performance effectiveness of a PHP would be known from the uncertainties measured with various measuring quantities. The uncertainties associated at evaporator and condenser sections could be evaluated from the relation proposed by Kline *et al*.(1953).

Accordingly,

$$\%U_e = \sqrt{\left(\frac{\Delta T_1}{T_1}\right)^2 + \left(\frac{\Delta T_2}{T_2}\right)^2 + \left(\frac{\Delta T_3}{T_3}\right)^2 + \left(\frac{\Delta T_4}{T_4}\right)^2} \tag{3}$$

$$\text{and}\%U_c = \sqrt{\left(\frac{\Delta T_5}{T_5}\right)^2 + \left(\frac{\Delta T_6}{T_6}\right)^2 + \left(\frac{\Delta T_7}{T_7}\right)^2 + \left(\frac{\Delta T_8}{T_8}\right)^2} \quad (4)$$

3. RESULTS AND DISCUSSIONS

3.1 Effect of Fill Ratio

The effect of fill ratio on overall thermal resistance and heat transfer coefficient for acetone at zero orientation is shown in Figs. 4 and 5 respectively. The overall thermal resistance (Rama Narasimha 2008) for a PHP is defined as;

$$R = \frac{T_e - T_c}{Q} \quad (5)$$

Where T_e and T_c are the average wall temperatures of the evaporator and condenser respectively. While Q in Eq. 3.1 is the heat input applied to the evaporator which can be calculated as Q = VI. Similarly the local heat transfer coefficient for a PHP can be calculated as;

$$h = \frac{Q}{A(T_e - T_c)} \quad (6)$$

Where A is the surface area of the cooling chamber provided at the condenser section.

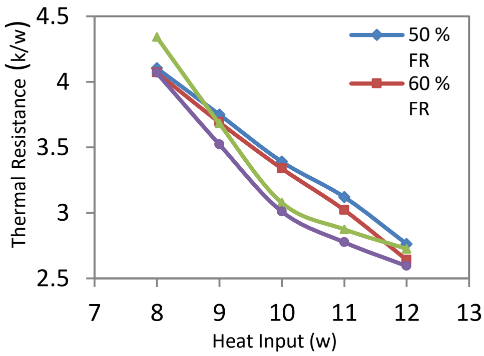

Fig. 4. Effect of fill ratio on thermal resistance for acetone at zero orientation.

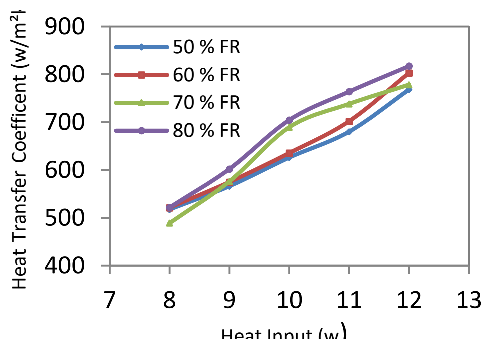

Fig. 5. Effect of fill ratio on heat transfer coefficient for acetone at zero orientation.

Lower thermal resistance of 2.6 K/W is observed for acetone working at a fill ratio of 80% consequently the higher thermal performance is reported at this fill ratio. The temperature rise and/or fall through a low conductive material is a time consuming phenomena and hence reported lower temperature difference between the evaporator and condenser sections. Equation 5 dealt the presence of lower thermal resistance followed by lower temperature difference at higher fill ratio. Moreover the working fluid(acetone) contains maximum liquid inventory compared to vapor pumping elements at higher fill ratio, and the slug flow becomes the predominant flow pattern. Therefore, at higher fill ratios the nature of heat transfer through PHPs made of brass is mainly in theform of sensible heat rather than latent heat form. Since sensible heat is the predominant mode of heat transfer, the buoyancy induced fluid circulation is taken place.

3.2 Effect of Diameter

The effect of diameter on overall thermal resistance and heat transfer coefficient for acetone at 50% fill ratio and zero orientation is shown in Figs. 6 and 7 respectively. The role of the tube diameter is vital in establishing the pulsating flow in a PHP. Lower thermal resistance of 1.7 K/W has been reported in the case of larger diameter PHP operation and hence increase in diameter enhances the heat transfer rate below its critical value. Lesser viscous effects possessed by higher diameter PHP cause the liquid pressure to drop to a lower value which leads to lower overall thermal resistances at higher diameters, increasing the heat transport.

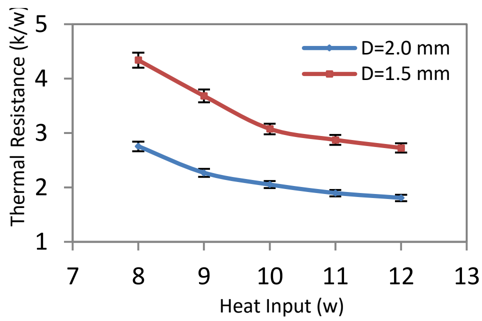

Fig. 6. Effect of diameter on thermal resistance for acetone at 50% FR and zero orientation.

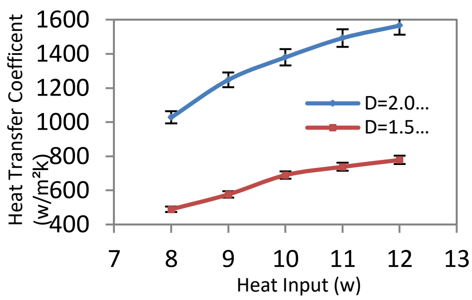

Fig. 7. Effect of diameter on heat transfer coefficient for acetone at 50% FR and zero orientation.

Below the critical diameter, the formation of distinct liquid slugs and vapor bubbles could be possible, which is a required characteristic by a PHP for its effective heat transfer. The formation of the train of liquid slugs and vapor plugs is attributed to the dominant surface tension forces over the gravity forces in the PHP operation, and this leads to the definition of Bond number. According to the PHP design criteria,

$$Bo = \sqrt{\frac{\sigma}{g(\rho l-\rho v)}} \approx 2 \quad (7)$$

As long as the hydraulic diameter remains within this limit, increasing the diameter generally increases the overall heat transport capability of the PHP. Beyond which, the surface tension gets decreased leading to stratification of phases.

3.2 Effect of Orientation

The effect of orientation on temperature difference for Methanol at 50% fill ratio and a heat throughput of 9W is shown in Fig. 8. It is depicted in the figure that a lower temperature difference between evaporator and condenser is observed at 30^0orientation, instead of 0^0. Consequently, lower thermal resistances are reported by PHPs at 30^0 orientations and yields better performance than any other positions studied. In horizontal mode, the formation and departure of vapor nuclei from active sites gets delayed for PHP operation. Due to the absence of the gravity forces in horizontal mode, the thermally induced pressure forces exist between the evaporator and condenser which causes the movement of the slug/plug flow. In horizontal orientation, the surface tension effect dominates in the absence of gravity. The high surface tension causes the additional bubble friction and restricts the flow. If the same fluid is to be used as working fluid, the rise in driving force would be obtained if the PHP is operated at high evaporator temperature keeping the condenser temperature constant. Otherwise, for the same evaporator temperature to be maintained, then some other working fluid with higher P_{sat} at this temperature as well as a steeper$\left(\frac{dP}{dT}\right)_{sat}$ should be used. This problem could be overcome by the use of a working fluid like Methanol whose surface tension is lower. It is observed that Methanol performs with a better heat transfer rate in the horizontal mode of PHP operation and acetone performs better for vertical orientation.

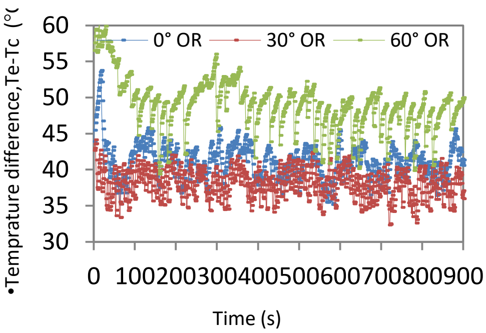

Fig. 8. Effect of orientation on temperature difference for methanol at 50% FR and Q=9W.

3.4 Effect of Working Fluid

Effect of working fluid on overall temperature difference, thermal resistance and heat transfer coefficient has been shown in Figs.9,10 and 11 respectively.

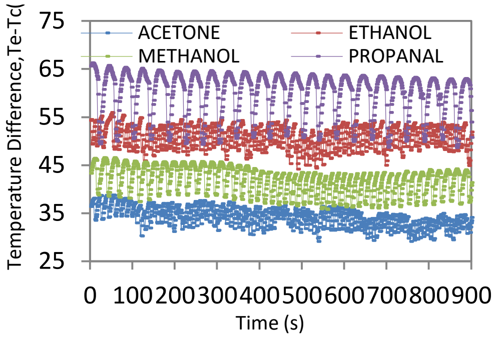

Fig. 9. Effect of working fluid on temperature difference at 70% FR and 30^{0}orientation.

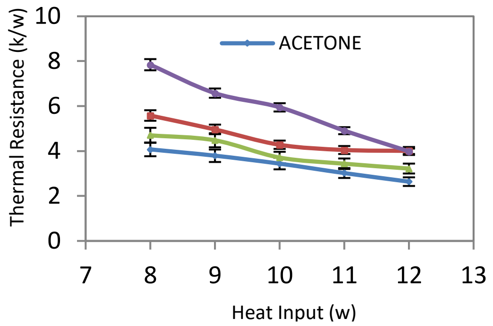

Fig. 10. Effect of working fluid on heat transfer coefficient at 70% FR and 30^{0}orientation.

It is seen from Fig.9 that the temperature difference between the evaporator and the condenser is less for Acetone and more for the Propanol. This is due to the fact that the saturation temperature for Acetone is much lower when compared to Propanol due to which there is a presence of more vapor bubbles in the case of Acetone. This shows that Acetone can transfer heat with less temperature difference compared to Propanol. The temperature difference between the evaporator and condenser for Acetone is found to be 34^{0}C and for Propanol is 65^{0}C.

From Fig.10, it is understood that the thermal resistance decreases with an increase in heat input for all the working fluids considered. Further it shows that lower thermal resistance is recorded by Acetone compared to other working fluids. This is because of the lower temperature difference observed between evaporator and condenser in the case of Acetone. Lower values of thermal resistance for Acetone indicate better heat transport capability through it compared to other working fluids.

It is seen from Fig.11 that the heat transfer coefficient increases with the increase in heat input for all the working fluids. Acetone yields higher thermal conductance compared to other working fluids. As discussed in the literature, the lower latent heat value associated with Acetone generates more vapor bubbles enhancing the fluid movement and decreases the temperature difference between evaporator and condenser.

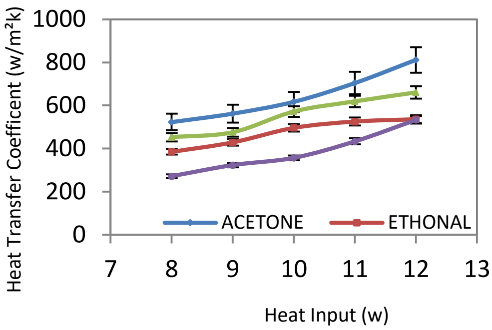

Fig. 11. Effect of working fluid on heat transfer coefficient at 70% FR and 30^{0}orientation.

Discussion on colour change with the use of Acetone:

While some studies indicate that copper reacts with acetone under certain conditions [] which could mean that there may be material stability problems with the use of acetone as a working fluid in copper pipes, this issue was neither purposely investigated nor was reported as an incidental observation in earlier studies that used this combination in heat pipes []. The material used in this study, brass, is an alloy of copper and zinc and is known to be more stable under corrosive conditions. It was thus presumed that stability of material will not be a problem when acetone is used as working fluid. Further, no color change, which is a typical indication of reactions between the materials, was observed neither in acetone nor the pipe surface during the course of experiments performed under this study wherein the acetone was left in contact with brass for long durations of time. However, more direct and thorough investigations are needed to address the issue of possible long term stability of copper and brass pipes when acetone is used as the working fluid in the heat pipes.

3.5 Effect of Heat Input

Effect of heat input on temperature difference for Methanol at 70% fill ratio and a 0° orientation is shown in Fig.12. From the figure, it is clear that the temperature difference between the evaporator and condenser decreases with an increase in heat input. Since the availability of thermal energy is less at the lower heat input, the fluid movement becomes very slow. This in turn is associated with a lot of perturbations with higher temperature difference between the evaporator and condenser at lower heat inputs. It is also observed that the increase in temperature difference increases as the time elapsed.

The heat input added at the evaporator increases the pressure and temperature of the vapor and would become the driving potential for fluid flow. The addition of heat contributes the mass influx for the adjacent plug due to vaporization of slug vapor. Hence the vapor plug density also increases. Consequently, a rising plug pressure is expected and the heat transport through the vapor is increased. The overall thermal resistance decreased drastically with the increase in heat input.

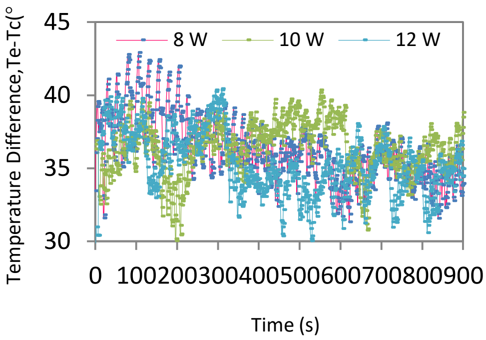

Fig. 12. Effect of heat input on temperature difference for methanol at 70% FR and 0° orientations.

3.6 Significance of Capillary Force in Pulsating Flow

The driving force causing the pulsating flow in a PHP has to overcome the (i) viscous force which arises due to the interaction between the liquid/vapor and the walls(ii) vapor pressure force which arises due to volume expansion and contraction of bubbles (iii) inertia force and(iv) capillary force which arise due to contact angle hysteresis. This capillary force may be positive or negative depending on the operating conditions. Capillary negative force diminishes the driving force whereas the capillary positive force help to boost up the pulsating flow.

Due to physical and chemical heterogeneity of the tubes used for making of PHPS, distinct values of the apparent angle are formed at two liquid/gas interfaces that are in contact with a liquid slug in a Taylor bubbles flow. These angles are dynamic in nature and known as apparent advancing θ_a and receding θ_r angles respectively depending on the direction of motion. The difference between the advancing and receding contact angles is known as contact angle hysteresis. The contact angle hysteresis gives rise to development of capillary forces and this contributes the additional pressure drop. Assuming the bubble cap radii are to be spherical in geometry, the capillary force acting across the section is estimated as;

$$F_{cap} = A\left(\frac{2\sigma}{R}\right)(-\cos\theta_a + \cos\theta_r). \quad (8)$$

If N plugs are blocking the flow in a capillary tube then the contribution of the capillary force is estimated

$$F_{cap} = AN\left(\frac{2\sigma}{R}\right)(-\cos\theta_a + \cos\theta_r). \quad (9)$$

The numerical model carried out on a pulsing flow in order to quantify the implication of various forces signifies that the increase in number of vapor bubbles fixing other operating conditions develops the capillary forces considerably when compared to pressure and viscous forces.

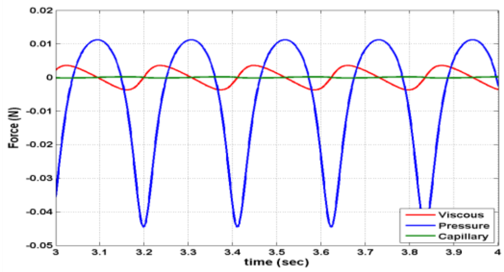

Fig. 13(a). Significance of capillary force for N=10 bubbles.

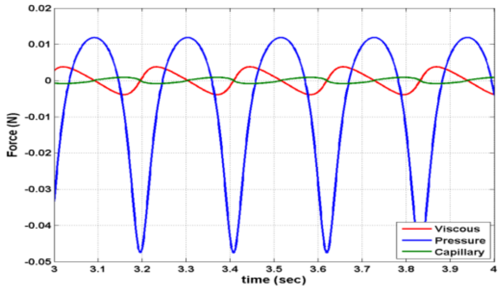

Fig. 13(b). Significance of capillary force for N=50 bubbles.

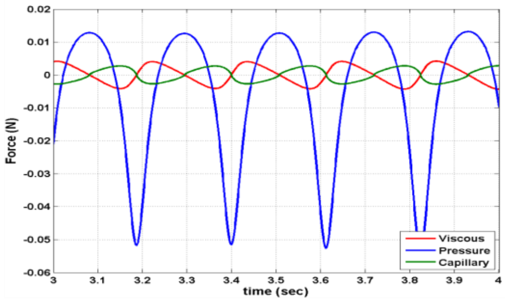

Fig. 13(c). Significance of capillary force for N=100 bubbles.

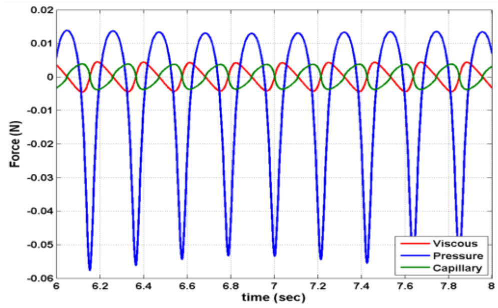

Fig. 13(d). Significance of capillary force for N=200 bubbles.

4. CONCLUSIONS

From the thermal performance study carried out on a horizontal single loop PHP made of brass, the following conclusions have been drawn ;

1. The variation in evaporator temperature with respect to the time is found to be periodic in nature due to continues pressure pulsations.
2. 80% fill ratio is witnessed as optimum for PHP operation enhancing heat transfer rate in the form of sensible heat.
3. Increase in diameter below the critical value enhances the heat transfer rate.
4. The slow and intermittent motion in the horizontal mode of operation causes the thermal resistance to enhance in the PHP.
5. The PHP performs better at 30°orientationpossessinglower fluid friction.
6. The lower values of latent heat of vaporization and surface tension for Acetone tend to form rapid vapor bubble generation which in turn enhances the fluid momentum and better heat transfer rate.
7. Increase in heat input decreases the thermal resistance at all orientations and hence observed better heat transfer rates.
8. As the number of vapor bubbles increases, development of capillary force is found to be significant when compared to pressure and viscous forces at fixed operating conditions.

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