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Experimental Investigations for Start Up and Maximum Heat Load of Closed Loop Pulsating Heat Pipe

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Abstract

Startup heat load, maximum heat load and optimum fill ratio of Pulsating Heat Pipe (PHP) of 16 turn, 1 mm ID, 2 mm OD and 9.6 m total length are found out experimentally for water and ethanol as working fluids. PHP is operated in vertical bottom heat mode. Evaporator and condenser temperatures are maintained at 100°C and 28°C respectively. Temperature fluctuations of adiabatic section at startup and maximum heat loads are reported. Experimental results indicate that, startup heat load is independent of fill ratio, but maximum heat load depends on fill ratio. Optimum fill ratio for maximum heat load depends on working fluid for a given PHP and operating temperatures.

Keywords: Pulsating Heat Pipe, Optimum Fill Ratio, Start up Heat Load, Maximum Heat Load

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Nomenclature

d	diameter (m)
g	gravity acceleration (m/s^2)
R	thermal resistance (°C/W)
Greek symbols	
σ	surface tension (N/m)
ρ	density (kg/m^3)
Subscripts	
cond	conduction
l	liquid
php	pulsating heat pipe
tot	total

1. Introduction

Pulsating Heat Pipe (PHP) is a two phases, metastable and passive heat transfer device. It is useful in various applications like chip cooling, air-conditioning, air to air heat exchanger, solar and waste heat recovery systems, due to its simple structure, ease of manufacturing and no maintenance cost. Akachi [1] was first to develop this new kind of heat pipe which works on pulsating movement of liquid slugs and vapor bubbles, known as Pulsating Heat Pipe (PHP). PHP consists of small inner diameter tubes or capillary tubes with number of U-turns. The evaporator and condenser sections are located in these U-turns with one end as a condenser section and other end as an evaporator section. In addition to these sections, PHP may have an adiabatic section, which is located between evaporator and condenser sections. PHPs can be categorized

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into two main types: open loop and closed loop. In open loop PHP, both ends are not connected, however in closed loop, the same are connected to each other. Closed loop has better circulation of working fluid than open loop and hence better thermal performance [2]. The success of PHPs lies in the closed (constant volume), vapor bubble and liquid slug system formed inside the tube-bundle due to the dominance of surface tension forces, which is possible if (a) inner diameter is small enough and satisfied by Eq. 1 [3] where, d_i, ρ_l, ρ_v, σ_l and g are inner diameter, liquid density, vapor density, liquid surface tension and gravity acceleration respectively (b) The fill ratio should be between 20 to 80% [4] (c) heat flux in the evaporator section should be sufficient to start the pulsation [2] known as startup heat flux.

$$d_i = 1.8\sqrt{\frac{\sigma_l}{g(\rho_l - \rho_v)}} \qquad (1)$$

Numbers of researchers have presented their experimental results for optimum fill ratio and maximum heat load of pulsating heat pipe [4] [5] [6] [7]. Yang *et al*., [6] reported the effect of fill ratio on the performance of pulsating heat pipe. Their experimental observations indicate that, the optimum fill ratio for maximum heat load at a given evaporator and condenser temperature lies between 40 to 70%. Zhang [8], reported, start up heat load of water, ethanol and FC-72 at particular fill ratios. But there is no further investigation for variation of start up heat load with fill ratio. It is also not known, whether start up heat load varies with fill ratio, in the same manner like maximum heat load. Present experimental investigations are similar to the experiment of Charoensawan *et al*., [4], only in terms of parametric variations that inner diameter, fill ratios and working fluids. But the experimental procedures and findings like start up and maximum heat load variations with fill ratio and optimum fill ratio are new. This paper deals with these investigations by presenting the experimental results of 16 turn, 1 mm ID, 2 mm OD and 300 mm total length PHP with evaporator, condenser and adiabatic lengths each 100 mm. Working fluids are water and ethanol. Evaporator and condenser temperatures are 100°C and 28°C respectively. PHP is operated in bottom heat load. Present experimental set up is also designed in an innovative way to maintain all most constant evaporator temperature with least variation and minimization of heat loss.

2. Experimental setup and procedure

Setup consists of three sections: evaporator, condenser and adiabatic sections. Evaporator section consists of an enclosure, SS 304 tube having 49 mm ID, 51 mm OD and 185 mm length. Evaporator section of the PHP is suspended inside this enclosure by a cover plate. Cover plate consists of a circular PVC sheet of 49 mm diameter and 5 mm thickness. 32 notches are made over the periphery of this plate to fix 32 copper tubes of 16 turn PHP. This plate is sealed to the top of the evaporator enclosure. This is shown in Fig. 1 (b). Water is filled in evaporator enclosure to a level of 50 mm. A 3M strip heater of 25.4 mm height and 152.8 mm length is stuck to the outer wall of the evaporator enclosure. Electrical resistance of this strip heater is 105.9 Ω. Thermocouple is attached to the evaporator container through a thermo-well of 5 mm ID and 45 mm length to measure the water temperature. The section is insulated by one layer ceramic wool insulation of 25.4 mm thickness. There are also provisions for vacuum gauge; silicon tube water level indicator and steam vent tube attachments. This is shown in Fig. 1 (c). The condenser section also consists of an enclosure, SS 304 tube having 49 mm ID, 51 mm OD and 120 mm length. The condenser section of the PHP is completely submerged inside the enclosure. The PHP is attached to the enclosure by another cover plate like evaporator section. The condenser enclosure has inlet and outlet ports for cooling water. The adiabatic section consists of bare tubes and a T-section of internal diameter 2 mm for evacuation and charging. The adiabatic section is insulated like evaporator section. This is shown in the Fig. 1 (c). The 16 turn PHP is tested for 0, 25, 37.5, 50, 62.5, 75 and 100% fill ratios after evacuation and charging. After each fill ratio, evacuation is carried out by vacuum pump and PHP is charged with working fluid by injection syringe. Four thermocouples are connected at four different locations of two tubes. These tubes are part of adiabatic sections. Two K-type thermocouples are attached at a distance of 15 mm from condenser section and other two K-type thermocouples are at a distance of 15 mm from evaporator section. Adiabatic temperatures are recorded by NI DAS for different heat inputs. Complete experimental set up with NI DAS is given in Figure 1(a).

Thermocouples with DAS were calibrated and maximum error found as ±1.4°C. Maximum error in power meter was ±1.3%. Experiment starts with, setting a higher heat input at around 100 W for 10 to 12 minutes, so that water in evaporator section boils and steam is generated. As evaporator container is open to atmosphere, this ensures constant evaporator temperature of 100°C. Condensation of steam over evaporator section of PHP provides heat input. Due to high heat transfer coefficient of condensation heat transfer, wall temperature variation is limited to 0.5°C. Similarly, cooling water flow rate in condenser container is adjusted to maintain a constant condenser temperature of 28°C, where heat rejection from PHP takes place. Due to convection current inside condenser container, temperature variation along length of condenser section of PHP is limited to 1.0 to 1.5°C and average PHP condenser surface temperature variation with heat loads is limited to ±2°C. The heat input increases in steps of 1.0 W for these fill ratios and if there is an initiation of temperature fluctuations, which are indicated by four thermocouples attached to adiabatic section, corresponding heat input is taken as start up heat load. Similarly for maximum heat load, the steam vent tube is continuously observed. At maximum heat load, steam is about to come out of the vent tube. At these fill ratios experiments are repeated for several runs for verify repeatability.

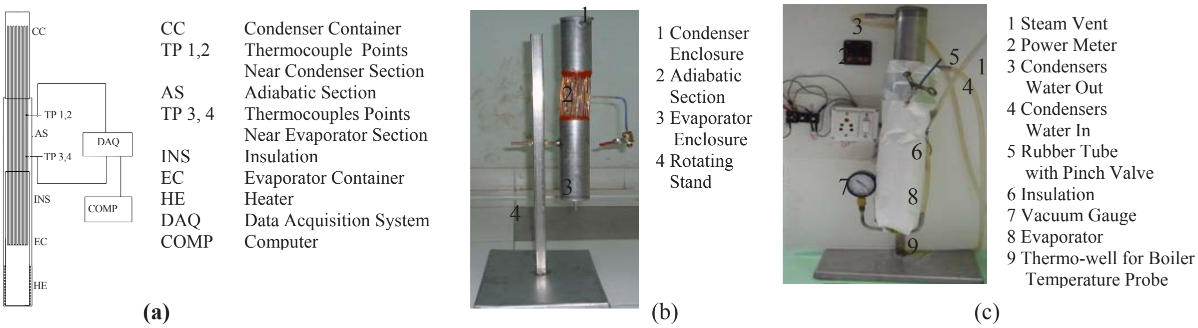

Fig. 1: (a) Schematic of PHP setup (b) Photograph of PHP setup without insulation(c) Photograph of PHP Setup with insulation

3. Results and discussions

Heat losses for various heat loads have been determined experimentally and heat load for a particular heat input is found out by curve fitting of these experimental data. Heat losses are in the range of 6 to 8 W. Once water in evaporator container attains 100^{o}C, maximum heat load of PHP is tested at 0% and 100% fill ratio for water and ethanol as working fluids. It has been observed that, heat load at 0% is 19.8 W and at 100% fill ratio, 20.3 and 21.3 W for ethanol and water as working fluids respectively. These heat loads exclude losses. Higher heat loads at 100% fill ratio are due to higher thermal conductivities of liquids. As thermal conductivity of water is more than that of ethanol, water as a working fluid has more heat load than that of ethanol at 100% fill ratio.

3.1. Start up heat load

Once water starts boiling, heat input is reduced to 6.0 W, because of heat loss in the range of 6 to 8 W and increased in steps of 1 W to observe initiation of temperature fluctuation of adiabatic section. Temperature fluctuations are given in Figure 2 and 3 for water and ethanol as working fluids at start up for various fill ratios. Time interval for temperature data is taken as 10 s. These temperatures are indicated by one of the thermocouple, which is close to condenser section (TP 1 in Fig. 1 (a)). Temperature fluctuations for a particular fluid are all most similar for different fill ratios. As indicated by Qu and Ma [2], start up condition of PHP occurs by nucleation. Nucleation occurs at favourable sites inside evaporator section of PHP. At these sites, vapour bubbles are formed and grow, which increase pressure. Oscillation starts due to this pressure imbalance. It can be observed from Figs. 2-3 that, there is a waiting period of 22 to 23 minutes both for water and ethanol as working fluids. During this period, heat is accumulated to raise the liquid temperature to its boiling temperature, after which boiling starts and vapour bubbles grow at nucleation sites, create pressure imbalance and start pulsation. During waiting period, pressure difference is not sufficient to sustain pulsation. It has been observed that, minimum heat load required for temperature fluctuations for a particular fluid is almost independent of fill ratio. In present experiment, start up heat load variations with fill ratios for water and ethanol are 20.2 to 21 W and 12.5 to 13.9 W respectively. These heat loads exclude heat losses to ambient. Liquid plugs and vapour bubbles are distributed naturally inside PHP. This small variation in start up heat load and waiting period may be because of variations in initial distribution of liquid plugs inside PHP. Nucleation occurs at inner surface at favourable sites, where liquid plugs are present. Heat transfer for nucleation and bubble growth occurs directly to these liquid plugs, if they are present in evaporator section, otherwise heat transfer occurs by axial conduction through wall of the PHP to these liquid plugs. So start up heat load hardly depends on fill ratio. Higher start up heat load for water can be attributed to higher latent heat, higher thermal conductivity and higher thermal mass than that of ethanol.

3.2. Maximum heat load

Temperature oscillations at maximum heat load for water and ethanol are given in following Figs. 4-5. Water and Ethanol have maximum heat loads at 62.5 and 50% fill ratios respectively, which are known as optimum fill ratios. Maximum heat loads are 56 and 96 W for water and ethanol respectively. Time interval for temperature data collection in this case has been reduced to 0.1 s for capturing temperature fluctuations, which have higher frequency than that of startup condition frequency. It can be observed from these figures that, resulting temperature oscillations are superposition of short cycle period and long cycle period oscillations, which are known as local flow direction switch and bulk circulation respectively as reported by flow visualization study of Xu *et al.* [9]. More short cycle period oscillations and smalle time period, in

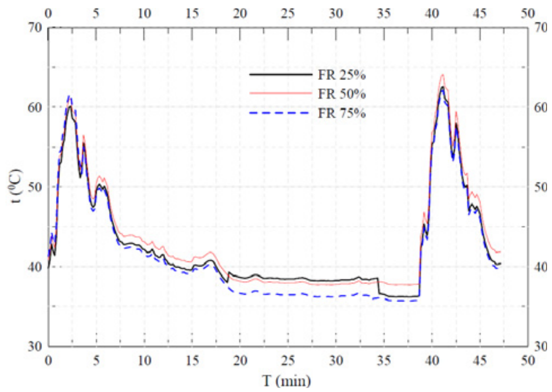

Fig. 2: Temperature Oscillation of Water at Start up (n_{turn} 16, l_{tot} 300 mm, d_i 1 mm, t_e 100°C, t_c 28°C)

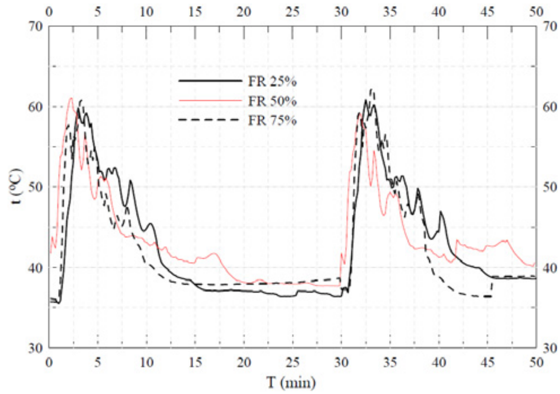

Fig. 3: Temperature Oscillation of Ethanol at Start up (n_{turn} 16, l_{tot} 300 mm, d_i 1mm t_e 100°C, t_c 28°C)

case of ethanol may be due to lower latent heat of vaporization. Fig. 6 shows, PHP thermal resistance variations with fill ratio for water and ethanol as working fluids. These thermal resistances exclude losses. Thermal resistance of PHP can be calculated by following Eq. 2, where $R_{tot,}$ R_{cond} and R_{PHP} are total thermal resistance, conduction resistance and PHP resistance respectively.. Thermal resistance is ratio of temperature difference and heat load. Heat loads are taken at 0% fill ratio, for calculating R_{cond} and heat load at particular fill ratio is taken for calculating corresponding R_{tot}. As shown in this figure, R_{cond} is 3.63 °C/W, R_{PHP} decreases with increase with fill ratio, attains a minimum value at optimum fill ratio and increases with further increase in fill ratio. Minimum PHP thermal resistances are 2 and 0.95 °C/W for water and ethanol respectively. As reported by different researchers, major part of heat transfer in PHP, around 90%, consists of sensible heat transfer between liquid plug and tube wall [10] [11] [12].

$$\frac{1}{R_{tot}} = \frac{1}{R_{cond}} + \frac{1}{R_{PHP}} \tag{2}$$

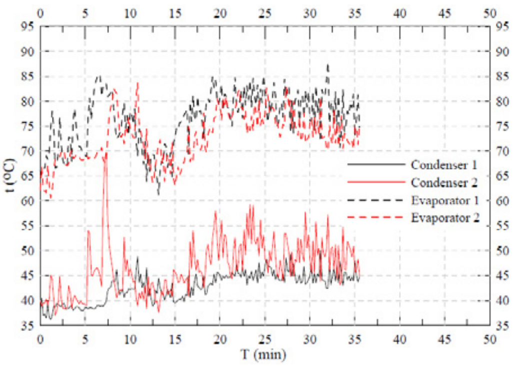

Fig. 4: Temperature Oscillation of Water at Maximum Heat Load (n_{turn} 16, l_{tot} 300 mm, d_i 1mm, t_e 100°C, t_c 28°C, FR 62.5%)

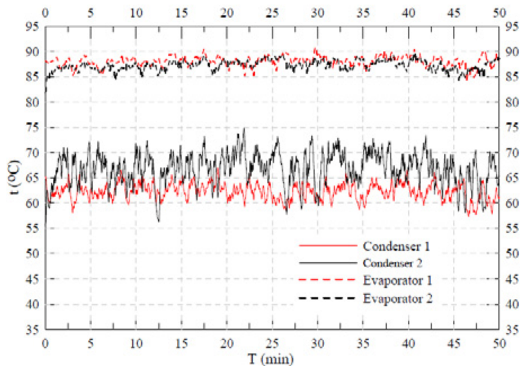

Fig. 5: Temperature Oscillation of Ethanol at Maximum Heat Load (n_{turn} 16, l_{tot} 300 mm, d_i 1mm, t_e 100°C, t_c 28°C, FR 50%)

Oscillating motion in PHP is similar to forced vibration of spring mass damper system [13]. Oscillation frequency is same as driving force frequency, which depends on operating temperatures. At lower fill ratio, average length of liquid plug is small, oscillation and velocity amplitudes are high. Liquid plugs take less time to attain tube surface temperature due to smaller length and higher heat transfer coefficient between tube wall and liquid plug. As a result, no heat transfer takes place during rest of liquid plugs travel which limits heat load of PHP. In the contrary, at high fill ratio, average length of liquid plugs is more; oscillation and velocity amplitude are less. In this case, heat transfer coefficient between tube wall and liquid plug is less due to lower velocity and liquid plug travel over the tube surface is also less due to lower amplitude. So, most parts of liquid plugs do not contribute to heat exchange between wall and liquid plug which limit heat transfer rate. So there has to be an optimum fill ratio for maximum heat transfer rate. This optimum fill ratio depends on thermo physical properties of working fluid, operating temperatures and PHP parameters.

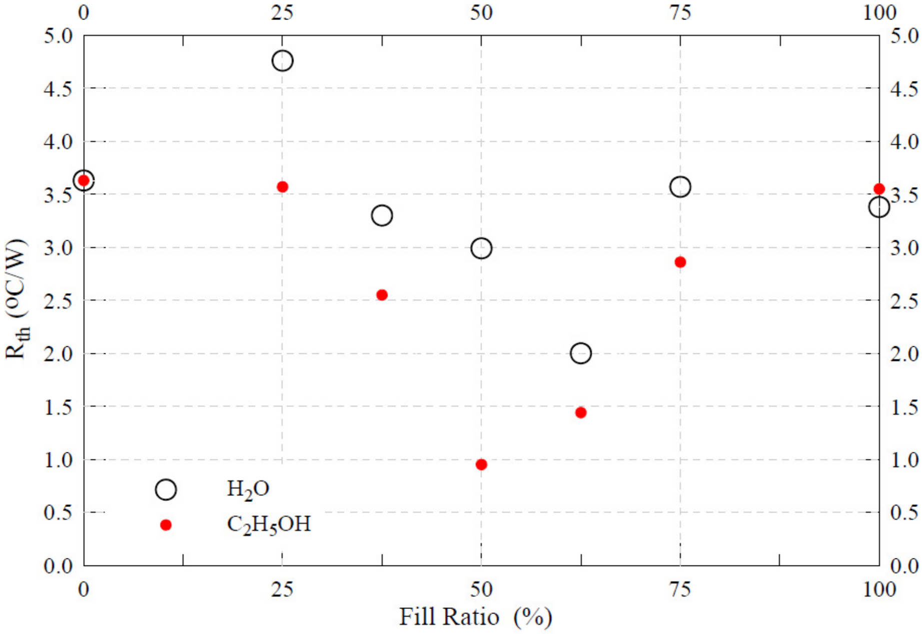

Fig. 6: Variation of Thermal Resistance with Fill Ratio (n_{turn} 16, l_{tot} 300 mm, d_i 1mm, t_e 100°C, t_c 28°C, excluding losses)

4. Conclusions

Experimental results of 16 turn, 300 mm total length and 1 mm ID PHP was presented for water and ethanol as working fluids. Evaporator and condenser temperatures were maintained at 100°C and 28°C respectively. Initiation of pulsation was detected by observing temperature oscillation of adiabatic section. Corresponding heat load at this pulsation was start up heat load. Start up heat load variations were 20.1 to 21 W and 12.5 to 13.9 W excluding losses for water and ethanol respectively. Waiting periods were 20 to 23 minutes. It was also observed that start up heat load does not vary with fill ratio. Maximum heat loads are 56 and 96 W for water and ethanol as working fluids respectively and corresponding minimum PHP thermal resistances are 2°C/W and 0.95°C/W. This optimum fill ratio depends on thermo physical properties of working fluid, operating temperatures and PHP parameters.

Acknowledgements

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