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Thermal Performance of Closed Loop Pulsating Heat Pipe Using Different Working Fluid: A Review

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ABSTRACT: *Heat pipe is very efficient device for dissipating heat from the device. But new technology introduces which is nothing but Pulsating Heat Pipe. Thermodynamic characteristic of PHP is been highlighted in this paper. Three thermo dynamical boundary condition should be met to make PHP work properly which includes internal tube diameter, the applied heat flux and amount of the working fluid in the system. Number of turns of the device and thermo physical properties of the working fluid also plays vital role in determining thermal behavior apart from this fluid.Unsolved issues regarding PHP with various working fluid and application are discussed.*

KEYWORDS: *pulsating heat pipe*

I. INTRODUCTION

Akachi proposed and patented Pulsating or Loop type Heat Pipein 1990s [1]. It is a member of wickless heat pipes the oscillation of working fluid and phase change phenomina in capillary tube is basic principle. To make liquid and vapour plugs to exist diameter of tube must be small. It can work at higher heat fluxes. It has excellent feature like high thermal performance, rapid response to high heat load, simple design and low costSo PHP has been considered as one of the promising technology regarding electric cooling, cell cryopreservation, the spacecraft thermal control system, etc.A Pulsating heat pipe consists of meandering tube of capillary dimensions with many U-turns, as see in figure 1[2]. In contrast to a conventional heat pipe, there is no additional capillary structure inside the tube. There are three ways to arrange the tube- Open Loop System, Closed Loop System, and Closed Loop System with additional flow control check valves As the name suggest, in close loop structure, the tube is joined end to end. The tube is evacuated and then filled partially with working fluid, which distributes itself naturally in the form of liquid vapor plugs and slugs inside the capillary tube. One end of this tube receives heat, transferring it to the other end by pulsating action of the liquid vapors/ bubble slug system. There may exist an optional adiabatic zone in between evaporator and condenser.

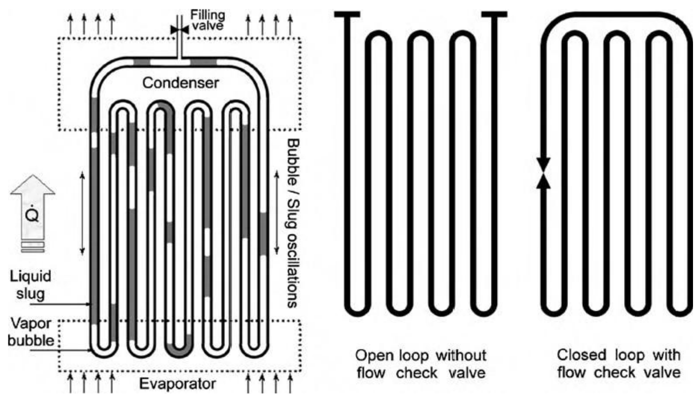

Figure1. Schematic of a pulsating heat pipe and its design variations [2]

The PHP is first evacuated and then partially filled with the working fluid. Effects from surface tension cause the formation of liquid slugs interspersed with vapor bubbles. When one end of the bundle of turns of the undulating capillary tube is subjected to high temperature, the working fluid inside evaporates and increases the vapor pressure, which causes the bubbles in the evaporator zone to grow. This pushes the liquid column toward the low temperature end (condenser). The condensation at the low temperature end will further increase the pressure difference between the two ends. Because of the interconnection of the tubes, motion of liquid slugs and vapor bubbles at one section of the tube toward the condenser also leads to the motion of slugs and bubbles in the next section toward the high temperature end (evaporator). This works as the restoring force. The inter-play between the driving force and the restoring force leads to oscillation of the vapor bubble and liquid slugs in the axial direction. The frequency and the amplitude of the oscillation are expected to be dependent on the shear flow and mass fraction of the liquid in the tube

II. PRINCIPLES OF OPERATION

1. Thermodynamic Principles

Heat addition and rejection and the growth and extinction of vapor bubbles drive the flow in a PHP. Even though the exact features of the thermodynamic cycle are still unknown, Groll and Khandekar [3] described it in general.

2. Fluid Dynamic Principles

Fluid flow in a capillary tube consists of liquid slugs and vapor plugs moving in unison. The slugs and plugs initially distribute themselves in the partially filled tube. The liquid slugs are able to completely bridge the tube because surface tension forces overcome gravitational forces. There is a meniscus region on either end of each slug caused by surface tension at the solid/liquid/vapor interface. The slugs are separated by plugs of the working fluid in the vapor phase. The vapor plug is surrounded by a thin liquid film trailing from the slug.

3. Heat Transfer Principles

As the liquid slugs oscillate, they enter the evaporator section of the PHP. Sensible heat is transferred to the slug as its temperature increases, and when the slug moves back to the condenser end of the PHP, it gives up its heat. Latent heat transfer generates the pressure differential that drives the oscillating flow. The phase change heat transfer takes place in the thin liquid film between the tube wall and a vapor plug and in the meniscus region between the plug and slug, which requires complex analysis.

III. INFLUENCE PARAMETERS AFFECTING PHP PERFORMANCE

Looking into the available literature, it can be seen that six major thermo-mechanical parameters have emerged as the primary design parameters affecting the PHP system dynamics. These include [4]:

a. Internal diameter of the PHP tube,
b. Input heat flux to the device,
c. Volumetric filling ratio of the working fluid,
d. Total number of turns,
e. Device orientation with respect to gravity, and
f. Working fluid thermo-physical properties.

Other conditions which influence the operation are:

a. Use of flow direction control check valves,
b. Tube cross sectional shape,
c. Tube material and fluid combination, and
d. Rigidity of the tube material, etc.

Apart from these variables, the performance is also strongly linked with the flow patterns existing inside the device (which in turn depends on the complex combination of other design parameters). Various flow patterns other than capillary slug flow, e.g. bubbly flow, developing or semi-annular flow and fully developed annular flow (in case of CLPHPs) have also been reported which have a significant effect on the thermal performance of the device.

1. Tube Diameter

The internal tube diameter is one of the parameters which essentially define a PHP. The physical behavior adheres to the 'pulsating' mode only under a certain range of diameters. The critical Bond number (or Eötvös) criterion gives the tentative design rule for the diameter. The theoretical maximum inner diameter of capillary tube can be calculated as-

$$D_{cri} = 2\sqrt{\left(\frac{\sigma}{g\,(\rho_l - \rho_v)}\right)}$$

If D < Dcri, surface tension forces dominate and stable liquid plugs are formed. However, if D > Dcri, the surface tension is reduced and the working fluid will stratify by gravity and oscillations will cease. The OHP may operate as an interconnected array of two-phase thermosyphons.

2. *Applied Heat Flux*.

The applied heat flux affects the following

1.1 Internal bubble dynamics, sizes and agglomeration/breaking patterns,

1.2 Level of perturbations and flow instabilities, and

1.3 Flow pattern transition from capillary slug flow to semi-annular and annular.

PHPs are inherently suitable for high heat flux operation. Since the input heat provides the pumping power, below a certain level, no oscillations commence. In case of CLPHPs, a Unidirectional circulating flow has been observed at high heat fluxes. In addition, the flow also gets transformed from oscillating slug flow to annular flow. Once a flow direction is established, alternating tubes sections become hot and cold (hot fluid flows from evaporator in one tube and cold fluid from the condenser flows in the adjacent tube). Further increase of heat flux will lead to some dry out mechanism(s) induced by thermo-hydrodynamic limitations. These have not been clearly identified and studied so far.

3. Working Fluids

A First consideration in the selection of a suitable working fluid is the operating vapor temperature range. Within the approximate temperature band, (50 to 150 ^{o} C) several possible working fluids may exist. A variety of characteristics must be examined in order to determine the most acceptable of these fluids for the application considered. The prime requirement are: compatibility with heat pipe material, thermal stability, wettability, reasonable vapor pressure, high latent heat and thermal conductivity, low liquid and vapor viscosities, and acceptable freezing point.For most commercial electronics cooling applications, the thermodynamic attributes of water makes it better than any other fluids for the pulsating heat pipes. Its high latent heat spreads more heat with less fluid flow. This result in low pressure drops and high power throughout. Its high thermal conductivity minimizes the temperature difference associated with conduction through the two phase flow in the PHP. Water is also a safe substance.Although water high surface tension allows a it to generate a large capillary force and allow the heat pipe to operate in any orientation. It may have adverse effect on the operation of PHP in other words, the high surface tension may cause additional frictional and hinder the two phase flow oscillation in the PHP. Methanol with lower surface tension (about 1/3rd of water) is a good substitute particularly if the heat pipe is used for sub ^{0}C application [5].

4. Total Number Of Turns

The number of turns increases the level of perturbations inside the device. If the number of turns is less than a critical value, then there is a possibility of a stop-over phenomenon to occur. In such a condition, all the evaporator U-sections has a vapor bubble and the rest of the PHP has liquid. This condition essentially leads to a dry out and small perturbations cannot amplify to make the system operate self-sustained.

IV. DESIRABLE PROPERTIES OF WORKING FLUID

The experience gained so far by earlier studies suggests that the working fluid employed for pulsating heat pipes should have the following properties:

· High value of (dP/dT)sat: ensuring that a small change in evaporator temperature generates a large change in corresponding Psat inside the generated bubble which aids in the bubble pumping action of the device. The same is true in reverse manner in the condenser

. Low dynamic viscosity: This generates lower shear stress.

· Low latent heat: should be desirable, aiding quick bubble generation and collapse, given the fact that sensible heat is the predominant heat transfer mode.

· High specific heat: is desirable complimenting the low latent heat requirement; although there are no specific studies which explicitly suggest the effect of specific heat of the liquid on the thermal performance. It is to be noted that if a flow regime change from slug to annular takes place, the respective roles of latent and sensible heat transport mechanism may considerably change, as explained earlier. This aspect requires further investigation.

· Low surface tension: This, in conjunction with dynamic contact angle hysteresis may create additional pressure drop.

The above noted property trends are based on the available knowledge so far and are subject to change as more studies reveal the thermo-mechanical physics. In addition, quite often instead of individual thermo physical properties, groups of properties affect complex real systems like PHPs result in low pressure drops and high power throughout. Its high thermal conductivity minimizes the temperature difference associated with conduction through the two phase flow in the PHP. Water is also a safe substance.

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V. EFFECT OF WORKING FLUIDS

Kaya and Ku [7] have compared the LHP performance by using three different working fluids: ammonia, water and acetone. The model results are shown in Figure 2. It can be seen that the PHP operating limits are different for each working fluid. The water and acetone PHPs are limited by the absolute vapour pressure at low power levels: the absolute vapour pressure represents the maximum pressure that is available to overcome the total system pressure drops, even when the theoretical capillary pressure head is higher than the total pressure drops. A low pressure corresponding to a fluid temperature near the freezing point severely limits the PHP operation. While ammonia exhibits many desirable heat transfer characteristics, its freezing point is too high to prevent freezing in the condenser line during a safe mode on a satellite platform.

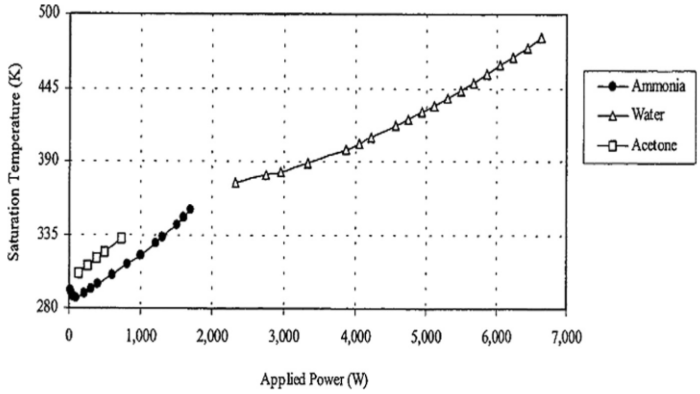

Fig. 2. Effect of the working fluid on the LHP operating temperature (Kaya and Ku [7]).

S.Khandekar et.al. [8] [2002] were conducted Experiments on a PHP made of copper capillary tube of 2-mm inner diameter. Three different working fluids viz. water, ethanol and R-123 were employed. The PHP was tested in vertical (bottom heat mode) and horizontal orientation. The results strongly demonstrate the effect of input heat flux and volumetric filling ratio of the working fluid on the thermal performance of the device.Wide range of experimental studies of pulsating heat pipes is thereby providing vital information on the parameter dependency of their thermal performance by P.Charoensawan *et.al.* [9] [2003]. The influence characterization has been done for the variation of internal diameter, number of turns, working fluid and inclination angle of the device. CLPHPs are made of copper tubes of internal diameters 2.0 and 1.0 mm, heated by constant temperature water bath and cooled by constant temperature water–ethylene glycol mixture. The number of turns in the evaporator is varied from 5 to 23. The working fluids employed are water, ethanol and R-123. The results indicate water filled devices showed higher performance as compared to R-123 and ethanol in vertical orientation for the 2.0 mm devices. In contrast R-123 and ethanol showed comparable performance in case of1.0 mm devices with water showing very poor results. This is seen in Fig.5

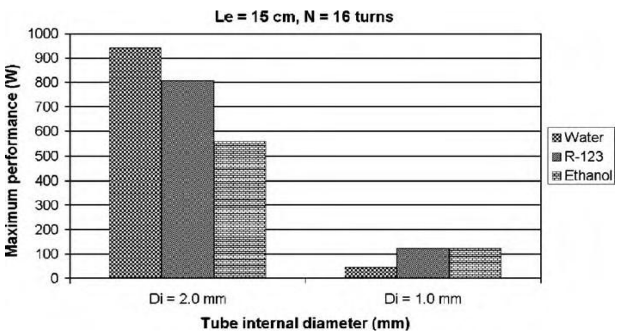

Fig. 5. Effect of working fluid on the thermal performance [9].

P. Meena *et.al.* [10] [2009]. A set of CLOHP/CV was made of copper tubes in combination of following dimension: 1.77 mm inside diameter: 10 turn: 5, 10 and 15 cm equal lengths for evaporator, adiabatic and condenser sections. The working fluid was filled in the tube at the filling ratio of 50%. The evaporator section was given heat by heater while the condenser section was cooled by volume water in a cold bath. The results obtained, as follows. When working fluids change from R123 to Ethanol and water the critical heat flux decreased.

VII. UNSOLVED ISSUES RELATED TO WORKING FLUIDS

1. At different situations, different pure working fluids have their advantages. But till now, mixtures used as working fluids in PHP have not been thoroughly investigated. The non-azeotropic mixtures, which have the characteristics of phase transition with temperature floating, can make heat source and working fluids match well in temperature [11].
2. The optimum quantity of working fluid needed depends on various parameters and is still an area of research [9].

VIII. CONCLUSION

PHPs are highly attractive heat transfer elements, which due to their simple design, cost effectiveness and excellent thermal performance may find wide applications. Since their invention in the early nineties, so far they have found market niches in electronics equipment cooling. The work compiled here significantly increases the understanding of the phenomena and effect of working fluids that govern the thermal performance of pulsating heat pipes. Many unsolved issues related to working fluids still exist, but continued exploration should be able to overcome these challenges.

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