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PULSATING HEAT PIPES: A CHALLENGE AND STILL UNSOLVED PROBLEM IN HEAT PIPE SCIENCE

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ABSTRACT

Modern micro electronics thermal management is facing considerable challenges in the wake of miniaturizing of components leading to higher demands on net heat flux dissipation. This paper highlights the salient features of Pulsating Heat Pipes (PHPs), a novel research topic in the heat pipe science. This apparently simple cooling device, is considerably intriguing for theoretical and experimental investigations alike. Fundamental operating principle, flow characteristics, design parameters and limitations are discussed in detail. The unresolved open questions which are subject to further investigations are also outlined.

Keywords: electronics cooling, pulsating heat pipe, slug flow.

INTRODUCTION

A closed loop pulsating or oscillating heat pipe consists of a metallic tube of capillary dimensions wound in a serpentine manner and joined end to end as shown in Figure 1. It is first evacuated and then filled partially with a working fluid, which distributes itself naturally in the form of liquid-vapor plugs and slugs inside the capillary tube. One end of this bundle of tubes receives heat transferring it to the other end by a pulsating action of the liquid-vapor system. There may exist an optional adiabatic zone in between. A PHP is essentially a non-equilibrium heat transfer device, performance success of which primarily depends on the continuous maintenance or sustenance of these non-equilibrium conditions within the system. The liquid-vapor slug transport is due to thermally driven pressure pulsations in the respective tubes. There is no external power source required for fluid transport as in the case of DREAM Pipes [1,4].

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Consider a case when a PHP is kept throughout isothermal. In this case the liquid and vapor phases must exist in equilibrium at a saturation pressure corresponding to the fixed isothermal temperature. In Figure 2, points A and B represent the thermodynamic state of all the liquid and vapor plugs respectively, irrespective of their sizes and positions. Let the temperature of the entire PHP be quasi-statically increased to a new fixed value. Then the liquid-vapor slug system will slowly come to a new corresponding saturation pressure, point A' and B'. In doing so, there will be some evaporation mass transfer from the liquid until new equilibrium is reached again. A similar phenomenon will be observed if the system is quasi statically cooled to new equilibrium points A" and B" (exaggerated for clarity). In an actual working PHP, there exists a temperature gradient between heater and cooler. Temperature differences also exist amongst the U-bends of the heater and the condenser due to local non-uniform heat transfer rates, always expected in real systems. The net effect of these temperature gradients is to cause non equilibrium pressure conditions, which provide the primary driving forces for thermo-fluidic transport. In this way a sustained non-equilibrium state exists between the driving thermal potentials and the natural causality which tries to equalize the internal pressure. Thus self-sustained thermally driven oscillating flow is obtained.

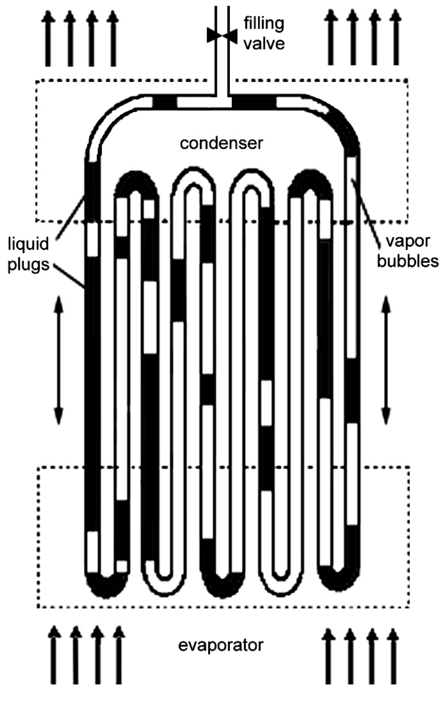

Fig. 1. Schematic of a PHP

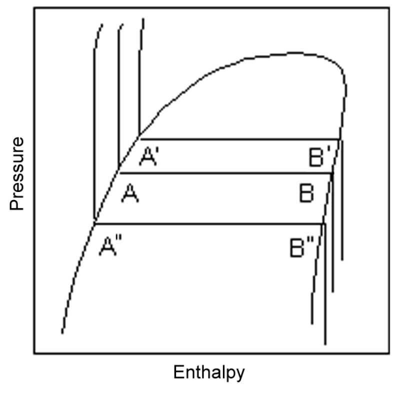

Fig. 2. Typical p-h diagram

1. DESIGN PARAMETERS

Various experimental investigations have been done with the aim of parametric study of a PHP [8,9,10]. The results may be summarized by the parameter dependency chart as shown in Figure 3. It is evident that there are multiple variables which simultaneously affect the operation and performance of PHPs.

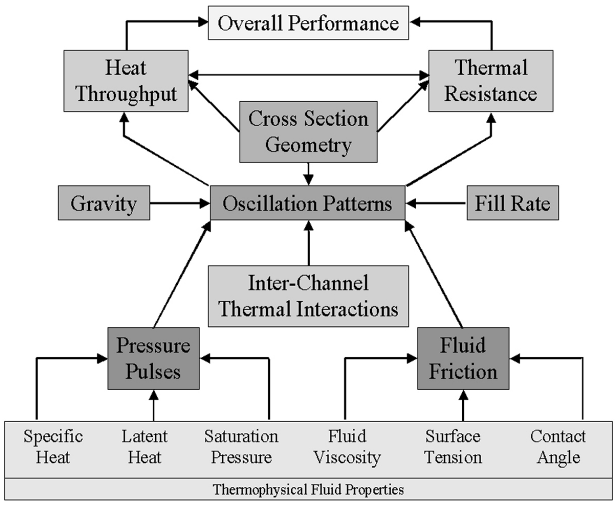

Fig. 3. Parameter dependency chart of a PHP [9]

2. OPERATIONAL CHARACTERISTICS

A typical liquid plug along with the adjoining vapor bubbles is shown in Figure 4. The liquid and vapor plugs are subjected to pressure forces from the adjoining plugs, internal viscous dissipation and wall shear stress as they move. In the evaporator, liquid plugs receive heat simultaneously followed up by evaporation mass transfer to adjoining vapor bubbles. The liquid plugs may also break up with creation of new bubbles in between as a result of nucleate boiling. The saturation pressure and temperature thus increase locally. Probability of events frequently places vapor bubbles in direct contact with the evaporator tube surface. In this case the bubbles receive heat through the liquid thin film with simultaneous evaporation. These processes are repeated in a reverse direction in the condenser. In the adiabatic section, while passing from the evaporator to the condenser, complex, non equilibrium, metastable conditions exist. There occurs no classical steady state in a PHP operation.

A given PHP has two operational extremities with respect to the filling charge, i.e. 0% filled (or an empty device) and 100% filled. It is obvious that at 0% fill ratio, a PHP structure with only bare tubes and no working fluid, is a pure conduction mode heat transfer device and obviously has a very high thermal resistance. A 100% fully filled

PHP is identical in operation to a single-phase thermosyphon. Since there exist no bubbles in the tube, 'pulsating' effect is obviously nonexistent but substantial heat transfer can take place due to liquid circulation in the tubes by thermally induced buoyancy [7].

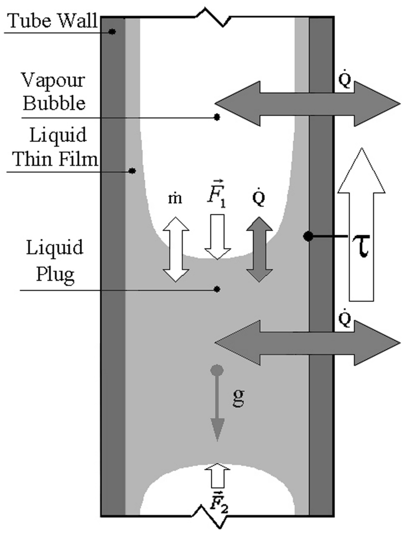

Fig. 4. A typical liquid plug

In between these two extremities lies the present area of interest. In this region also there exist three distinct sub-regions (Figure 5):

(a) Nearly 100% fill ratio: In this mode there are only very few bubbles present rest being all liquid phase. These bubbles are not sufficient to generate the required perturbations and the overall degree of freedom is very small. The buoyancy induced liquid circulation, which was present in 100% filled PHP, gets hindered due to additional surface tension generated friction of the bubbles. Thus the performance of the device is seriously hampered and the thermal resistance much higher than for the 100% filled PHP.

(b) Nearly 0% fill ratio: In this mode there is very little liquid to form enough distinct slugs and there is a tendency towards dry-out of the evaporator. The operational characteristics are unstable. The device may, under some operating conditions, work as a two-phase thermosyphon.

(c) PHP true working range: Between about 10% to 90% fill charge the PHP operates as a true pulsating device. The exact range will differ for different working fluids, operating parameters and construction. More the bubbles (lower fill charges), more is the degree of freedom but simultaneously there is less liquid mass for sensible heat transfer. Less bubbles (higher fill charges) cause less perturbations and the bubble pumping action is reduced thereby lowering the performance. Thus an optimum fill charge exists.

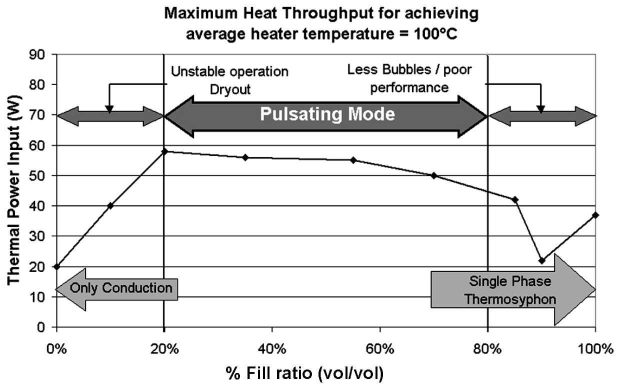

Fig. 5. Operational regimes of PHP [6]

3. FLOW CHARACTERISTICS

The flow pattern existing in a PHP can be broadly classified as capillary slug flow. Although some other types of flow / bubble patterns have been observed [7] slug flow dominates in major portions. Since a PHP is expected to function at all orientations, it is important to distinguish the salient characteristics of capillary slug flow in vertical, horizontal and inclined positions. In general, common features of capillary slug flow are as follows [11]:

- The flow can exist in horizontal as well as vertical flow due to the strong dominance of surface tension. In other words, the general flow pattern in a capillary tube is not severely affected by the flow direction.
- If the wettability of the continuous phase (liquid) is good, it has always been observed that the movement of the suspended phase (bubble) takes place inside a thin film of the continuous phase.
- Separated flow is hardly seen. The flow pattern is axisymmetric irrespective of the flow direction. As the pipe size decreases, the circumferential distribution of film thickness becomes more uniform causing an axisymmetric flow pattern. The smaller the pipe size, the thinner the liquid film around a large bubble.
- For a general case, the velocity of bubbles in slug flow is affected simultaneously by viscous, inertia, interfacial tension and buoyancy forces (in case of vertical flow).
- Small bubbles in a liquid plug or in a liquid film are scarcely observed.
- Dynamic contact angle hysteresis may cause additional pressure drop.
- In horizontal slug flow, there is no drift flux due to buoyancy. Nevertheless the bubbles still move faster than the average liquid velocity as the available area for flow is less due to the presence of liquid thin film.
- It is believed that some metastable flow conditions exist in the condenser tube. Flashing of the vapor is imminent as the fluid pressure falls during the flow. Instantaneous subcooling and superheating are also expected as mass transfer within the two phases has a finite inertia.

The pressure drop in a slug flow is conveniently divided into three parts:

1. Pressure drop in the liquid slug,
2. Pressure drop around the ends of the bubble and
3. Pressure drop along the body of the bubble, which is practically zero.

The last point is supported by the fact that if the gas density and velocity are much lower than those of the liquid, the gas in the bubble is practically at constant pressure. Further, if the bubble curvature is constant, pressure drop cannot exist in the bubble body. It has also been observed that the terminal velocity of cylindrical bubbles rising vertically upwards in stagnant liquid is generally unaffected by the length of the bubble, thus supporting the theory.

Therefore, if we compare the pressure drop of two-phase capillary slug flow with that of the single-phase flow, it is observed that an approximately triangular or saw-tooth alternating component of pressure drop is superimposed on the average pressure gradient as shown in Figure 6 This can excite oscillations and pressure perturbations in the flow. The modeling of actual pressure drop is complicated due to frequent flow reversals, chaotic behavior and bubble agglomeration patterns.

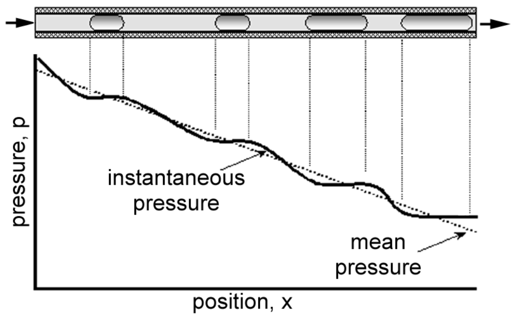

Fig. 6. Pressure drop in slug flow

4. SENSIBLE VS. LATENT HEAT TRANSFER

In a conventional heat pipe, latent heat of vapor is the primary medium of heat transport. While *prima facie*, the two-phase flow characteristics of a PHP apparently suggest that latent heat may also play a sizable role, it is quite the contrary. This can be explained as follows:

A PHP is a constant volume device and if maintained throughout at a fixed temperature, liquid and vapor slugs will be in thermodynamic equilibrium at saturated conditions. If a vapor bubble is collapsing, thereby giving away its latent heat, there has to be a complimentary bubble generation elsewhere in the system, either by flashing or by receiving heat from the environment since the overall volume of the system is constant. Therefore it follows that when a PHP is operating in nearly steady state, the time averaged fill ratio (volume of liquid / total volume) remains constant.

Operating the device at a slightly higher temperature necessarily maintains the same average fill ratio while the average vapor density in the bubbles increases.

In the desired operating temperature range of say, 20°C to 120°C, the saturated liquid density of usual working fluids is an order of magnitude greater than the corresponding saturated vapor density. Experimental evidence suggest that PHPs usually operate with a fill ratio of about 30% to 80%. Therefore the actual mass of the vapor bubbles is significantly lower than the mass of the liquid plugs. Therefore even if complete condensation and collapse of vapor bubbles is considered, the latent heat transported is significantly lower than the corresponding sensible heat transfer from liquid plugs during this time. For example, if saturated water and vapor mixture at 100°C leaves one of the evaporator U-tubes of a PHP and comes out of the condenser tube as saturated water at 30°C, assuming a fill ratio = 0.5, the ratio of latent to sensible heat transfer is about 5.55×10^{-3}. Therefore latent heat does not play a major role in the thermal performance of PHPs. Nevertheless, bubbles are certainly needed for self-sustained thermally driven oscillations.

5. CRITICAL DIAMETER OF PHP

From the construction of the device it is evident that distinct liquid and vapor plugs are essential for the PHP operation. The formation of plugs is attributed to the balance of gravity and surface tension forces. This balance leads to the definition of the Bond number (Bo) or alternatively the Eötvös number (Eö) ($\mathrm{Bo} = d\sqrt{g(\rho_l - \rho_v)/\sigma} = \sqrt{\mathrm{E\ddot{o}}}$) [3]. As the radius of the PHP tube increases, the surface tension force is reduced which leads to stratification of phases. Therefore it seems to follow that above a maximum critical diameter the device will stop functioning as a PHP. The PHP geometry may rather function as an interconnected array of two-phase thermosyphons.

The existence of a terminal rise velocity of single bubbles rising in cylindrical tubes is well known. As the tube diameter decreases (i.e. Eö becomes smaller), the terminal velocity reduces and becomes zero when Eö is of the order of 4 (this value of critical Eö is certainly not unique and varies somewhat with different experimental setups). This reduction of terminal velocity is generally attributed to the dominance of surface tension. Since this dominance leads to the formation of distinct liquid plugs, an essential prerequisite for proper PHP operation, the theoretical maximum tolerable inner diameter of the PHP capillary tube can be calculated as [1]: $d_{crit} = 2\sqrt{\sigma/(g(\rho_l - \rho_v))}$.

In vertical orientation, slug flow is known to exist even at larger diameters in devices such as a standard bubble pump depending on the heat flux [2]. The transition from bubbly flow to slug flow is characterized by churn-turbulent region. In this region, if agglomeration of smaller bubbles leads to the formation of stable Taylor-type bubbles, the flow transforms into the slug regime. The larger bubbles, which are nearly fill the tube diameter, are then able to transport liquid up the tube. In horizontal flow where there is no drift flux due to buoyancy, there exists a greater possibility of flow stratification as the diameter of the tube increases. In the light of these facts, the PHP critical diameter, as suggested above, requires further investigation to be established as a design rule.

While the maximum diameter is guided by the dominance of surface tension, the pressure drop in the pipe is critical for the smallest diameter. For a desired heat throughput, pressure drop will increase with decreasing diameter. Also, in the wake of the fact that sensible heat is the primary transport mechanism, all other geometry remaining the same, a smaller diameter tube means less mass of liquid present in the system and thus less sensible heat transport.

6. MATHEMATICAL MODELING

Mathematical modeling and theoretical analysis of PHPs has been attempted in the recent past with many simplified approaches which may be categorized according to the simplification scheme adopted. These may be summarized as [as cited in Khandekar et al., 2002a] (a) comparing PHP action to equivalent single spring-mass-damper system, (b) kinematic analysis by comparison with a multiple spring-mass-damper system, (c) applying fundamental equations of mass, momentum and energy conservation to specified PHP control volume, (d) mathematical analysis highlighting the existence of chaos under some operating conditions and (e) modeling based on Artificial Neural Networks [6]. It is worth noting that extreme simplification has been adopted in all the above approaches and the results have only limited validity and contribution in the overall understanding of the device, not to mention in their performance prediction and optimization. This remains a challenge at the present time.

7. CONCLUSIONS

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. Their complex operational behavior which is not yet fully understood has raised an ever growing academic interest. Up till now it has not been possible to simulate the PHP performances and there exist no complete engineering design tools.

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