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The operational characteristics of a pulsating heat pipe (PHP) under different startup modes

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Abstract

A pulsating heat pipe is a two-phase passive heat transportation device. It is a serpentine capillary tube which is partially charged with the working fluid. A PHP does not have any moving parts and does not require any additional power source to operate. Its simple structure, scalability, effectiveness, and low manufacturing cost have made the PHP an attractive option for thermal management of electronic devices. Two startup modes of the PHP, a soft or gradual startup, and a hard or sudden startup have been reported in the literature. These startup modes govern the behavior of a PHP during the startup period, and it is presently hypothesized that it further affects the PHP performance under its steady-state operation. This study focuses on understanding the operational characteristics of a PHP as a function of the mode of startup. Experimental investigations were conducted on a single loop PHP over a range of heat inputs, and an attempt has been made to gain insights into the mechanisms of different startup modes using CFD modeling.

Introduction

A recent trend in electronic technology is to make small but powerful devices. Efficient thermal management techniques are now needed to run these powerful devices smoothly without getting overheated. A pulsating heat pipe or PHP [1] is a very effective two-phase heat transportation device; it is very efficient and has a very high heat removal rate [2]. It has a simple construction, consisting of a capillary tube bent in the form of a closed loop. The tube is partially filled with a working fluid, which forms a chain of liquid slugs and vapour bubbles. Usually, a PHP is divided into three sections, an evaporator section, an adiabatic section, and a condenser section. Under operation, heat is supplied to hot (evaporator section) side, and after that heat is transported from the hot end to cold end by pulsating motion of liquid slug and vapour bubble chain. Owing to its simple construction and ability to work efficiently at high heat fluxes, the PHP has become a suitable candidate for high heat flux electronic cooling. The internal thermo-hydrodynamics of a PHP is very complex. Many parameters govern the operating mechanism of a PHP; these include filling ratio, heat load, number of turns, orientation, the diameter of the tube and properties of the working fluid. In the past, numerous studies have been conducted on various PHP parameters [3–8].

A PHP does not start instantly on the application of heat load. It takes some time to achieve the quasi-steady state of heat transportation; this phase is called the startup period. Once the quasi-steady state is attained, a PHP will start transferring heat from the heat source to a heat sink. The startup phase, i.e., from time t = 0 to attainment of operating state is called the startup period. Two startup modes of the PHP, a soft or sudden startup, and a hard or gradual startup have been reported in the literature [9,10]. A hard startup is characterized by an initial temperature overshoot (also called as type 1 startup). A smooth rise in temperature recognizes the soft startup (or type 2 startup), these startups are illustrated in figure 1.

The startup of a PHP is a very dynamic process and needs to be understood. It has been hypothesized that the level of initial (i.e., before startup) evaporator flooding has a direct impact on the startup behavior. The present work is, therefore, an attempt to understand the cause of the different types of startup exhibited by a PHP [9,10] and their effect on the thermal performance of a PHP. Numerical and experimental techniques are applied; in particular numerical simulations are used to study the impact of the initial evaporator condition.

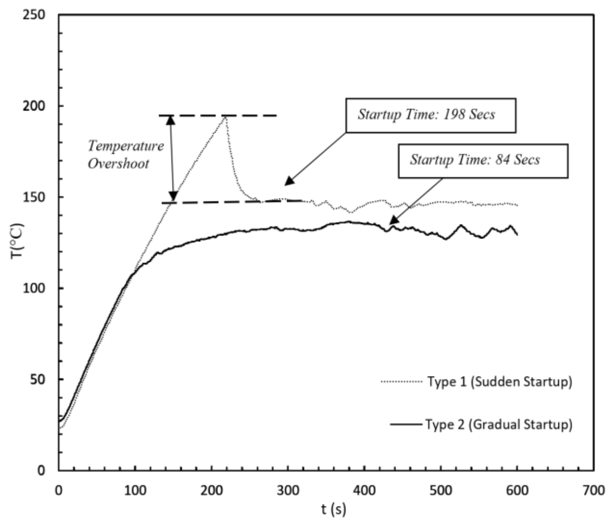

Figure 1Types of start-ups.

Experimental Setup and Procedure

A copper tube was bent in the form of a loop to create a single turn close loop pulsating heat pipe (CLPHP). The total length of the tube was 670 mm, internal and external diameters were 3.25mm and 4.75mm respectively. The CLPHP was divided into three sections, an evaporator section, a condenser section, and an adiabatic section. The evaporator section consists of an aluminum block, with a cartridge heater inserted into it. The aluminum block was covered with insulation (super wool 607). The condenser block comprises a helical copper tube wrapped around the CLPHP tube. The adiabatic section and condenser sections were further covered in insulation to minimize heat losses. The helical tube was connected to a water supply which was regulated by a valve. A variac was used to supply power to the CLPHP. To calculate precisely the amount of power going into the CLPHP a clamp meter and a multi-meter were used to measure current and voltage. Seven K type thermocouples (accuracy ±0.2℃ after calibration) were used at various locations to measure the temperature of CLPHP walls.

The PHP was evacuated to a pressure of 10^{-2} mbar by using a vacuum pump. The negative pressure thus created was used to draw in the required amount of fluid into the CLPHP. The amount of fluid going in was controlled by measuring the mass of the fluid. The vacuum pump and charging assembly are connected using a three-way valve. So as soon as the required amount of fluid was drawn in, the three-way valve was closed. Subsequently, the power supply was switched on, and temperature readings were taken. On completing the experiments, working fluid was discharged using compressed air, to ensure all traces of fluid has been flushed out. Experiments were conducted for power inputs 20 W, 33 W, 55 W, and 76 W and for filling ratios of 50%, 60%, 70%, and 80%.

Results and Discussions

Commencement of a PHP operation can be identified by the fluctuation of wall temperatures across the PHP. Once a PHP attains the quasi-steady state, it will start transferring heat. The time between the instant when the heat source is switched on, and the first fluctuation of wall temperatures, is defined as the startup time. As reported in the literature [9,10], two types of startup were also observed in the present study for a similar power input.

Type of Startup, Heat Load, and PHP Performance

One of the most important parameter for PHP is the heat load. The importance of heating load has been cited by many authors [8,11,12]. The overall working and performance of the PHP have been directly linked to the amount of power input (heat load). A PHP might not work satisfactorily, or it might not even reach the operating state if the heat load is too low.

Since heat load is an important parameter, its effect on the type of startup was studied. Some of the earlier studies suggest that hard startup occurs at low heating power while soft startup occurs at higher heating power [9,10]. However, there are studies which claim that the type of start-up is not associated with heat input; instead, they are linked to the initial spatial distribution of vapor bubbles at the evaporation section [13]. In the present study type 1 (T1) and type 2 (T2), start-ups were observed at higher power inputs as well as at lower power inputs. The occurrence of both types of startup at various power inputs is shown in figure 2. It is evident that no direct relationship can be established between heating power and the type of startup. So, it can be inferred that for the current PHP configuration, the type of startup is independent of heating load.

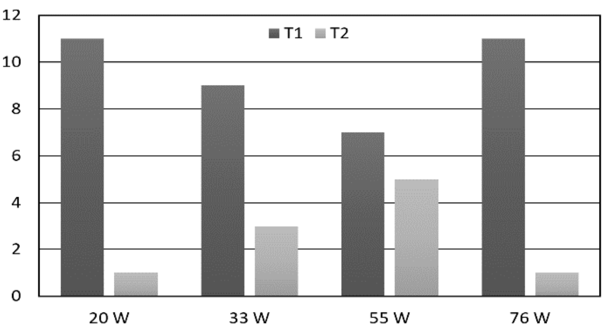

Figure 2 Occurrence of different types of startup with power input.

The performance of a PHP is measured based on its thermal resistance R_{th} which is defined as:

$$R_{th} = \frac{\overline{T}_e - \overline{T}_c}{\dot{Q}} \quad (1)$$

where, $\overline{T}_e$ and $\overline{T}_c$ are average of temprature measured at the evaporator and condenser side respectively and $\dot{Q}$ is total power input. Thus, a PHP with low thermal resistance will exhibit a better performance in transferring heat. The thermal resistance of a PHP decreases as the heat input increases, signifying that the performance of PHP is better at higher heat inputs. For all the 48 tests carried out in the present study with different configurations of filling ratio and power input, average values of thermal resistances for type 1 and type 2 start-ups at different power inputs are shown in Table 1. Data in the table shows that when the PHP undergoes a type 1 (sudden) startup, its performance is somewhat lower. However, after type 2 (smooth) startup, the PHP performs slightly better.

Startup Type	Thermal Resistance (K/W)			
	20 W	33 W	55 W	76 W
Type 1	1.680	1.049	0.592	0.458
Type 2	1.595	0.945	0.574	0.418

Table 1. Average values of thermal resistances at various power inputs for different start-up types.

Also, It was observed that the startup time for a PHP following a type 1 startup mode is always higher than that of type 2 startup. Referring back to Figure 1, it shows the startup behavior and time for both startup types at power input of 50 W and filling ratio of 70%. Startup time for the sudden startup was 198 seconds whereas startup time for the gradual startup was 84 seconds. For both the startups, once the operating state was reached, the temperature of the evaporator block attains a nearly constant temperature (referred to its operating temperature). Further, for sudden startup, the operating temperature is almost 20°C higher as compared to smooth startup. For a cooling device, it is essential that it start transferring heat as soon as possible and it should keep operating temperature within the safe (temperature) limits specified for the equipment it is being used on. Therefore, under operation, type 1 startup should be avoided if possible. In conclusion, a type 1 startup reduces the thermal performance of a PHP, delays startup and forces PHP to operate at a higher temperature.

Startup Types and Filling Ratio

The pulsating action of the PHP is the result of simultaneous phenomena of bubble expansion at the evaporator section and shrinking (or collapse) of the bubbles at the condenser section [14]. Therefore, bubble generation and bubble collapse are important aspects of PHP operation. Hence, it was speculated that the initial spatial arrangement of bubbles at the evaporator section could be the responsible factor in deciding the startup mode of a PHP [13]. The initial distribution of bubbles inside a CLPHP is random, and for a certain filling ratio, different arrangement of bubbles and liquid are possible. Due to the uncertainty of the initial state of bubbles in a PHP, a direct connection between startup and filling ratio is difficult to establish. Therefore, to get some insights a probability-based approach was taken, figure 3 shows the occurrence of all the type 1 startup at various FR in percentage. The pie chart shows that the most number of type 1 startup among all FR and for all power inputs was observed for 80% filling ratio.

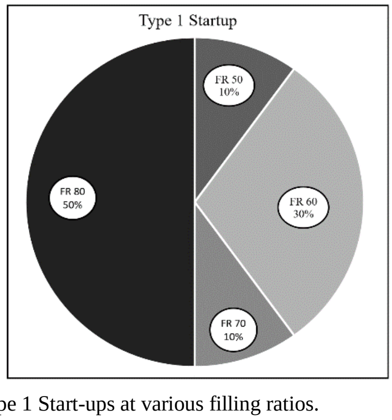

Figure 3 Type 1 Start-ups at various filling ratios.

For a PHP an ideal initial condition is having an optimal number of bubbles at the evaporator and condenser sections. When enough bubbles are present at the evaporator section, heat supplied will directly go into expanding the bubble (by evaporation at the vapour-liquid interfaces). While in the case of low bubble count in the evaporator section or when the evaporator section is flooded with liquid, heat supplied will first go into heating the liquid, and then into the formation of bubbles (by nucleation) and then to the bubble expansion. This increases the startup time and the overall temperature of the device and as discussed in the previous section, a delayed startup. High startup time is a trait of a type 1 startup. At higher FR the probability of evaporator being flooded with liquid is high, and therefore the probability of PHP undergoing a type 1 startup is high as well.

CFD Modelling

An CFD study was carried out using ANSYS fluent, to gain further insight into the type of startup processes and their relation to the amount of liquid in the evaporator section. Volume of fluid (VOF) method was used to track fluid interfaces. Continuum surface force (CSF) model was used for resolving the effect of surface tension along fluid interfaces. A UDF was used to take care of the source term in the energy equation [15]. The boundary condition at the evaporator section was set to a power input of 60 W, and a negative heat flux condition was applied at the condenser section. Zero heat flux boundary condition was defined for the adiabatic section. For each case, the filling ratio was kept at 70%. Four cases were considered, as shown in figure 4, where the condition at the condenser section was kept identical for every case. For the evaporator section, the amount of liquid was varied. For case 1, the evaporator section had liquid only, and for later cases, the volume fraction of the liquid at the evaporator section was decreased.

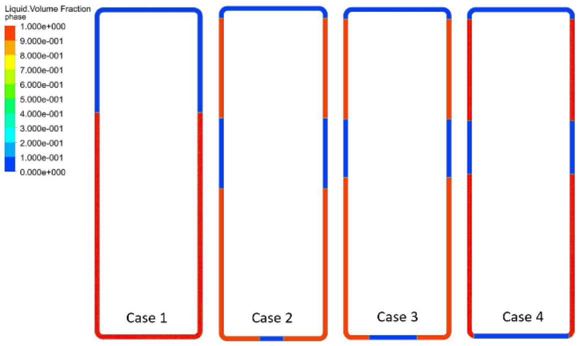

Figure 4 Different cases for CFD study.

Velocity variation was used to track startup (first pulsation). Initially, a PHP will remain in the state of rest hence there will not be any velocity variation. However, as soon as PHP reaches a startup state, pulsation will start and rise in velocity at different parts of the PHP will be observed. Thus, by looking at velocity profiles, we can easily track the first pulsation. Figure 5 shows the velocity profiles for the four cases (case 1, case 2, case 3 and case 4). These velocities were obtained from four locations, two near the evaporator and two near the condenser. During the startup, fluid will be pushed from the evaporator section towards the condenser section. Since the current PHP is single looped, any variation in one tube will directly affect the other. Therefore, during startup velocity fluctuations should be visible throughout the PHP. Also, Figure 6 shows the movement of the fluid in the PHP during the startup process by way of volume fraction plots; for each case, there are four snapshots. Each plot shows the distribution of liquid (shown in red) and bubbles (blue colour) at different stages during startup. These four stages are, (a) bubble generation, (b) start of pulsation (startup), (c) pulsations (leading to peak velocity peaks) and (d) the end of pulsation.

In figure 5, the PHP startups are highlighted by rectangular boxes. Initially, for all the cases the velocities at all points were almost zero. However, after some time an abrupt increase in velocities can be seen, showing bulk fluid movement or startup. Although for case 1 there is some early variation of velocities (shown by a circle), these are believed to be due to localized fluid movement from initial bubble generation and collapse. As mentioned earlier during a sudden startup, the temperature of the evaporator section drops suddenly after reaching a maximum temperature (see figure 1).

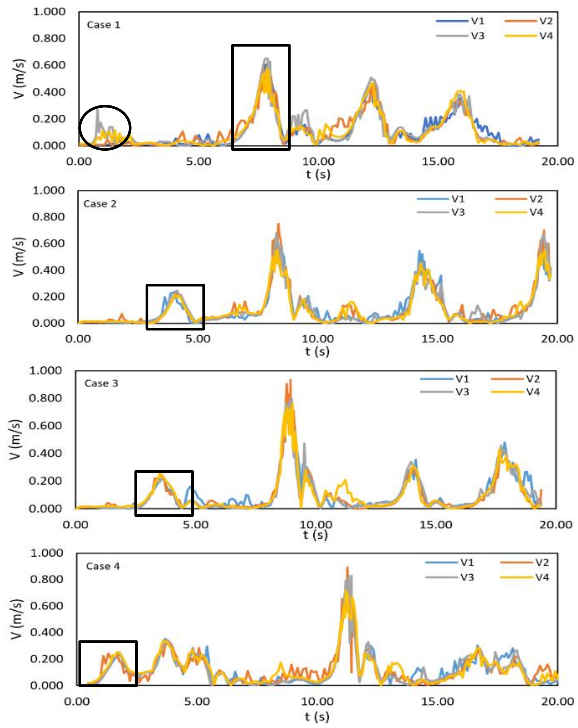

Figure 5 Velocity profiles of CLPHP.

The abrupt drop of temperature suggests that a large amount of colder fluid has reached the evaporator section, signifying that there was a large amplitude pulsation towards the evaporator section. Similar behaviour can be seen in case 1, up to 6 seconds the velocity profile shows no movement, i.e. stagnant fluid across the PHP. Between time interval t=6.24 sec and t= 7.62 sec, the velocity at all locations rises sharply from almost 0 m/s to around 0.6 m/s, suggesting that there is a significant movement of fluid across the PHP. This movement can also be seen in the volume fraction maps in figure 6. During startup, the fluid starts to move in the anticlockwise direction, and by the end of the startup phase, all the fluid which was initially at the evaporator section reached the condenser section and vice versa. Further, as compared to other cases, case 1 has a maximum startup time of around 6 seconds. On introducing more vapour bubbles at the evaporator section startup reduces; for case 2 and case 3 the startup time is 3 seconds and 2.5 seconds respectively. For case 4 where almost the entire evaporator section holds vapour, startup time is only 0.72 secs, minimum amongst all the cases.

During a PHP startup, heat received at the evaporator section will go into either sensible heating of the liquid or expansion of a vapour bubble or both. At the same time, in the condenser section, vapour bubbles are either shrinking or condensing completely. Liquid around the evaporator section gets a push from the expanding bubble or by bubble generation. The liquid plugs and bubbles move towards the condenser section to accommodate the collapsing volume. This replacement mechanism repeats itself throughout the PHP operation [16]. Under similar conditions of bubble distribution at the condenser section, the evaporator section in the case of higher amount of liquid will take more time to generate bubbles and be able to drive the liquid towards the condenser section. During this time, more vapour will condense at the condenser section, creating lower pressure due to the collapsing volume. Now, once the evaporator section has enough bubbles to push the fluid, along with the larger amount of void at the condenser section, a large amount of fluid will flow into the condenser section. The fluid movement will cause a significant temperature drop, similar to a sudden startup. Also, the process mentioned above will take more time hence higher startup time.

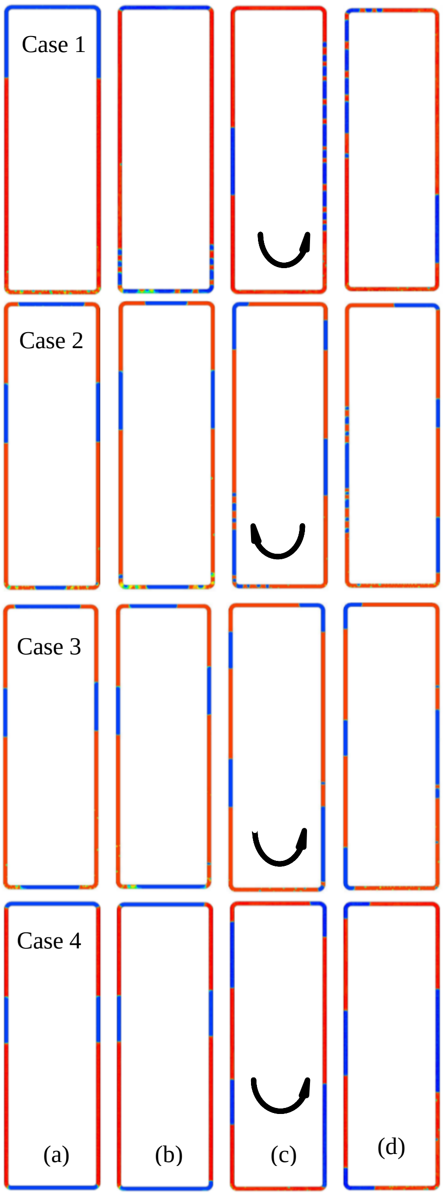

Figure 6 Fluid movement during startup.

Conclusions

The findings from the present work suggest that the type of startup is independent of heating load. Sudden startup in a PHP leads to increases in thermal resistance of a PHP. Further, a PHP, depending upon volume fraction of bubbles and liquid at evaporator section can undergo sudden or smooth startup. However, the probability of a sudden startup is higher for the high filling ratio. Also, during type 1 steep drop in temperature (just after startup) is due to a large amount of fluid movement from the condenser section to the evaporator section.

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