Closed Loop Flat Plate Oscillating Heat Pipes: An Overview on the Thermohydraulic Principles, Thermal Performances, and Developing Trends

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Abstract— Thermal management of latest micro- and high-power electronic systems has become a progressively challenging issue due to current trends in miniaturization and increased heat generation. Traditional cooling techniques, such as natural and forced convection, have proven inadequate in addressing the emerging demands within the electronics industry, transportation, and space applications. In these domains, the size, mass, autonomy, high density, and overall reliability of thermal management systems play pivotal roles. Unlike active technologies, heat pipes serve as passive heat transfer devices devoid of moving components, resulting in prominent reliability, albeit constrained by factors like capillarity, viscosity, and gravity. In contrast, the closed loop flat plate oscillating heat pipe (CL-FP-OHP) has recently become a source of increasing interest: first, due to fascination for the complexity of the internal two-phase heat transfer; and secondly, due to emerging applications, which are rapidly increasing the technology readiness level of this heat pipe, for both ground and space environments. Several experimental and theoretical investigations have been carried out on CL-FP-OHP over the past few decades since it was first proposed by Akachi in 1990. Nevertheless, due to the intricate coupling effects of hydrodynamics and thermodynamics, the operational mechanism of CL-FP-OHP remains exceptionally intricate and has yet to be fully elucidated. With high hopes for future applications of CL-FP-OHP, this paper aims to examine the development of CL-FP-OHP by systematically summarizing the most recent findings from both experimental and theoretical studies. Simultaneously, it also highlights some promising and groundbreaking applications of CL-FP-OHP. This paper is anticipated to serve as a fundamental point of reference for future research endeavors.

Key words: Closed Loop Flat Plate Oscillating Heat Pipe (CL-FP-OHP)

I. INTRODUCTION

In recent times, the miniaturization of electronic components has led to the generation of high heat flux. Alongside demanding requirements such as compactness, lightness, and low energy consumption in aerospace, transportation, and energy applications, this has presented challenging issues in managing heat. One of the most promising cooling technologies among highly efficient passive heat transfer devices for electronic equipment is the Closed Loop Flat Plate Oscillating Heat Pipe (CL-FP-OHP). CL-FP-OHPs operate based on thermally driven two-phase passive mechanisms involving phase change-induced liquid movement and capillary forces. They can be described as a single capillary tube or channel bent in multiple interconnected turns. This heat pipe is partially filled with a working fluid at the liquid/vapor saturation state and distributed through surface tension effects in the form of liquid slugs and vapor plugs. When subjected to heat sources, pressure fluctuations in the evaporation and condensation regions initiate a complex two-phase flow, spanning from bubbly flow to slug/plug flow and annular flow, all of which impact the overall heat transfer capacity of the CL-FP-OHP, transferring heat from the heated to the cooled zones.

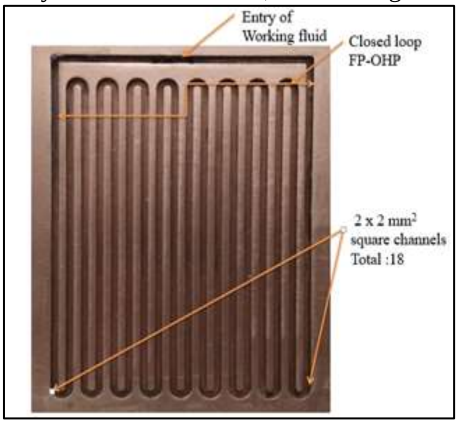


Fig. 1: Copper plate with a square serpentine channel machined on its top

Due to the growing interest in this field, a plethora of research papers have been published on the topic of oscillating heat pipes since their inception in the early 1990s. Comprehensive reviews and books by scholars such as Ma [1], Bastakoti et al. [2], Marengo and Nikolayev [3], [4], and Khandekar et al. [5] have delved into various aspects, encompassing their definition, manufacturing processes, thermal performance, hydraulic behavior, and more. This paper, however, will center its focus on a specific subtype of Oscillating Heat Pipes, namely the "Closed loop flat plate heat pipe" (CL-FP-OHP). These are characterized by a flat plate with an engraved/machined (or obtained through additive/etching manufacturing) single, usually square or rectangular channel that forms a serpentine path between one or more hot sources and one or more cold sources. To enclose the channel, a smooth plate cover is sealed. Fig 1 illustrates a copper plate with a square serpentine channel machined on its top (a) Mehta et al.,and an example of a Micro-Cl-FP-OHP designed and tested by Kamijima et al. [6].

This paper will solely concentrate on experimental investigations carried out on flat plate oscillating heat pipes and will be subdivided into three supplementary segments:

To begin, Section II will detail the thermal and hydraulic characteristics of CL-FP-OHPs; commence with a discussion of the fundamental principles governing the primary physical phenomena. Subsequently, delved into the unique aspects of capillary flows within channels featuring sharp corners. The section includes an in-depth examination of the hydrodynamics of flow patterns observed within the CL-FP-OHP channels, accompanied by comprehensive visualizations.

Moving on to Section III, focus shifted to the key factors influencing the thermal performance of these devices. This encompassed an exploration of operating conditions, such as heat power, charge ratio, and orientation. Furthermore, it elaborated the geometrical aspects, particularly concerning the hydraulic channel diameter and shape, as well as the thermophysical properties of the working fluid.

Finally, Section IV will provide an overview of the primary application fields for which these devices have been constructed and tested by researchers. These applications span from traditional electronic cooling to space, transportation, and renewable energy conversion applications.

II. THERMAL-HYDRODYNAMIC BEHAVIOR OF OPERATING CLOSED LOOP FLAT PLATE OSCILLATING HEAT PIPES

This section serves as a general introduction to the studies that have added to the characterization of CL-FP-OHP behavior and general physical phenomena involved in the operating of CL-FP-OHP.

A. *Basic physical phenomena in CL-FP-OHP*

The fundamental physical processes governing the operations of CL-FP-OHPs have achieved a relatively solid foundation of understanding. However, the intricate nature of the phenomena involved and the multitude of intense heat and mass transfer zones within the tubes and channels pose challenges to modeling approaches. The primary aim of this section is to underscore the key underlying physical phenomena responsible for both heat and mass transfer within CL-FP-OHPs. This understanding will provide a solid foundation for the subsequent analyses and considerations.

Nikolayev and Marengo [4] have contributed significantly to comprehension of CL-FP-OHPs physics, following prior reviews by Zhang and Faghri [7] and Ma [1]. In general, it is assumed that the fluid flow pattern in the capillary tubes and channels of oscillating heat pipes exhibits slug flow, often referred to as "Taylor bubble flow." Initially, liquid slugs and vapor plugs are distributed within the partially filled tube and move in response to various driving forces acting between them. This phenomenon becomes possible when the hydraulic diameter of the channel falls below a critical threshold known as the critical diameter (Dcrit). Most authors characterize Dcrit using the Bond number, which is defined in static isothermal conditions as the ratio of gravitational forces to surface tension forces. As the channel diameter decreases below Dcrit, the dominance of surface tension forces results in the separation of vapor bubbles and liquid plugs by menisci [72].

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

B. *Flow in square/Rectangular channel*

Although circular channels have been used by several authors [8,9], the majority have shown a preference for employing CL-FP-OHPs equipped with square or rectangular channels. This choice is primarily driven by the ease of manufacturing facilitated by machining processes. Additionally, the presence of sharp angles in these channels leads to the creation of capillary pressure imbalances between their edges and corners. In comparison to the extensive body of research focused on two-phase flows within circular tubes, investigations pertaining to two-phase flows in square channels remain rather limited.

For instance, consider the work of Han and Shikazono[10], who conducted measurements of liquid film thickness in a micro-square channel, revealing its variations along the channel's perimeter. This variability introduces added complexity to the theoretical understanding of two-phase flow. Vital information concerning the distribution of film thickness along the perimeter, encompassing its minimum and maximum values, remains elusive, despite its pronounced relevance to two-phase microfluidic systems. One of the primary consequences of the presence of corners is the provision of pathways for trapped liquid films between the bulk meniscus and adjacent vapor bubbles. Even under dry-out conditions or in the absence of moving bubbles, liquid is transported within these films through the influence of the pressure gradient induced by the capillary effect, which stems from variations in meniscus curvature along the interface.

A significant benefit offered by CL-FP-OHPs lies in their capacity for comprehensive visualization of fluid flow. This can be accomplished by introducing a transparent window on the upper surface while preserving the metallic substrate. Numerous experiments have been conducted, building upon the initial tests conducted by [11,12]. Given the scarcity of observational data in the existing literature, the primary fluid flow patterns will be elucidated in the subsequent sections. A special emphasis will be placed on vertical and horizontal orientations, as these orientations lead to distinct fluid flow modes, particularly in the context of this device. A clear distinction will be made between "standard" CL-FP-OHPs (characterized by a channel diameter of approximately 1–4 mm) and "micro" CL-FP-OHPs (featuring channel diameters below 1 mm. Quantitative insights will be summarized toward the conclusion of this section. It's worth noting that all the observations detailed below are contingent upon the specific geometric and operational conditions of each test, including channel dimensions, charge ratios, and working fluid, and must be evaluated in relative terms.

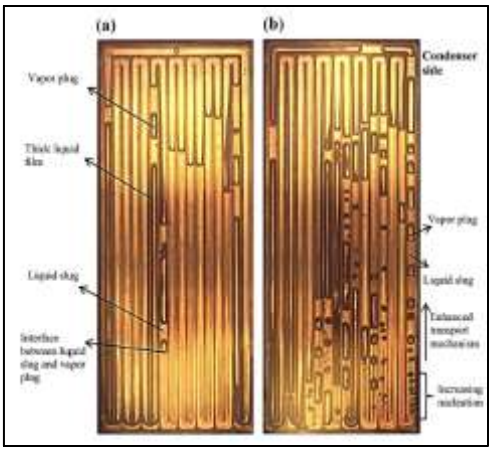


Fig. 2: Flow regimes in copper CL-FP-OHPs (square 2 × 2 mm2 channels): (a) Q˙ = 21 W; (b) Q˙ = 49 W (methanol, FR = 40%, BHM) [13]

III. THERMAL PERFORMANCE OF CL-FP- OHPS: THE INFLUENTIAL PARAMETERS

Based on the same underlying physical principles as tubular OHPs, CL-FP-OHPs often exhibit responses to the same influential factors. For instance, numerous researchers have demonstrated that OHPs with sealed ends consistently deliver superior heat transfer performance when compared to those with open ends. This specific point will not be extensively addressed here, as the principal observations are set to follow, founded on parametric investigations into channel dimensions, the choice of working fluid, geometric aspects, and operational conditions—most notably, the applied heat power, orientation, and charge ratio.

One of the parameters frequently employed by authors to assess the thermal performance of oscillating heat pipes is the thermal resistance, which can be expressed as [14] [15]:

$$R_{th} = \frac{(T_{ev} - T_{cd})}{Q}$$

In this equation, T_{ev} and T_{cd} represent the averaged evaporator and condenser (or secondary cold source) temperatures in both space and time, while Q signifies the applied heat power. This calculation may also take into account heat losses and heat conduction through the device's plate.

A. Operating Conditions

1) Heat flux

Below, an endeavor will be made to delineate the primary factors that exert influence over the operational dynamics of flat plate oscillating heat pipes. However, this analysis appears to be remarkably intricate, given the interconnections between many of these factors. Among these, the parameter most frequently and systematically examined is the augmentation of power, resulting in a commensurate reduction in thermal resistance. Nevertheless, it's important to note that the threshold values for such changes evidently exhibit variation among different researchers.

For example, according to [16], in the case of CL-FP-OHPs, the initiation of heat transfer was achieved at an input power of 12 W for acetone and 18 W for ethanol under identical operational conditions (involving 10 turns, 1x1 mm² channel dimensions, and a 50% charge ratio in the Bottom Heated Mode, BHM). However, when examining Ayel et al.'s findings [17], variations in the necessary heat input for CL-FP-OHP initiation were observed in certain tests, depending on the initial distribution of the fluid. In the initial stages of startup, the formation and expansion of vapor bubbles at the evaporator serve as the driving force behind fluid flow. It's been observed that the minimum power level required to induce this motion increases with rising charge ratios startup occurred at 40 W, 60 W, and 80 W for charge ratios of 25%, 37.5%, and 50%, respectively [18] (comprising 5 turns, Dh = 2.5 mm², employing water in the BHM configuration).

2) Charge Ratio

Despite the numerous experiments exploring the impact of charge ratio, reaching definitive conclusions remains a challenging endeavor. This challenge arises from the strong dependence of optimal charge ratios on operational conditions, especially the orientation (horizontal or vertical), the configuration of the BHM (Bottom Heated Mode) or THM (Top Heated Mode), and inclinations. The working fluid's nature, the separation between the evaporator and condenser, and their respective lengths are also crucial factors. Yang et al. [19] expounded that when the charge ratio falls below or is close to 20%, the CL-FP-OHP behaves as an interconnected array of thermosyphons. With an increase in charge ratio, a transition to semi-annular flow occurs, which includes liquid slugs in the channels.

Much like in tubular OHPs, most authors within this configuration have discovered that the optimal charge ratio tends to converge around 50%. However, the width of this optimal range varies in accordance with their specific operating conditions.

3) Orientation

While some studies have reported the incapacity of CL-FP-OHPs to operate in horizontal inclinations, in instances where they do operate, the most favorable conditions have consistently been identified in the vertical bottom-heated mode (BHM). As outlined in the preceding section and depicted in Figure 14a-c, CL-FP-OHPs tested by Yang et al. [19] (comprising N = 20 with 2 × 2 mm² or N = 33 with 1 × 1 mm² channel dimensions, employing ethanol at TII◦ = 20 ◦C) exhibit operational proficiency across all orientations, even in the top heat mode. Nevertheless, the gravitational vector exerts a beneficial influence on the driving forces, thereby enhancing performance in the BHM orientation relative to all other orientations.

In the context of micro-CL-FP-OHPs, Qu et al. [20] conducted tests encompassing a range of orientations, from horizontal to vertical BHM. Much like conventional CL-FP-OHPs, the most favorable thermal performance was observed in the vertical BHM configuration. As the devices transitioned from horizontal to BHM orientation, thermal resistances demonstrated a tendency to decrease, and the onset of dry-out was delayed. These findings underscore the significance of gravity's impact, even in micro-CL-FP-OHPs with hydraulic diameters as diminutive as 251 μm [20].

B. Geometrical Aspects

Considering the influence of channel dimensions, Winkler et al. [21] engaged in a comparative assessment of the heat transfer performance of two CL-FP-OHPs, each sharing identical overall dimensions (50 × 100 mm², employing acetone with an FR of 50%). However, they differed in channel dimensions and count (1 × 1 mm²/N = 13 and 1.5 × 1.5 mm²/N = 10). Their objective was to maximize channel density per surface. Their findings revealed that a larger channel diameter resulted in reduced thermal resistances, both in horizontal and vertical BHM orientations. Nonetheless, it's worth noting that premature dry-out manifested in horizontal inclination at 130 W for the larger channel diameter, whereas it remained absent with the 1 × 1 mm² channel up to 180 W. As the heat input escalated, the amplitude and velocity of liquid plug oscillations increased, which becomes particularly noteworthy when the diameter is substantial. This proximity of slug menisci diameters to the critical diameter is discussed in previous section. For both CL-FP-OHPs, operations became orientation-independent for heat inputs exceeding 50 W.

In the context of specific CL-FP-OHP cases, it appears that the inclusion of sharp corners enhances their heat transfer performance and efficacy when juxtaposed with circular channels.

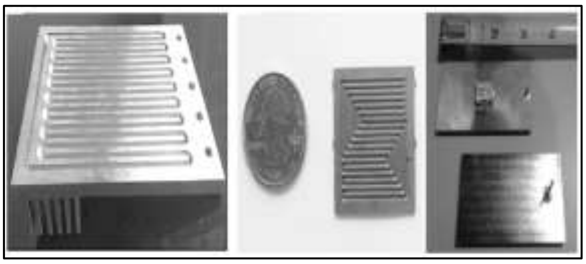
C. Working Fluid

In the quest to enhance the performance of CL-FP OHPs, particularly in horizontal orientation, several authors have proposed various theories and assumptions. For instance, Kearney et al. [22] posited that higher surface tension leads to an augmented critical channel diameter, thereby enabling pulsations in larger tubes and consequently boosting heat transfer capacity. A working fluid with a low latent heat of vaporization tends to evaporate more rapidly, generating an increased volume of vapor, which subsequently elevates vapor flow and pumping power. A secondary advantage is that it facilitates startup at lower heat inputs. Moreover, a working fluid characterized by low liquid viscosity engenders more robust pulsations. An enhanced heat capacity results in a higher sensible heat transfer for liquid slugs. Naturally, a substantial $(\partial P/\partial T)_{sat}$ is a desirable trait since pressure elevation due to temperature increases drives pulsations. This insight is deduced from a comprehensive understanding of the principal physical phenomena governing the operation of OHPs.

Lastly, in addition to efficiency, factors such as safety, compatibility with the solid substrate, and environmental and security considerations should be factored in when selecting a working fluid tailored to a specific application.

IV. APPLICATION

A. Electronic Cooling



(a) (b) (c)

Fig. 3: (a) CL-FP-OHP embedded in heat sink for MOSFET cooling [15] (b) spreader CL-FP-OHP for power electronics and (c) laser diode in communication and defense systems [29]

Due to their distinct shape and fabrication method, flat plate oscillating heat pipes (OHPs) should be assessed differently from tubular OHPs in terms of their applications. Their flat external configuration facilitates effective contact with flat heat sources, making them well-suited for dissipating heat generated by electronic components. Additionally, they can serve as efficient heat spreaders. However, they do have certain drawbacks, including limited flexibility in integration compared to tubular OHPs and potentially higher mass due to the continuous solid material within the massive plates. Furthermore, they are not generally suitable for use as enhanced heat exchangers between two fluids, as is the case with thermosyphon heat pipes (TPHPs).

As previously mentioned, one of the most promising application areas for CL-FP-OHPs is the cooling of dissipative electronic components. Mehta and Mehta [23] provided a concise review of the development of CL-FP-OHP products, emphasizing their applications in heat spreading, heat dissipation, and electronic cooling in the forthcoming years. Li and Jia [24] conducted experiments with aluminum flat plate OHPs equipped with natural convection fins to cool high-power LEDs (up to 100 W). Their research demonstrated that a high-power LED could be effectively cooled by a CL-FP-OHP with finned surfaces, aided by natural air convection, with the fins' area exerting a notable influence.

Boswell et al. [25] explored a lightweight heat sink integrated with a CL-FP-OHP for thermal management of circuit board assemblies. Mehta [15] tested a CL-FP-OHP embedded within a substantial aluminum heat sink to cool MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) in a vertical orientation through natural convection, employing acetone as the working fluid.

Certainly, CL-FP-OHPs can be integrated with various other solutions, such as a vertical radiator with a flat evaporator end and multi-pulse condenser ends, suitable for CPU cooling applications. Laun et al. [26] engineered a radial CL-FP-OHP with a highly intricate channel configuration to investigate the impact of centrally heating a 30x30 mm² heat source on a 100x100 mm² heat spreader. The heat power reached 525 W, corresponding to a heat flux of 58 W/cm².

B. Space and Transport Application

Flat plate oscillating heat pipes (OHPs) have been considered for space applications, serving the same role in cooling electronic components as discussed in the preceding section but in a microgravity environment [27]. Taft and Irick [28] present the results of six months of space flight experiments involving their ASETS-II (Advanced Structurally Embedded Thermal Spreader) aluminum Oscillating Heat Pipes. The comprehensive dataset comparison encompasses three devices filled with butane and R134a, which were subjected to testing in microgravity conditions aboard the X-37B reusable space plane. The results indicated that heat transfer performance matched the expectations based on ground tests. More precisely, the CL-FP-OHPs exhibited no significant hysteresis effects and consistently delivered successful performance during a continuous six-week operation.

Similarly, Ayel et al. [17] tested a copper flat plate OHP filled with FC-72 (featuring channel dimensions of 1.6 × 1.7 mm²) under both ground and hyper/microgravity conditions during the 60th parabolic flight campaign of the ESA. They demonstrated that, when tested in a horizontal orientation, the CL-FP-OHP was unaffected by changes in gravity levels, particularly during the 22 seconds of microgravity. This confirmed that such a system could serve as an efficient solution for thermal control in various space applications, provided that a larger channel size is combined with a sufficient number of turns. The same authors conducted further investigations, involving flow pattern visualizations in copper/borosilicate glass CL-FP-OHPs filled with FC-72 (during ESA's 62nd and 64th parabolic flight campaigns). Their findings suggested that heat transfer performance tends to improve with an increasing channel hydraulic diameter under microgravity conditions, up to a specific limit associated with the fluid and its corresponding critical diameter, considering inertial and viscous forces. According to Taft et al. [27], when an OHP is not self-sufficient on Earth, it is likely to perform more efficiently in a microgravity environment.

C. Heat Recovery Application

Numerous industrial manufacturers currently offer CL-FP-OHPs for diverse cooling applications, such as heat sinks for both air and liquid cooling, heat diffusers for power electronics and amplifiers, as well as laser diodes in industrial communication and defense systems, and thermal straps for high-power, temperature-sensitive devices, including long-distance or flexible 3-D structures [29]. In less common scenarios, Chao et al. [30] effectively implemented a distinct design of defrosting plates using CL-FP-OHPs as a substitute for the conventional heat pipe design, while Natsume et al. [27] conducted experiments on a flat-plate cryogenic OHP filled with H_2, Ne, and N_2 to enhance cooling for "High Temperature Superconductors" (HTS) magnets operating in the temperature range of 20–77 K.

The exceptional performance of these fluids at such low temperatures, ranging from 18 K to 84 K, has sparked interest in OHPs and CL-FP-OHPs for cryogenic applications. In the context of sustainable development, another critical area of application involves the thermal management of renewable and conversion energy systems, often featuring electric dissipative components. Alizadeh et al. [31] proposed the use of a flat plate OHP to reduce the rear surface temperature of a photovoltaic solar panel, comparing various architectural scenarios employing air convection or water flow channels to cool the condenser.

An alternative approach was suggested by Zabek et al. [32], utilizing temperature fluctuations driven by the outer walls of CL-FP-OHPs for waste heat recovery and thermal energy harvesting. This involved utilizing pyroelectric generators to charge a storage capacitor and convert thermal energy from high-frequency temperature oscillations into electrical energy that can be discharged. Although the amount of electrical energy produced may be relatively low, this approach has the potential to cover a wide range of heat power, from watts to kilowatts, and can replace traditional blower fans and large-sized heat sinks. It also has the capacity to provide electrical power ranging from µW to mW for wireless sensor nodes, internet of things devices, and battery-less technologies.

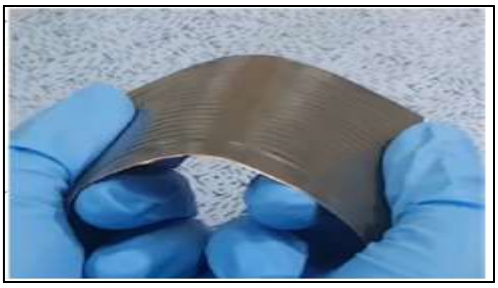


Fig. 4: photograph of bent flexible CL-FP-OHP [33]

Of course, the range of potential applications is extensive, and virtually any system can be considered, as long as energy production and conversion systems can ensure efficient thermal management.

In a more recent development, Jung et al. [33] introduced a different type of adaptable CL-FP-OHP consisting of a 0.5 mm-thick polycarbonate plate (referred to as "PC," as shown in Fig. 4). This plate features 15-turn alternating micro-channels and is enveloped in flexible 70 μm copper-clad-laminates ("FCCL"). This packaging effectively prevents the infiltration of non-condensable gases from the surroundings while maintaining its flexibility Once filled with HFE-7000, the device exhibits a maximum thermal conductivity approximately 2.7 times greater than that of copper when subjected to a heat flux of 2.8 W.cm^-2.

V. CONCLUSIONS

In this paper, a comprehensive examination of numerous recent scientific experimental and some theoretical investigations into the thermal and flow characteristics of closed loop flat plate oscillating heat pipes (CL-FP-OHPs) and two-phase flows in rectangular miniature and micro channels is presented. The primary goal is to enhance comprehension of the thermofluidic operational principles of rectangular-channel CL-FP-OHPs. While it is challenging to offer a synthesis of the combined impact of various factors influencing their performance, the key trends are summarized as follows:

- The fundamental equations governing the physics of CL-FP-OHPs remain akin to those of conventional tubular OHPs.
- Observations of flow patterns within the channels of these devices reveal a blend of flow types, ranging from slug flow to annular flow patterns, particularly in the case of vertical bottom heating. In certain instances, nucleate boiling occurs in the evaporator region.
- The thermal performance of CL-FP-OHPs hinges on numerous factors, with heat flux or heat input at the evaporator region being the most significant. Higher heat flux levels lead to improved thermal efficiency. Other factors such as the choice of working fluid, charge ratio, and orientation exert considerable influence on their operation. Generally, CL-FP-OHPs with more U-turns are less affected by these variables.
- The square or rectangular geometry of the channels results in capillary pumping at the corners, enhancing wetting in the evaporation zone and improving evaporation compared to circular channels. This has been experimentally validated in both individual channels and complete CL-FP-OHP systems.
- Due to their design features, flat plate oscillating heat pipes have found application in electronic cooling. In microelectronic and portable electronic applications, CL-FP-OHPs with microchannels are preferred due to their compact size. Conversely, aerospace and high-power applications require more efficient thermal dissipation systems capable of dispersing heat over longer distances.

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