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Comprehensive parametric and design review for reducing pulsating heat pipes dependence on space orientation

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Abstract

It has been three decades since pulsating heat pipes were first introduced and garnered more attention due to their uncomplicated structural design and superior heat transfer capabilities. The pulsating heat pipe of the original design is strongly affected by space orientation, which is connected with the influence of gravity. Even though more turns will hold pulsating heat pipe operational in any orientation, more space is needed to handle pulsating heat pipes, limiting its potential in space and the power electronics industry. This paper aims to present a comprehensive review of pulsating heat pipe's progress based on the most recent findings of both experimental and theoretical investigations of parametric influence on pulsating heat pipe thermal performance in horizontal and top heating modes. It aims to identify research gaps in pulsating heat pipe functioning in different orientations. Additionally, a comparative analysis of pulsating heat pipe design features described in the existing literature is conducted to determine the most promising designs for orientation-independent pulsating heat pipe systems. It is concluded that the integration of design attributes, encompassing an uneven-turn design, a channel structure featuring alternating shapes and size of cross-section, and the utilization of nanofluids and binary mixtures as heat carriers are expected to serve as the basic reference for researchers aiming to achieve a stable pulsating heat pipe operation devoid of gravitational influences.

Keywords: Pulsating heat pipe; Inner diameter; Number of turns; Zones lengths; Cross section

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1. Introduction

Heat transfer is one of the key processes for functioning of different apparatus such as, for example, steam generators, heat exchangers, solar collectors intended for both heat supplying and water desalination [1–3] cooling and thermal control systems for space and electronic devices and many others in different areas of industry. In most cases efficiency of heat transfer defines overall efficiency of apparatus functioning. That's why increasing of heat transfer efficiency is one of the main problems in power engineering, heat waste recovery, heating, ventilation, and air conditioning (HVAC) systems, energy efficient technologies, electronics cooling etc. Heat pipes were found out as one of the most effective solutions of this problem. Amongst them, pulsating heat pipe (PHP), a novel idea proposed by Akachi [4]

Nomenclature

Bo – Bond number
D – capillary tube diameter, m
D_h – hydraulic diameter, m
D_i – inner diameter of PHP, m
g – acceleration due to gravity, m/s^2
L_{eff} – effective length of PHP, m
R_h – thermal resistance in a horizontal orientation, K/W
R_v – thermal resistance in a vertical orientation, K/W
R_{vb} – thermal resistance in vertical bottom heating mode, K/W
R_{vt} – thermal resistance in vertical top heating mode, K/W

Greek symbols

ρ_g – density of vapour, kg/m^3
ρ_l – density of liquid, kg/m^3
σ – surface tension, N/m

Abbreviations and Acronyms

AB-PHP – additional branch pulsating heat pipe
CEMPHP – closed end micro pulsating heat pipe
CLMPHP – closed loop micro pulsating heat pipe
CLPHP – closed loop pulsating heat pipe
CTPHP – capillary tube pulsating heat pipe
DI – deionized
FPPHP – flat plate pulsating heat pipe
FR – filling ratio
ID – inner diameter
PHP – pulsating heat pipe

in 1990, fulfils all existing cooling requirements. Unlike conventional heat pipes, pulsating heat pipe have simple structure and are completely free from wick, providing an advantage over its manufacturing aspect. PHP is made of capillary tube in form of serpentine with multiple meandering turns. Due to the small inner diameter of the capillary tube, the size of the PHP heat transfer device can be very small too. Key benefits of PHP are quick-thermal response, compact size, and simple construction. PHP is gaining more popularity due to its versatility and significance in advancing thermal engineering solutions across broad industries. In solar energy, PHPs enhance efficiency by minimizing irreversibility during heat transfer in heat waste recovery [5]. It can contribute to sustainability efforts in aerospace thermal management ensuring precise temperature control, and in electronic industry dissipating heat effectively from various devices can solve problem of cooling highly compact and dense electronic gadgets.

PHP should have low temperature difference and thermal resistance, high transferred heat flux to operate effectively as heat transfer device. Achieving of such characteristics when PHP is used in most power engineering applications, such as heat exchangers, solar collectors etc., is relatively simple task because, as a rule, there is a lot of space to place PHP with big number of turns and overall working heat flux is high. Due to combination of these factors PHP can have low thermal resistance and it can be almost insensible to space orientation. The opposite situation is observed in the field of electronics cooling. The evolution of electronic devices, as they become smaller, faster, and more efficient, has set a challenge for the electronic industry, to dissipate high heat flux from electronic chips. One of the significant challenges is fitting devices into smaller spaces, which makes it more difficult to retain them at operating temperatures.

The downside of PHP, however, is that its working philosophy is still needs to be fully established and it is unable to function effectively at all orientations [6,7]. Gravity effects pose a significant threat to this form of cooling technology. Various parameters, such as inner diameter, number of turns, inclination angle, filling ratio (FR), channel geometry, type of working fluid, and heat input, have a significant impact on the heat transfer efficiency of PHP, and numerous studies are performed to investigate the PHP's heat transfer characteristics. The parametric investigation on PHP conducted in the last decade, both experimentally and computationally, has been reviewed and published [8–12]. The influence of geometrical, operational, and working fluid property parameters was reviewed in depth from 2009 till 2017 [8,10]. A complete review is conducted by Nazari et al. [9] to provide researchers with a deeper understanding of how to choose the best working fluid based on the latent heat of vaporization and boiling point, surface tension, thermal conductivity and dynamic viscosity. In recent studies, the combining utilization of hybrid nanofluids and geometrical alterations in heat exchangers has showcased substantial advancement in augmenting heat transfer efficiency [13,14]. Concurrently, active initiatives are also underway to enhance the thermal performance of PHPs through the integration of diverse nanofluids. A thorough literature study of the nanofluids used in PHPs was also carried out. In a recent review, Zhang et al. [11] explored the impact of cross-section, fluid properties, and external field action (i.e., magnetic field, ultrasonic wave, etc.) on PHP start-up characteristics. A flat plate pulsating heat pipe (FPPHP) is a promising design for electronics cooling. An in-depth review of thermohydraulic working principles and thermal attributes of FPPHP was conducted by Ayel et al [15]. A comprehensive critical assessment of the progress made in the theoretical modeling and simulation of PHP to date is provided in a detailed review conducted by Nikolayev [16], and it was concluded that performing PHP simulations in horizontal position and top heating mode is necessary for a better understanding of PHP working mechanisms. Mameli et al. [17], in their review of innovations in PHPs, stated that the development of ideally independent from orientation PHP is one of the future challenges in the fields of FPPHP development and application of non-conventional fluids (binary mixtures, nanofluids) as heat carriers. An insufficient quantity of visualization research on PHP working under horizontal and top heating conditions was noted by Su et al. [18].

As it can be seen, there is plenty of data on the influence of different parameters, including inclination angle, on PHP performance, but on the other hand, many reviewers note the necessity of PHP functioning investigation in horizontal and vertical top heating positions. It is because researchers paid more attention to studying of PHP performance in vertical bottom heating mode or at inclination angles between this mode and horizontal orientation. To the best of the authors knowledge, limited reviews have been published addressing the critical parameters influencing the thermal performance of pulsating heat pipes with a specific focus on mitigating the impact of gravity. Meanwhile, knowledge about PHP functioning in horizontal and vertical top heating (or so-called anti-gravity) modes has great importance for better understanding of principles of PHP operation, designing of PHP with fully orientation independent performance and practical PHP application. In the present investigation, a comprehensive analysis is undertaken to assess the influence of geometrical parameters - encompassing cross-sectional area, inner diameter, number of turns (Fig. 1), channel design, and zone length (Fig. 1); operational parameters – encompassing orientation and heat input, working fluid parameters – encompassing fluids physical properties, fluid category, and filling ratio (Fig. 2).

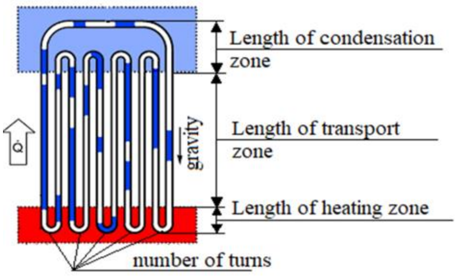

Fig. 1. Some parameters influencing PHP functioning (bottom heating mode is depicted).

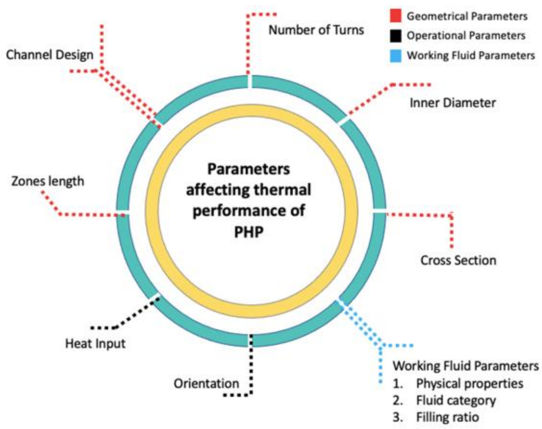

Fig. 2. Parametric review categorization.

The primary objective is to identify and address research gaps associated with PHP functionality, specifically in horizontal and top heating modes. A review of PHP design features described in the literature and their comparison is also made to find the most prospective designs of orientation-independent PHP.

2. Geometrical parameters

2.1. Inner diameter

The PHP's distinctive feature is its ability to produce liquid slugs and vapor bubbles in the channels. When the inner diameter of the channels is less than a critical diameter, surface tension forces overpower gravitational forces and the working fluid spreads across the tube in the form of liquid slugs and vapor plugs [19]. The major design restriction for PHP is the Bond number (Bo) – Eq. (1) [8], which limits the capillary tube diameter and gives the minimum internal diameter required for the capillary tube to operate in its true nature

$$Bo = \sqrt{\frac{g(\rho_l - \rho_g)}{\sigma} D^2}. \tag{1}$$

Very few researchers focused solely on the influence of inner diameter on PHP performance. They focused mainly on the impact of a range of other characteristics combined with an inner diameter on PHP output. The PHP's thermal resistance decreased as the inner diameter grew larger, which was attributed to the fact that a smaller inner diameter gave more friction resistance [20–23]. PHP's ability to manage large heat load is found to be closely related to diameter. In this regard, a larger choice of diameter would be advantageous, as for the same filling ratio, PHP with a 2 mm hydraulic diameter in horizontal mode could withstand a heat input of up to 390 W before its dry-out, whereas 1 mm hydraulic diameter PHP catches dry-out at a heat input of 190 W [22]. The heat transfer performance was also shown to increase with a 3 mm diameter tube compared to a 1.5 mm diameter tube [24]. Likewise, thermal resistance almost dropped to half when the diameter was raised from 1.05 mm to 1.9 mm [25]. Similar results were obtained when closed loop pulsating heat pipe (CLPHP) was experimented with a single turn [26]. Moreover, PHP showed different results when tested at different orientations. In horizontal mode with water as a working fluid, thermal resistance was reduced to nearly 52% with a 2 mm inner diameter compared to 1 mm, but only a marginal change was observed when ethanol was used as a working fluid [20]. The study reported by Rittidech et al. [27] found that thermal performance in horizontal orientation is not just a function of inner diameter but it is greatly affected by the properties of working fluid, as an experimental investigation revealed that heat transfer efficiency for R123 was higher, while ethanol performed poorly at a larger internal diameter. When the PHP was evaluated for a space application with a diameter bigger than the static critical diameter, which was 1.68 mm, the PHP may respond in microgravity like a real oscillating system [28]. Ayel et al. [29] concluded that the effect of gravity is more in a vertical position when experiments are carried out under conditions of hyper and microgravity, whereas the performance of PHP remained undeterred in horizontal positions, largely attributed to higher hydraulic dimeters; results of this paper were compared with experimental work by Mameli et al. [30] in the same working environment. Recently, a theoretical model was also developed to provide the absolute limit of the inner diameter and Bond number, which could allow PHP to work under microgravity conditions [31].

From the above findings, it can be seen that decreasing the PHP inner diameter leads to decreasing of gravity influence on PHP performance. But, on the other hand, the smaller PHP inner diameter the less maximal transferred heat flux. Thus, some optimal value of the inner diameter should be chosen to provide high PHP thermal characteristics independent from gravity. This precise value of the internal diameter that yields optimum performance is still in doubt, still researchers agree that the physical properties of the working fluid play a significant role in influencing the internal diameter on PHP's thermal performance.

2.2. Number of turns

Since the inception of PHP, researchers have agreed that a large number of turns has several advantages for reducing gravity's influence on PHP operation. When the number of turns approaches 80, the thermal resistance is independent of the orientation but occupies more area, limiting demand [19]. Increasing the number of turns could increase internal pressure disturbances and achieve better results in heat transfer [32]. The necessity of increasing of number of turns to provide of possibility of PHP operation in horizontal position was experimentally shown by Kravets and Alekseik [33]. Among PHPs with 4, 7 and 9 turns, tested by authors, only the latter was able to operate in both positions: vertical with bottom heating and horizontal. Moreover, experimental work carried out on square micro-channels with the number of turns varying from 5–20 (steps of 5) revealed that the dependence of maximum permissible heat flux on the angle of inclination becomes weaker as the number of turns increases and, as the number of turns increases to 20 or more, the PHP device can operate independently of its space orientation [34]. PHP study conducted with 20 turns resulted in successful operation at all inclination angles, and PHP with higher diameter comparatively produced 10% lower thermal resistance in horizontal operation [21]. Meanwhile, to limit the effect of gravity on the PHP output, 16 turns of copper PHP were used [35]. While extensive research on the impact of meandering turn numbers on CLPHP thermal performance has been published in the past, little theoretical study has been done to establish the optimal number of turns for greater heat transmission. Experimental research carried out on both horizontal and vertical CLPHP has successfully established a correlation to predict the optimum meandering turn number of the pulsating heat pipes in the vertical, closed loop, still, the same could not be determined for horizontal closed-loop pulsating heat pipes, as heat flux varies directly with the number of turns [36]. Numerical work has also been carried out to predict the optimum number of turns; in this regard, Noh and Kim [37] obtained a merit-number correlation to determine an optimum number of turns, which could guide the design of the pulsating heat pipe by optimizing the pulsating heat pipe's thermal performance while maximizing its merit number. According to literature data only PHP with 20 or more turns can be operated independent of gravity influence [34,37–39]. Still, such PHPs has large sizes which contradicting modern trend on miniaturizing of electronic components and equipment. So, it is necessary to find out methods which make working of PHP with fewer turns (less than 20) independent of space orientation.

2.3. Cross-section of PHP

PHPs of the same hydraulic diameter but varied cross sections, such as round, square, and triangular, flowed in the channel differently. The sharp angled corners formed due to varied cross section appear to collect more working fluid, resulting in increased capillary action [22]. Besides the commonly used circular cross-section, many researchers attempted to experimentally observe PHP's thermal characteristics by switching it to another cross-section. Khandekar et al. [40] experimentally verified the performance of PHP with rectangular and circular cross-sections for the same hydraulic diameter. The thermal resistance of the rectangular cross-section was observed to be lower than the circular cross-section when experimented with a filling ratio (FR) of less than 10%. However, there was not much difference in the improvement in thermal performance, and thermal resistance observed for both cross-sections in a horizontal mode of operation was more than 4 K/W. Similarly, as demonstrated by Hua et al. [41], using a rectangular section improves start-up characteristics while reducing thermal resistance by 60–70% compared to traditional PHP. A silicon-based micro PHP with trapezoidal channels could increase temperature uniformity in the evaporator section considerably [42]. Likewise, the PHP performance with a triangular cross-section resulted in a lower thermal resistance than a square channel as reported by Li and Jia [43]. A similar trend was also observed in a comparative study between square and circular channel [44,45]. A recent study on FPPHP confirmed that using a dual cross-section ratio (Adjacent channels with different width ratio in condenser and evaporator) between adjoining channels can provide practically orientation independent performance with over 34% less thermal resistance at horizontal orientation over a varying filling ratio and 40 W heat input [46]. However, Takawale et al. [47] conducted a recent study that contradicted previous observations. Comparison of PHPs made of flat plates (FPPHP) and capillary tubes (CTPHP) using ethanol as a working fluid revealed that CTPHP had a total thermal resistance was approximately 48% lower than FPPHP when operating under the same parameters. The researchers attributed this difference to lateral conduction between adjacent channels and brief perturbations in the amplitude of FPPHP. Nevertheless, a comparison of results obtained between Ayel et al. [29] and Mameli et al. [35] in the same conditions which include not only different orientation in space but also changes in gravity level from micro- to hyper-gravity has shown that FPPHP has less sensitivity to gravity influence than CTPHP.

While much work has been done to find out PHP's thermal performance with various cross-sections, there still needs to be clear understanding of which cross-section would result in better thermal efficiency. Past literature indicates a research gap about the cross-section impact of PHP on its thermal efficiency at different orientations. To understand the effect of cross-section on its thermal performance with regard to orientation, experimental research into the combined effect of cross-section and orientation, along with comparative analysis under similar conditions is necessary.

2.4. PHP channel design

Initially, numerical simulations were used to explore the use of uneven capillary forces in order to enhance flow circulation and, ultimately, to improve heat transfer by varying the diameter of the channels [48]. Similar strategies were then experimentally tested by Liu et al. [49] on three closed-loop PHPs with slightly different channel diameters and have been found to be effective in building and sustaining efficient working fluid circulation. By experimental investigation on vertical top heated PHP, Hathaway et al. [50] noticed a significant decrease in sensitivity to gravity when using coil-type, or what is commonly referred to as three-dimensional (non-planar) PHP systems with uneven turn combinations, such as a 20-turn evaporator and a 14-turn condenser. Pagliarini et al. [51] also manufactured and tested coil-type or three-dimensional PHP but with 13 turns in both evaporator and condensation zones. This PHP successfully operated in all space orientations. However, the functioning of the PHP was not fully independent from orientation. Thus, thermal resistance in the horizontal position was up to approximately 1.4 times higher and at top heating mode – up to 2.6 times higher than at bottom heating mode. Even at high heat loads (more than 120 W) where, according to authors' statement, PHP was independent from gravity, this ratio was 1.05–1.36 for horizontal position and 1.36-2.31 for top heating mode. In addition, it was found that PHP sensitivity to gravity decreases with increasing condenser temperature [51].

The three-dimensional design was also applied by Alekseik and Kravets [52] to make PHP-based cooler for electronic components. However, this was three-dimensional design of another kind than in [50–51]. The authors transformed conventional planar 24-turn PHP into three-dimensional PHP by arranging turns into 8 rows, as it is shown in Fig. 3, to place all turns on copper plate with dimensions 50×50 mm which acted like a thermal interface between PHP and cooled component. This PHP successfully operated at any orientation, including top heating mode, but its characteristics were still under gravity influence. For example, thermal resistance in top heating mode was up to 4.16 times higher than in bottom heating mode at the cooling of condensation zone by natural convection and up to 2.14 times higher

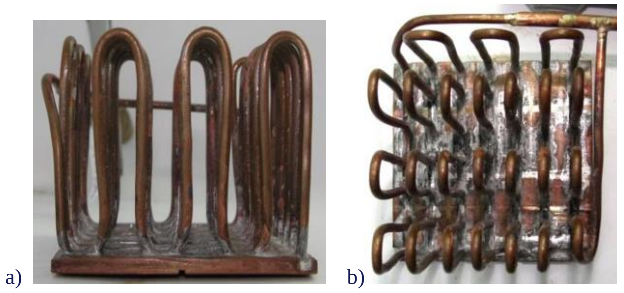

Fig. 3. Multi-row pulsating heat pipe [52]: front view (a), top view (b).

at forced convection. The same ratio for horizontal position was up to 2.06 at natural convection conditions. It should be noted, that in all these three cases, [50–52], PHP functioning at any orientation can be provided not only by three-dimensional design but also by large number of turns.

It was found that the PHP system could function horizontally with square channels of varying sizes. But the system could not operate in a horizontal position with uniformly arranged square channels [53]. Tseng et al. [54] further supported these findings by developing a strategy for operating CLPHP in a horizontal position. They conducted a comparative analysis between uniform and no-uniform PHP designs. Uniform design is a standard PHP design with round channels of an internal diameter 2.4 mm, and in non-uniform design round channels alternate with channels flattened to an oval shape with a minor diameter of 1.5 mm. The study found that when operated horizontally, the PHP with alternate channel design started at a relatively low heat input and produced substantially low thermal resistance, up to 65% compared to the conventional uniform diameter design [54]. Sedighi et al. [55] recently fabricated PHP with an additional branch (AB-PHP; Fig. 4a on Pyrex glass and compared it to standard flat plate PHP (FP-PHP). Due to an additional branch, thermal resistance decreased in the range of 11% to 20% at different FR, and flow circulation improved, resulting in better oscillation starting.

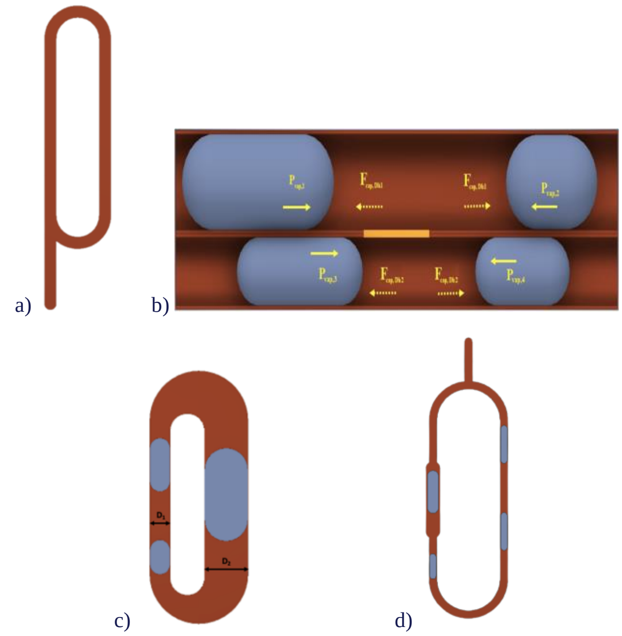

Fig. 4. Different channel design configurations: a) PHP with an additional branch [55], b) alternate double-pipe tube diameters with extra open connections [56], c) asymmetric PHP [57], d) PHP with asymmetric adiabatic channel [58].

Even after using many turns and geometric modifications, the PHP device can operate horizontally but fails to work in top heated position. To refine this problem, Tseng et al. [56] suggested a novel design using a mix of alternate double-pipe tube diameters with extra open connections between the dual pipe, as shown in the Fig. 4b. This novel design could allow PHP to operate in both top and bottom heated positions by adding an "extra unbalanced pressure force" for fluid circulation. The results of this new design were compared with Tseng et al. [54] and found that, due to this new design, thermal resistance decreased to 0.0729 K/W compared to 0.17 K/W with traditional CLPHP. Using of asymmetric PHP [57] like one shown in Fig. 4c showed 45% decrease in thermal resistance compared to symmetric PHP. Although proposed PHP model tested by Kwon and Kim was verified for one turn, but it was confirmed that increasing in the number of turns could allow asymmetric PHP work without gravity influence through this model [57]. A recent experiment

[58] was conducted on an asymmetric adiabatic channel (Fig. 4d), which yielded comparable results to the previous study. The findings indicated that PHP was ineffective when operated horizontally but could function at a lower inclination angle. When subjected to similar operating conditions with a heat input of 25 W, PHP exhibited a 30–33% decreasing in thermal resistance compared to conventional designs [58]. Therefore, it was clearly stated that even in the case of horizontal operation, using of non-uniformity in the channel layout could improve flow circulation. So in order to measure the effect of channel layout on thermal performance, the concept of effective dissimilarity was first introduced recently by Lim and Kim [59] and investigated micro pulsating heat pipe with HFE-7000 as a working fluid (50% FR) at various values of effective dissimilarity. Effective dissimilarity is a ratio between dissimilarities which show difference between current channel layout and both: uniformly arranged channel layout and decreasing channel layout. Due to using of non-uniformity in channel layout the channel with maximum effective dissimilarity reported 32% higher thermal conductance than channel with minimum effective dissimilarity in horizontal operation. Using of alternating channels with width 1.5 mm and 0.5 mm allowed horizontal operation of flexible flat-plate closed loop micro-PHP as it was reported by Jung et al. [60]. However, thermal characteristics of this PHP was still influenced by gravity. For example, its effective thermal conductivity in horizontal position was on 20.4% lower than in bottom heating position. From the other hand, its possibility of working in horizontal position can also be caused by large number of turns which was equal to 15.

Most recently, the influence of the tandem tapered nozzle on three-dimensional glass tube CLPHP was studied both experimentally and numerically [61]. Results revealed that after the modification, the thermal resistance was decreased by 29.5%, and the unidirectional flow was greatly encouraged. In addition, the dry-out condition that existed at 40% FR in the ordinary CLPHP was also removed in the tapered model. Similarly, Jang et al. [62] conducted an experiment on a radial pulsating heat pipe with diverging channels of both uniform and non-uniform sizes under horizontal operation, and discovered that the PHP with non-uniform diverging channels exhibited a thermal resistance that was up to 11.7% less than that of the uniformly designed channels However, the author did not explore how orientation impacts PHP performance [62].

The idea of non-uniform diameter PHP was further developed by Fallahzadeh et al. [63]. They fabricated and tested a single-turn triple-diameter PHP. Inner diameter of the left arm of heating and adiabatic zone was 2.5 mm, right arm of heating and adiabatic zone – 3.5 mm and condensation zone – 4.5 mm. Water was used as working fluid with variable FR from 40% to 70%. PHP was tested at inclination angles from 10° to 90°. Obtained results [63] has shown that using of triple-diameter allows to improve start-up and thermal performance, even at near-horizontal positions (inclination angles 10°–30°), and to decrease thermal resistance in comparison with single- and double-diameter PHP. Thus, applying of triple-diameter can be regarded as one of the prospective ways of decreasing of PHP sensitivity to space orientation but its effect still needs to be investigated on multiturn PHP at horizontal and top heating mode.

It can be seen that applying three-dimensional design and channels with no-uniform diameter or cross-section are prospective methods for decreasing of PHP sensitivity to space orientation. The latter can be implemented in two ways: alternating diameter or cross section of channels in an adiabatic section or making different PHP sections of different diameters. Both are proven to be effective but mostly for single-turn PHP at bottom heating and horizontal operation. It is still necessary to investigate the efficiency of these ways for multi-turn PHP and at top heating mode.

2.5. Zones length

In addition to using asymmetry in channels as one criterion to improve circulation, few authors have attempted to improve PHP performance by incorporating different sizes of evaporator lengths, adiabatic and condenser zones.

The influence of the heating zone length on PHP performance was investigated [20], which stated that the thermal resistance decreased with decrease in evaporator length and maximum performance occurred at 50 mm evaporator length. However, these findings contradict the results of a comprehensive study performed on flat plate solar collectors in combination with pulsating heat pipes [64]. It was observed that the longer the length of the evaporator, the higher the temperature of the outlet. Therefore, an increasing evaporator's length resulted in more heat being added to the tank. However, the heat transfer rate decreased with decrease in inclination, and optimum inclination of 200 for heat transfer to be maximum was observed. Similar findings from a recent study on an ethane-based low-temperature PHP also supported the idea that the PHP's heat transfer characteristics can be enhanced (the evaporator temperature may be stabilized and thermal resistance may be decreased) by lengthening the evaporator [65]. However, these results were obtained only for the vertical mode of operation with bottom heating.

Regarding the influence of adiabatic length, all researchers have come to a common conclusion that the larger the length of the adiabatic region, the greater the thermal resistance [66,67]. It was also recorded that thermal resistance was increased by just 30% by increasing adiabatic zone length by 500%, showing the possible benefits of PHPs to transmit heat over a long distance efficiently [68]. The effect of the adiabatic section length on the start-up and heat transfer efficiency was also evaluated using a two phase flow CFD model [69]. The start-up time of the PHP was reduced as the adiabatic section length increased, but the thermal resistance of the PHP increased too, and the PHP's anti-dry-out capability was weakened.

Kim and Kim [70] tested the effect of condenser length on micro-PHP and confirmed the existence of optimum condenser length for which the evaporator temperature was lowest (condenser temperature being constant). Moreover, the length ratio of the heating section to the cooling section was used as a criterion for assessing the performance of the closed-loop PHP via CFD simulation. It was found that raising the ratio leads to accelerating start-up and decreasing thermal resistance at the same FR and heat input [66]. To improve PHP performance, the effect of PHP zone length was also investigated in terms of its real-life potential application. Considering the entire length of PHP (evaporator to condenser), it is experimentally established that with increasing PHP length, thermal performance deteriorates [71].

It is evident from previous research that the findings on how each zone length affects PHP's thermal performance are contradictory. Additionally, there needs to be more research conducted on the effect of heating zone lengths less than 50 mm on the thermal performance of PHPs at various inclination angles, despite the fact that such lengths are relevant to modern electronics cooling. It is also noted that the length of the zone and the configuration of the PHP channel have a huge influence on thermal efficiency. In this regard, a novel channel design can take care of PHP working at any orientation and varied zone length can increase thermal efficiency, but there is no research to date on the combined effect of these two factors.

3. Working fluid parameters

3.1. Physical properties of working fluid

A PHP's work and thermal performance depend enormously on the properties of the working fluid. The fluid attributes to be accounted while choosing the working fluid are surface tension, dynamic viscosity, latent heat, specific heat, thermal conductivity, boiling point and, the rate of pressure variance over-temperature under saturated conditions $(\mathrm{d}p/\mathrm{d}t)_{\mathrm{sat}}$. The following section will pay examine all these properties and list their impact on PHP thermal performance.

As specified in Eq. (1), the maximum permissible PHP diameter occurs when the gravitational force roughly equals the capillary force. It is a well-known fact that higher surface tension generates a large capillary force and allows PHP to operate in any orientation, but at the same time, blocks the flow during liquid slug oscillation. In support of these theoretical postulates, numerical and experimental studies were carried out by Bastakoti et al. [72] and Kumar et al. [73], respectively, revealing that lower surface tension was found to increase thermal efficiency. On the other hand, fluid with greater surface tension tends to increase the diameter of the operating tube which due to lower frictional resistance, in effect, decreases the pressure drop. Many researchers have started using surfactant solution to lower the surface tension. PHP thermal efficiency with surfactant aqueous solutions of cetyl trimethyl ammonium bromide (CTAB) in the concentration range of 0.025% to 0.25% has been studied recently [74]. It is noted that it can significantly reduce surface tension and increase wettability by adding a surfactant solution. Due to the addition of surfactant, thermal resistance at heat inputs of 100 W and FR 50% decreased by 48.5% when compared to water. Likewise, several researchers have recently made the same attempt to reduce surface tension with the aid of surfactant solution and have found positive results with regard to PHP thermal performance [75–77].

In line with the fact that a small viscosity value can minimize channel shear stress, experimental research documented by Liu et al. [78] stated that low dynamic viscosity helped boost start-up performance. Whereas in terms of heat transfer performance, lower dynamic viscosity was found to be the dominant property at lower heat input but its effect at higher heat input weakened [79]. A similar trend was observed even in silicon-based micro pulsating heat pipes fabricated with different hydraulic diameters; working fluid with lower dynamic viscosity (FC-72 and R113) could start up PHP operation at low heat input, while fluid with a high value of dynamic viscosity (water and ethanol) failed to start up [80].

Low latent heat fluids exhibit better oscillation and start-up characteristics but are likely to dry out if the heat input continues to increase [79]. In terms of the working fluid, PHP demonstrated comparatively better thermal properties for methanol than all other fluids for both closed and open loops. For open-loop PHP, methanol is considered the best fit working fluid in horizontal operation, pertaining to its high thermal conductance [81]. A circular tube cross-section with 0.9 mm diameter was used in this experiment and performance is compared with water and acetone. Using DI water and methanol, Srikrishna et al. [82] investigated the effect on closed-loop PHP (2.2×2 mm). Better heat transfer results were obtained for methanol than DI water at 70% FR. So, it is recommended to use small latent heat fluids for low heat flux applications and high latent heat fluids for high heat flux.

The thermal conductivity of the fluid and the specific heat are two other parameters that greatly influence on thermal performance, as their higher values are likely to increase heat transfer rate. Another important parameter that was given utmost importance due to its unique characteristic is $(\mathrm{d}p/\mathrm{d}t)_{\mathrm{sat}}$. The larger its value, higher the difference in vapor pressure between evaporator and condenser for small temperature change [7]. Ammonia, which has higher $(\mathrm{d}p/\mathrm{d}t)_{\mathrm{sat}}$ than water, was experimentally tested as a working fluid in a glass PHP with ID = 2 mm [83]. It was found that during horizontal operation, it was easy for PHP to start up at low heat input, but circulation was not that effective. In a recent study, authors [84] also emphasize fluid properties that can provide the least PHP thermal resistance. But when comparing all the working fluids used in these two experimental works [83, 84], it can be found that the fluids with the lowest boiling points provide the least thermal resistance across most of the temperature ranges of the condenser and evaporator.

The literature analysis indicates that high thermal conductivity, specific heat and lower boiling point values provide high thermal performance of PHP. The effect of other fluid properties is controversial. To take advantage of the surface tension property and its influence on capillary force, the fluid must be selected which provides a compromise between the useful and blocking action of capillary force. Low latent heat, low viscosity, and high $(\mathrm{d}p/\mathrm{d}t)_{\mathrm{sat}}$ provoke better start-up of PHP, but at high heat fluxes positive effect of these properties deteriorates. Therefore, a working fluid should be selected with regard to working range of heat fluxes and space orientation of PHP or some new alternative working fluids, such as binary mixtures, nanofluids, etc., should be used.

3.2. Fluid category

The most commonly used working fluids in PHP operation are water, ethanol, methanol, acetone, R123, and FC-72 [79,80,85]. Past studies have shown that one specific working fluid cannot meet all the requirements mentioned in the above section. Regarding PHP thermal performance, the combination of two different fluids, a binary mixture, has shown improvement. For example, as stated by Zhao et al. [86], using of binary mixtures reduces of PHP thermal resistance by 68.9% when compared to pure liquids.

Vertically placed and bottom-heated PHP with water-acetone mixture as heat carrier was investigated [87], Results have shown that at FR 35%, 45% and mixing ratios 13:1, 1:1, 1:4, 1:13 PHP has better start-up performance and 33.6–68.9% lower thermal resistance when compare with pure liquids. Increasing the fraction of pure water (mixing ratio 13:1) is effective against dry-out and increasing the fraction of pure acetone makes an opposite effect. Improving PHP thermal performance by applying the binary mixture at high FR 62% and 70% is insignificant when compared to pure liquids. A similar study was conducted by Pachghare and Mahalle [88], which used pure water, ethanol, methanol, acetone, and binary mixtures (1:1 by volume) of water-ethanol, water-methanol and water-acetone as heat carriers. It was found that the thermal resistance of PHP with all tested binary mixtures was lower than that with corresponding pure liquids at low heat input, but changes are marginal at higher values of heat input. Among binary mixtures, the best PHP thermal performance was obtained for the water-acetone mixture. In another study [89], it was found that, at higher FR and heat input, the thermal performance of PHP with binary mixtures essentially becomes a function of the energy carrying capacity of fluid which again is a function of latent heat value and specific heat of the fluid. All binary mixtures have shown better anti-dry-out performance at low and medium FR (35–55%) than pure liquids. However, this advantage of binary mixtures was not observed at high FR. At heat input of more than 65 W and large FR (62%) mixing ratio 1:1 can be a good choice but thermal resistance of PHP with binary mixtures at these conditions is higher than that of pure water. The experimental probe by Wang et al. [90] on PHP with acetone-based mixtures (2:1, 4:1, 7:1) of water, methanol, and ethanol reported that at both low and medium FR, acetone-water binary mixture outperformed all other fluid mixtures with regards to its dry out features, but reverse effects were observed at high FR, and pure acetone exhibited better thermal performance.

Recently, the effect of other immiscible binary mixtures such as those not discussed in the above findings, is also tested on PHP. Xu et al. [91] used a combination of deionized water and HFE-7100 at different proportions (4:1, 2:1, 1:1; 1:2, 1:4) and varied inclination angles (30°–90°), whereas FR (50%) was kept constant and heat input was given between 20–250 W. It was found that a binary mixture with a 1:2 proportion performed well at heat input range 130–250 W (inclination 90°). When experimented with different heat inputs, the effect of gravity showed different characteristics at low inclination angle; at low heat inputs such as 20 W, binary mixture with 1:1 ratio performed comparatively well in terms of thermal resistance, whereas binary mixture with 1:4 ratio showed good results at high heat input.

Apart from soluble mixtures like acetone and ethanol in water, a comparative study of insoluble mixtures such as toluene and hexane in water was also carried out by Zamani et al. [92]. The mixing ratio was 3:1, 1:1, and 1:3, FR was 50%, and again acetone-water (3:1), displaying consistent trend, outperformed all other combinations and pure liquids, in terms of overall results. In addition, it was noted that soluble mixtures showed better thermal performance than that of insoluble mixtures. However, authors [86], based on literature analysis, make the opposite conclusion: insoluble mixtures significantly improve PHP thermal performance and can be prospective topic for further investigations.

Partially miscible binary mixtures can be regarded as some intermediate variant between miscible and immiscible ones. Zhou et al. [93] tested a 3-turn closed loop PHP filled with a partially miscible mixture of HFE-7100-ethanol. They found out that PHP had the best start-up characteristics and the lowest thermal resistance at mixing ratios of 3:1 and 3.5:1. Unfortunately, PHP was tested only in bottom heating mode.

The next step in using mixtures as heat carriers in PHP is applying ternary mixtures. The first mention of ternary mixtures applied in PHP was made by Su et al. [94] but they called a mixture of binary fluid (de-ionized water + n-butanol) and nanofluid as ternary mixture. At the same time, the authors do not specify which fluid was used as the base fluid for the nanofluid. If it was one of the binary mixture components then this heat carrier was just a mixture with nanoparticles (graphene oxide) addition, but not ternary mixture. In other case, it can be regarded as ternary mixture. However, using of such so-called “ternary mixture” led to the enhancement of PHP heat transport performance by approximately 15% when compared to de-ionized water at vertical bottom heating mode. Recently, Markal and Varol [95] investigated flat-plate 8-turns PHP with uneven channel width and a ternary mixture of water-methanol-pentane with mixing ratios 1:1:1, 1:2:3 and 1:3:2 at FR 30%, 50%, 70%. They found out that the optimal FR for ternary mixtures is 50% and PHP with such mixtures has better thermal performance than PHP with pure liquids at vertical bottom heating mode. The best thermal performance was achieved with a mixing ratio of 1:2:3 due to low surface tension and low boiling point. In addition, this mixture enhances start-up characteristics because of low viscosity and high $(dp/dt)_{sat}$. Unfortunately, PHPs with ternary mixtures don’t operate better in the horizontal position than PHPs with pure liquids. However, ternary mixtures can still be regarded as prospective heat carriers for PHP because of their potential to enhance thermal performance and presence of rewetting phenomenon that prevents dry-out of the heating zone.

Another way to improve thermal performance of PHP is the application of nanofluids. Adding nanoparticles to the working fluid at an optimal proportion can effectively increase the thermal conductivity of the fluid, and, hence the heat transfer rate. According to [86], applying of nanofluids with non-metallic particles as heat carriers in PHP decreases thermal resistance up to 83.6%.

Initially, many researchers used nanoparticles made primarily of pure materials such as: gold, diamond, silver, and copper [96–100]. All the researchers have come to a common conclusion that using nanofluids in PHP operation can certainly improve its performance due to their better thermal conducting properties. Later, researchers began using oxides as materials for nanoparticles. One such comparative experimental work was carried out [101], where authors used Al_2O_3 and SiO_2 nanoparticles and found that Al_2O_3 nanoparticles give rise to better thermal performance than SiO_2 particles. However, its effect depends precisely on its concentration. A recent review by Xu et al. [102] described the detailed development of the use of nanofluids in PHP and the workings mechanism and strategies for stability improvement. Authors have concluded that future investigations should be intended to find out the optimal concentration of nanoparticles, which will enhance of PHP heat transfer performance and, at the same time, will not lead to significant increasing in nanofluid viscosity.

When PHP experimented with graphene oxide as a nanofluid in water (in the concentration of 0.25–1.5 grams/liter), it was found that thermal resistance of PHP was reduced to 42 % with 2.5 grams/liter concentration, but the reverse trend was observed with a higher concentration [103]. Moreover, the stability of the working fluid is another factor that affects its performance, as reported by Akbari and Saidi [104]. It is observed that a lower value of thermal resistance was obtained with titania-water (TiO_2) nanofluid than graphene-water nanofluid, as the former had more stability than latter. According to results obtained during the investigation of PHP with a slant angle 24°, a noticeable improvement in the performance is observed upon the introduction of silver nanoparticles in water. However, marginal improvements were seen for a higher filling ratio [105]. In addition, thermal conductivity, which is the root cause of heat transfer enhancement, particularly given the effect of nanofluid, is strongly affected by both the size and shape of the nanoparticles. It is reported that increasing nanoparticle size leads to an increase in the conductivity of a nanofluid [106]. Whereas, out of three shapes (platelet, blade, and brick) of Al_2O_3 nanoparticles which were experimented, brick shape outperformed all other shapes in terms thermal conductivity and stability [107]. On the other side, according to information from review [9], PHP filled with nanofluid made of binary mixture of deionized water and ethylene glycol with addition of aluminum nanoparticles in concentration 0.3% by volume showed the best performance with nanoparticles of cylinder shape at heat inputs lower than 100 W. And at heat input higher than 150 W the best performance was achieved with brick-like nanoparticles. Moreover, optimal concentration is also dependent on nanoparticles shape [9]. Such ambiguous results indicate that the influence of nanoparticles form on PHP performance still needs to be investigated.

While researchers gave much attention to improving thermal performance of PHP in vertical position using nanofluid, experimental research was also carried out to study the impact of gravity on CLPHP with DI-water and CuO nanofluid [108]. However, in horizontal operation, the tested PHP could not perform, suggesting that although nanofluid improves PHP thermal performance, it has little effect on gravity. However, PHP with water-based ferrofluid was able to operate at any orientation in presence of magnetic field as experimented by Mohammadi et al. [109]. Thermal performance was significantly elevated in horizontal operation at a larger filling ratio and heat input. In a parallel investigation, Goshayeshi et al. [110] dispersed Fe_2O_3 nanoparticles into kerosene and studied its effect on closed-loop copper PHP under a magnetic field. Even in horizontal operation, the PHP functioned successfully, although its thermal resistance increased from vertical to horizontal.

All the results mentioned showed that using of binary mixtures enhances PHP's thermal performance in compared with traditional pure working fluids in most cases. However, positive effect of applying binary mixtures takes place at low FR (less than 50%), and at high FR, it deteriorates. Information about optimal mixing ratio and impact of binary mixtures on PHP performance at different orientations is limited, and research work in these ways needs to be done. In addition, a question about the type of binary mixture (soluble or insoluble) that provides better PHP performance is still unsolved. Most researchers concluded that enhancing PHP thermal performance due to application of nanofluids is related to high thermal conductivity of these fluids. However, the optimal concentration of nanoparticles, stability, sizes and form, and thermal performance of PHP with nanofluids at different space orientations still need more attention.

3.3. Filling ratio

Filling ratio (FR) is ratio between volume of liquid heat carrier filled inside PHP and total inner volume of PHP. Past studies have found that for PHP to show its true nature, FR should range between 20% to 80% [7]. However, a critical review by Han et al. [89], showed that the most authors used FR of between 35% and 65% as the optimal value for almost all the working fluids. The properties of working fluid have a significant influence on the optimum FR. Experimental work reported by Han et al. [79] revealed that working fluid with low latent heat value was easier to dry out for the same FR. Results also showed that with regards to low thermal resistance, at low heat flux, FR of approximately 60 % is a fair choice for acetone, whereas, at high heat flux, the optimal filling ratio for methanol and DI water ranges from 60% to 70%.

Similar behavior was observed for acetone, as it displayed a lower thermal resistance value at 60% FR when PHP was tested at FR ranging from 50% to 90% [111]. Ethanol, on the other hand exhibited optimum performance at FR of 50% to 70% [112]. It was 70–80% for ammonia to avoid burn out of evaporator [82]. Besides working fluid properties, PHP performance in terms of FR often varies with PHP system orientation and cross section. When a flat plate aluminum PHP was operated with ethanol as a working fluid, the optimum FR was found to be 50–65% in horizontal and top heated positions, whereas it was between 40–70% with bottom heated mode [22]. At close horizontal orientations, the performance of water as a working fluid is lower than methanol with the same fill ratio, and, methanol displayed less thermal resistance when measured at 40% FR for inclination angles from 90° to 7.5° [82]. In another investigation, DI-water charged PHP with a circular channel showed the lowest thermal resistance at FR of 40% while, rectangular channel showed the lowest thermal resistance at 30% FR [41]. A recent study of liquid metal high-temperature 6-turn PHP filled with sodium-potassium alloy performed by Wu et al. [113] has shown that the best PHP thermal performance was obtained at FR equals to 48%. However, FR did not show a significant influence on PHP sensitivity to inclination angle: at FR equals to 22% PHP failed to start in horizontal position, but for all other tested FRs (35%, 48%, 64%, 80%) similar trend was observed – decreasing of inclination angle from 90° (bottom heating mode) to 0° (horizontal position) leads to increasing of thermal resistance.

Although FR is a crucial parameter to decide heat transfer characteristics of PHP devices, past studies show that optimum FR of a working fluid varies with a particular experimental design, which again is a function of many other parameters that were discussed. Theoretical studies that could establish the optimum FR for optimizing heat transfer characteristics are rare. One such study was carried out recently by Yin et al. [114], who developed a mathematical model to predict the effect of FR on startup heat flux. The study found that the heat input required to start the oscillation depends on FR, but the upper limit of FR is again considered to be a function of the type of fluid. It is, therefore, imperative that many experimental or computational tests need to be carried out in terms of FR to create a database that will help design future PHP devices at optimum FR.

4. Operational parameters

4.1. Heat input

The heat input to the PHP system relates directly to its operating temperature. About the application of PHP for cooling of electronic devices, the reliability of electronic components is closely linked to the failure factor (failure rate ratio at any temperature to failure rate at 75ºC), which increases exponentially with the system temperature [115]. It is, therefore, of utmost importance to build a PHP that can be operated over a wide range of temperatures and prevent electronic components from raising their temperature beyond its failure threshold.

A study carried out by Spinato et al. [11] on copper CLPHP (ID = 2 mm) using water, ethanol, methanol, and acetone as working fluid showed influence of heat input value on flow patterns inside PHP. Bubbly and slug flow patterns were observed in the upward flow under the impact of gravity after slug boiling at power up to 40 W, and semi-annular and annular flows were found in the downward flow. At high heat flux, the gravity effect showed no impact (70 to 80 W). In particular, it was shown that thin-film evaporation makes the most significant contribution to the overall local heat transfer coefficient for all the conditions studied and can be considered as the prevailing heat transfer process. This research suggested that the collective activity of bubble nucleation, agglomeration, and condensation is responsible for the two-phase flow movement. More recently, similar observations were made when utilizing gravity pulsating heat pipe to intensify the gravity impact of the working fluid for preventing dry-out at heat input range 30–230 W. These observations validated that film boiling heat transfer is the leading driving force behind stable operation [117].

As mentioned before, Spinato et al. [116] did not observe a significant effect of space orientation on PHP performance at high heat fluxes. Similar results were obtained by Torresin et al. [118] on double condenser PHP cooler, which demonstrated close to orientation-free PHP operation at high heat input (higher than 2000 W).

An attempt was also made to find out the liquid and vapor volume fraction within PHP by experimenting with water-based PHP (6 turns) using neutron imaging technique. It was found that the average liquid volume fraction was always less than 25% and more than 80% in the evaporator and condenser, respectively, during the steady-state oscillation within PHP [119]. The thermodynamic state of a vapor plug in the micro pulsating heat pipe (MPHP) was recently experimentally determined by Jun and Kim [120], and it was observed to be depend on the presence of the liquid film covering the vapor plug. The vapor plug becomes saturated when surrounded by a liquid film. On the other side, the vapor plug is superheated when it is in close contact with the dry wall without the liquid film (Fig. 5).

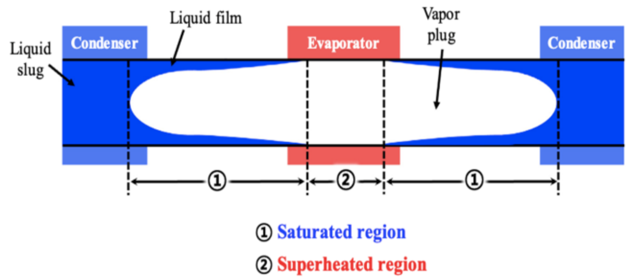

Fig. 5. Thermodynamic state of vapour plug inside PHP [120].

The startup analysis was conducted with binary fluids (acetone, ethanol, methanol) and surfactant solutions (sodium dodecyl sulphate) based on water. It was found that the onset of pulsation remained the same even after using PHP for more than 7 hours, but with a rise in evaporator temperature [121]. Although heat flux is responsible for generating a driving force required to bring PHP into operation, start-up heat flux is different for different working fluids.

Experimental testing of PHP at different orientations from horizontal to vertical has shown that each tilting angle displayed different starting heat input values. Furthermore, the operational range of allowable heat fluxes becomes narrower and closer to lower heat power values as the tilting angle increases [122]. Meanwhile, heating patterns significantly influenced startup process and thermal resistance of PHP as indicated numerically by Jiansheng et al. [123]. The PHP's start-up time was decreased due to the non-uniform heating pattern (heating at one or many turns), which was attributed to the additional imbalance stimulating the device's start-up. However, thermal resistance increased under the same conditions. Experimental analysis with non-uniform heating of 8-turn PHP with HFE-7100 as heat carrier at bottom heating mode carried out by Jang et al. [124] demonstrated findings similar to those of the previous study. A concept of "dimensionless heat difference (ratio of the difference in heat input between two sources to total heat input)" was used and thermal resistance was found to be increased due to early drying out on the higher side of the heat input with an increase in this factor. A recent experimental study on inclination angle influence on thermal performance of 4-turn CLPHP with ethanol and HFE-7100 as heat carriers conducted by Zhang et al. [125] showed decreasing of thermal resistance and PHP sensitivity to space orientation with application of non-uniform heating pattern when compare it to uniform at inclination angle range 45°–90°. These results contradict the results of previous studies.

However, the heating pattern does not only influence PHP performance. Okazaki et al. [126] experimentally shown that presence of large quantity of alternating heating and condensation zones has vital importance for ensuring of PHP functioning in horizontal position. They compared performance of circular single-turn PHP and serpentine multi turn PHP in horizontal position. Both PHPs had the same overall capillary tube length, quantity of check valves and quantity of alternating heating and condensation zones, both were filled with HFC-134a. Both PHP demonstrated almost similar thermal performance with a thermal resistance of approximately 0.45–1.1 K/W. This means that the presence of large quantity of alternating heating and condensation zones has more importance for ensuring of PHP operation in horizontal position than even large number of turns. Moreover, this result shows that PHP for a horizontal mode of operation can be designed without U-shaped turns at all.

Heat input level strongly affects thermo-fluid dynamics within PHP and, as a result, affects the thermal performance of PHP- Startup and dry-out heat input levels, which are the borders of PHP operational range of heat flux. High heat input levels significantly decrease PHP sensitivity to space orientation, but such levels not always achievable in practical applications. The application of non-uniform heat input patterns could be named as prospective method of improving PHP start-up characteristics. However, the influence of such patterns on PHP heat transfer characteristics needs further and deeper investigation in wide range of inclination angles, including horizontal and vertical top heating mode, because of contradictions in existing results. Furthermore, it is necessary to provide investigations and develop new PHP designs for minimizing of inclination angle influence on an operational range of heat flux.

4.2. Orientation of PHP

Gravity adds to the unequal distribution of pressure in the PHP, which could increase the perturbation of the fluid and the enhanced heat transfer that follows it. Moreover, gravity facilitates the backflow of the liquid phase into the evaporator at low heat flux, which is a significant element in stopping the evaporator from drying out. One of these benefits is missed by PHP in a horizontal position or vertical top heating mode. Therefore, PHP orientation indirectly brings gravity into the picture and plays a vital role in evaluating its thermal performance, which could also be described using Eq. (1). Several attempts have been made in the past, to make PHP work independently of its orientation and weaken the influence of gravity by finding out balance between the capillary and vapor pressure forces using new PHP designs [50,51,53,54,56]. It is observed that PHP's thermal performance becomes independent of the orientation using the number of turns as high as 80 [19]. Attempts have also been made to use a fewer number of turns (to minimize space) and yet be able to weaken the influence of gravity. The first attempt to understand the role of gravity in the operational characteristics of PHP is made by Khandekar and Groll [6], A 'stopover' phenomenon was observed and described as repetitive activity phase occurrence (large amplitude oscillations) and static phase occurrence (very small amplitude oscillations). Liquid plugs oscillate with very small amplitude in the condenser segment during the static phase. This 'stopover' phenomenon is also explained clearly by Jun and Kim (Fig. 6) [127]. Due to this issue, the liquid plugs do not circulate from the condensing to the heating zone, contributing to the evaporator drying out. This 'stopover' phenomenon seldom happens in PHP with large number of turns, because of sustained high amplitude oscillations.

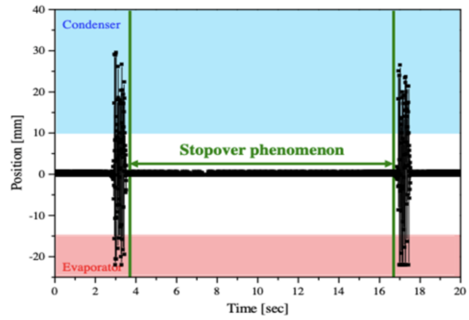

Fig. 6. Stopover phenomenon observed in 10 turn PHP during horizontal operation [127].

Therefore, quite recently, Jun and Kim [128] established a criterion through theoretical and experimental investigation on micro-PHP (10 turns) to prevent this 'stopover' phenomenon and to allow PHP function in horizontal mode. For normal PHP operation in horizontal mode, a figure of merit was introduced. Its analysis has shown that the ratio of the minimum thermal resistance in a vertical orientation to that in a horizontal orientation is proportional to the square of the ratio of the hydraulic diameter to the effective length of PHP [128]:

$$\left(\frac{R_{v,\,\min}}{R_{h,\,\min}}\right) \sim \left(\frac{D_h}{L_{eff}}\right)^2 \tag{2}$$

so as to prevent a 'stopover' defect in horizontal operation. It is also confirmed that the ratio of hydraulic diameter to the effective length of ethanol-filled micro-PHP must be greater than 0.03 for this purpose.

Moreover, simulation findings by Nekrashevych end Nikolayev [129] reveals that the variation in PHP performance is related to the difference in the phase distribution within the PHP evaporator at various orientations. Similar results were observed previously by Khandekar et al. [130] during the experimental study.

Findings from the literature imply that PHP can work at any orientation even without using a significant number of turns. A key to such functioning is balancing forces acting on heat carrier and phase distribution inside PHP. However, further investigations are necessary to discover physical insights and design solutions which provide optimal forces balance and phase distribution, allowing PHP function independently of orientation.

5. Comparison of design features enabling PHP functioning at different space orientation

As can be seen from previous sections, researchers try to apply some design features to make PHP operation at different space orientation possible. Some even call their PHP applicable to all orientations [53] or anti-gravity [71,132]. Moreover, according to published results working of these PHPs at any space orientation, including horizontal or even vertical with top heating is really possible. However, this possibility and full independence of PHP operation from space orientation are not the same. We regard the absence or minimal influence of space orientation on PHP performance in wide range of heat power as the latter. Let us compare different design features in terms of providing PHP operation independence from space orientation. The ratio of PHP thermal resistance at horizontal position (Rh) or at the top heating mode (R_{vt}) to thermal resistance at bottom heating mode (R_{vb}) is used for this purpose. Such an approach, for example, was used by Tseng et al. [132] to evaluate effectiveness of their design solution in comparison with other researchers. Thermal resistance is chosen because it is one of the main and most investigated PHP characteristics. The form of ratio (R_h/R_{vb} and R_{vt}/R_{vb}) is chosen to compare PHP thermal resistance in unfavorable orientations (horizontal and top heating mode) with that one in one of the most favorable orientations (bottom heating mode). If this ratio is equal or close to 1.0, then PHP works equally well in both favorable and unfavorable orientations. If it is higher than 1–1.1, then orientation has significant influence on PHP operation. The results of the comparison are presented in Table 1.

Table 1. Comparative table of design features enabling PHP functioning at different space orientation.

Operational parameter	Features of PHP design	Ratio of PHP thermal resistance at various space orientation		Reference
		R_h/R_{vb}	R_{vt}/R_{vb}	
Inner diameter	FPHP having more hydraulic diameter than critical value	1.56–1.89	N/A	[29]
Number of turns	Number of turns >>20	1.0–1.62	N/A	[34]
	Flat plate closed loop micro-PHP with 20 turns	1.0–2.15	N/A	[127]
	Flat plate closed end micro-PHP with 20 turns	1.0–1.09	N/A	[127]
Channel design	Closed loop FPPHP with square channels 1x1 mm and 2 x 2 mm	1.0–1.22	1.0–1.48	[22]
	FPHP dual cross section (different width ratio of adjacent channels in condenser and evaporator)	1.11–4.0	N/A	[46]
	Coil-type (three-dimensional) PHP with uneven-turn design: 20 turns in heating zone, 14 turns in condensation zone	N/A	1.0–2.31	[51]
	Coil-type (three-dimensional) PHP with 13 turns	0.56–1.36	1.03–2.57	[51]
	Multi-raw PHP	1.61–2.06	1.13–4.16	[52]
	Non uniform square channel	1.1–1.58	N/A	[53]
	Alternate tube diameter	1.19–7.78	N/A	[54]
	Double pipe PHP with alternate tube diameter and extra opening connection	N/A	1.32–15.0	[56]
	Flexible micro-FPPHP with alternating channels with width 1.5 mm and 0.5 mm	1.13–1.43	N/A	[60]
	Double condenser PHP with heat input at middle section	0.85–0.98	1.0–1.06	[118]
	Closed loop micro-FPPHP with D_h/L_{eff} = 0.038	0.91–1.2	1.0–1.93	[128]
	Ring-shaped rectangle PHP with dual cross section (round and oval-shaped)	N/A	1.04–2.06	[132]
Zones length	Coil-type PHP with zones length ratio $L_e : L_a : L_c = 1 : 1 : 1$	N/A	1.5–4.23	[71]
Physical properties of working fluid	Pure liquids: ammonia	2.4–7.6	N/A	[83]
	Liquid metals: sodium-potassium alloy with the potassium mass fraction of 78%)	1.27–3.11	N/A	[113]
	Binary mixtures: water-HFE (4:1, 2:1, 1:1, 1:2, 1:4)	1.09–2.07*	N/A	[91]
	Ethanol-pentane (1:1, 1:3, 3:1)	0.94–1.68	N/A	[131]
	Ternary mixtures: water-methanol-pentane (1:1:1, 1:2:3, 1:3:2)	1.02–2.04	N/A	[95]
	Nanofluids: water-copper 5% by mass, particle diameter 29 nm	1.15–1.66	1.15–2.09	[99]
	Water-Fe particles (magnetic ferrofluid) 7% by volume+magnetic field	1.55–1.9	N/A	[109]
	Kerosene-Fe_2O_3 (magnetic ferrofluid) 2% by volume, particle diameter 20 nm + magnetic field	1.12–1.25	N/A	[110]

*Ratio between thermal resistances at inclination angle 30° and at vertical bottom heating mode is presented.
N/A – data not available
L_e, L_a, L_c – length of evaporation, adiabatic and condensation zones respectively
HFE-7100 (methoxy-nonafluorobutane) is engineered fluid which was used as a heat carrier in PHP.

Data presented in Table 1 shows that the thermal resistance ratio for all listed design features changes in a wide range (much wider than 1–1.1) which means none of these features can provide PHP operation full independent from space orientation. However, despite this fact, there are some design features, which could be named, as prospective because they ensure the narrowest range of the thermal resistance ratio. Applying uneven-turn design, alternative channel design in form of non-uniform square channels [53] and using binary mixtures [91,131] and nanofluids [99,109,110] are among them. It is important to note that good results in [109] and [110] were achieved due to the application of magnetic field to PHPs filled with magnetic ferrofluids which is possible only in some specific practical applications.

One of the narrowest range thermal resistance ratios at horizontal position was obtained for double condenser PHP proposed by Torresin et al. [118]. Moreover, the values of the ratio are less than 1 (0.85–0.98) which means that PHP performance in horizontal orientation was even better than in vertical. As for the vertical orientation, there was no differences between possible variants of vertical orientation for this PHP in terms of mutual placement of heating and condensation zones because of its design: condensation zones were placed at both ends of the PHP and heating zone – between them in the middle part of the PHP. Thus, at any vertical orientation one of the condensers was always above the heating zone and the other one was below. Thereby, data on the top heating mode presented in table 1 for this PHP are quite conditional, and the difference in condensers channels design can explain insignificant difference of thermal resistance ratio from 1. Two important things should be noted about the results presented in [118]. First, they were obtained for high heat input in the range 500–2500 W, at which even PHPs of classical design have significantly decreased sensitivity to space orientation. Achieving such a result at lower heat power (up to 100–150 W), which is more conventional for electronics cooling, is much harder. Second, the thermal resistance presented in [118] is not the thermal resistance of PHP itself. In fact, it is a sum of PHP thermal resistance and thermal resistance of heat transfer from the outer surface of PHP to the cooling air because it was calculated by difference between maximal temperature in heating zone and temperature of cooling air.

Alternative channel designs such as double pipe PHP with alternate tube diameter and extra opening connection [55] and ring-shaped rectangle PHP with dual cross section [132] can be regarded as prospective because possibility of working of PHPs with these designs at top heating mode was proven experimentally. The relatively narrow range of thermal resistance ratio at top heating mode was obtained by authors [50] (1.0–2.31) and [132] (1.04–2.06). However, these results were also obtained for high heat input of 200–800 W.

The narrow range of thermal resistance ratios for both horizontal (1.0–1.22) and top heating mode (1.0–1.48) was obtained in [22]. However, these results can be explained by a large number of turns (20 and 33) and a high heat input 200–400 W.

It should be noted that in most cases listed in the Table 1, the lower border of the range of thermal resistance ratio is equal to 1–1.1. However, these ratios were obtained only for a few values of heat fluxes and not for whole working range of heat flux. It is also evident from Table 1 that most of the PHPs with design features were not tested at top heating mode.

Results different from those described above were obtained by Jun and Kim [127] on flat plate closed loop micro-PHP (CLMPHP) and closed end micro-PHP (CEMPHP) filled with ethanol at FR equal to 50% and tested at heat input range 2–82 W. 20-turns CLMPHP showed orientation independent performance in terms of thermal resistance (R_h/R_{vb} = 1.0) in the heat input range 42–82 W. The highest value of thermal resistance ratio was obtained at heat input lower than 20 W where PHP start-up takes place. It means that space orientation still influenced the start-up parameters of this PHP. This influence was absent for 15-turns CEMPHP which demonstra-ted full orientation independent performance in whole range of tested heat inputs (R_h/R_{vb} = 1.0–1.09).

These results confirm the possibility of designing of PHP free of space orientation influence. However, on the other hand, thermal resistance of these PHPs in the main working mode is in the range 1–2 K/W which is too high for some practical applications such as, for example, electronic cooling. Therefore, it is necessary to enhance the design of these PHPs to decrease thermal resistance.

The same authors in their subsequent work [128] found a criterion which allows designing of PHP with orientation independent performance. This criterion is the ratio D_h/L_{eff} (see Eq. (2)). They manufactured 10-turns CLMPHP with D_h/L_{eff} = 0.038, and ethanol as heat carrier (FR = 50%) and tested it in the range of heat input 12–44 W. According to the results obtained, thermal resistance ratio of this PHP for both horizontal and vertical top heating mode is equal to 1.0 at heat input range 22–44 W. This is the evidence of full independence of PHP performance from space orientation. However, at heat input lower than 20 W, thermal resistance ratios reach the value of 1.2 for the horizontal position and 1.93 – at vertical top heating mode. This indicates the influence of space orientation on start-up characteristics of PHP. Taking these results into account, proposed criterion can be regarded as one of the key parameters for providing of orientation independent PHP performance, but it needs some improvement and further experimental verification for a few reasons. First, it does not offer orientation independent performance during start-up period. Second, its derivation was based on visualization data obtained for micro-PHP and it was verified on ethanol as heat carrier. It is unknown how it works for PHP of conventional design and for other heat carriers. Third, it does not take into account the surface tension of heat carrier, which plays significant role in liquid slugs formation and movement, and PHP number of turns, which has a significant influence on PHP sensitivity to space orientation. The fourth, it contains effective length. Despite relatively frequently applying this parameter as characteristic length of PHP, in our opinion, it is not correct. This parameter appears in a field of conventional wick heat pipes. It is a sum of length on which mass flow rate of liquid heat carrier through a wick has maximal and constant value (adiabatic zone) and half-sum of lengths on which it linearly changes from zero to maximum (heating zone) and vice versa (condensation zone) [133]. However, PHP does not contain a wick; liquid and vapor phase of a heat carrier are not separated, as it takes place in conventional heat pipes, and flow as single two-phase stream; PHP is multichannel device and mass flow rate of liquid may differ from channel to channel at the same moment of time. Thus, it is necessary to find out the physical justification for applying of effective length to PHP or derivate some alternative characteristic length of PHP.

It can be summarized that applying of uneven-turn design, channel design with alternating shape and size of cross-section, double-condenser design, and using of nanofluids and binary mixtures as heat carriers are some of the most prospective ways of providing independent PHP working from space orientation. However, they still need improvement and additional investigation to decrease the thermal resistance ratio. In addition, it is necessary to investigate the influence of design features on PHP operation at top heating mode.

6. Conclusions

Space orientation has a significant impact on PHP's heat transfer efficiency. Despite several benefits of PHP in various applications involving efficient heat transfer requirements, the commercial aspect of PHP has been presented very narrow in the market. This is because of the fact that the original PHP works better when gravity assists the process. With such high hopes for PHP's future prospects, various challenges linked to reducing PHP space orientation dependence must be resolved, and some recommendations for further study are provided here:

1. In terms of cross-section, state-of-the-art claims that micro-PHP with a non-circular cross-section (such as rectangular, triangular, trapezoidal) has shown better thermal characteristics than these with circular cross section. However, there still needs to be a clear understanding of which cross-section would result in better thermal efficiency for PHP in general. In addition, there are research gaps regarding the combined effect of cross-section and space orientation of PHP on its thermal efficiency. Thus, investigations in this way are necessary.
2. In terms of geometrical parameters, PHP with an ID less than 2 mm can work in any space orientation. However, because decreasing ID increases thermal resistance, it is vital to develop a solution to reduce thermal resistance. There is lack of information about zone lengths influence on thermal performance of PHP. Moreover, information about the influence of this parameter on the possibility of PHP working at any orientation in space is absent. Therefore, this factor needs to be investigated. PHP with a number of turns more than 20 can operate independent to orientation in space. However, the sizes of such PHPs are too large for application in modern electronic devices. Therefore, it is necessary to find ways of making orientation-independent PHP with small number of turns such as from 1 to 10.
3. High thermal conductivity values of the working fluid and the specific heat provide high thermal performance of PHP. The effect of other liquid properties is controversial. Surface tension should have a value that provides a compromise between the useful and blocking action of capillary force. Low latent heat, low viscosity, and high $(dp/dt)_{sat}$ provoke better start-up of PHP, but at high heat fluxes, positive effect of these properties deteriorates. Therefore, a working fluid should be selected with regard to working range of heat fluxes and space orientation of PHP or some new alternative working fluids should be used.
4. Using binary mixtures and nanofluids greatly enhances PHP's thermal performance in compared with traditional pure working fluids in most cases. However, information about optimal mixing ratio of binary mixtures, optimal parameters of nanofluids: concentration, size and form of nanoparticle, stability of fluid and impact of these fluid categories on PHP performance at different orientations (especially horizontal and top heating mode) is limited and research works in these ways need to be done. In addition, a question about type of binary mixture (soluble or insoluble) which provides better PHP performance is still unsolved.
5. Filling ratio (FR) is one of the main parameters affecting thermal performance of PHP. Optimal FR range depends on many factors such as PHP design and physical properties of heat carrier. Many experimental or computational tests need to be carried out to create a database that will help design future PHP devices at optimum FR.
6. Applying three-dimensional design, uneven-turn design, channel design with alternating shape and size of cross section, double-condenser design and using of nanofluids and binary mixtures as heat carriers could be named as one of the prospective ways of providing independent PHP working from space orientation. However, they need to be improved and investigated to further decrease PHP sensitivity to space orientation. In addition, it is necessary to investigate the influence of design features on PHP operation at the top heating mode.

The findings of this study offer a reference for future research intended for stabilization of PHPs thermal performance across varying orientations. This stabilization holds promise for expanding PHP applications in domains where passive heat transfer is a critical requirement. The future scope of PHP researches is connected not only with decreasing of sensitivity to space orientation but also with PHP miniaturization, design modifications, further development of flat-plate PHP, applying of alternative casing materials and heat carriers in order to obtain compact high efficient heat transfer devices and thermal spreaders based on PHP.

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