Innovations in pulsating heat pipes: From origins to future perspectives

Mauro Mameli[1], Giorgio Besagni[2], Pradeep K. Bansal[3], Christos N. Markides[4]

[1] Department of Energy Systems Constructions and Territory, University of Pisa, Largo L. Lazzarino 2,
56121 Pisa, Italy.
[2] Politecnico di Milano, Department of Energy, Via Lambruschini 4a, 20156, Milano, Italy.
[3] Satya International Ltd., United States of America.
[4] Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering,
Imperial College London, London SW7 2AZ, UK.

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Abstract

Since the early 1990s, the pulsating heat pipe (PHP) has emerged as one of the most innovative, effective and potentially more convenient passive two-phase heat transfer systems, thanks to its good performance, versatility, and construction simplicity. On the other hand, the PHP is characterized by complex thermohydraulic behaviour that still presents a true challenge to designers, which has led to significant interest by a growing number of researchers.

The technological readiness level (TLR) of this technology is quite broad depending on the application: for instance, the industrial community is starting to consider the PHP as a reliable solution for electronic cooling in ground conditions, while implementations in the cryogenic temperature range and in space environments is also being extensively explored.

This vision paper aims at shedding light on the current knowledge and prediction capability of PHP numerical models, on unsolved phenomenological issues, on the current technological challenges and the future perspectives of this fascinating heat transfer device.

Specifically, after a general introduction and a brief overview of the current knowledge and the open issues of PHPs, special focus is devoted to the following topics: flat-plate PHP assessments; advancements in PHP modelling and simulation; flow stabilization techniques; non-conventional fluids subdivided into fluid mixtures, self-rewetting fluids, nanofluids; cryogenic applications, space applications, and finally the newest frontiers of flexible PHPs.

Each section is accompanied by a brief roadmap providing directions for future research based on key challenges, which are also gathered and summarized in the final outlook section.

Keywords: flat plate; heat transfer; heat pipe; oscillating heat pipe; pulsating heat pipe; thermal management, challenges, multi-scale.

Nomenclature

Symbol	**Definition**		
ANN	Artificial neural network	ISOPHP	International Symposyum on Oscillating/Pulsating Heat Pipe
CFD	Computational fluid dynamics	ISS	International space station
CLPHP	Closed loop pulsating heat pipe	JAXA	Japanese space agency
CNT	Carbon nano tubes	PHP	Pulsating heat pipe
CV	Check valve	SMA	Smart memory alloy
CWP	Continuous wave propagation	SMD	Spring mass damper

ESA	European space agency	SRF	Self rewetting fluid
FPPHP	Flat plate pulsating heat pipe	TRL	Technological readiness level
IHPC	International Heat Pipe Conference		

1 Introduction

Two patents dated 1990 and 1993 [1],[2] by the Japanese inventor Akachi described the basic working principles of a "*...novel, relatively simple structure of a loop-type heat pipe in which a heat carrying fluid [...], circulates in a loop form in itself under its own vapor pressure at high speed within an elongate pipe so as to repeat vaporization and condensation, thus carrying out a heat transfer*". This is the actual first description available in the literature of the wickless two-phase passive heat transfer device known as a pulsating heat pipe (PHP).

Over the years, the PHP have been called in many different ways, starting from the most known alternative oscillating heat pipe (OHP), the capillary tube heat pipe, meandering heat pipe, capillary thermosyphon, wickless heat pipe, and also the spaghetti heat pipe, amongst other. To-date, the heat pipe community has not yet converged on a singular, shared term to describe the impulsive and chaotic nature of the flow motion occurring inside the device, comprising both purely oscillating flow and average circulating flow primed by the local pressure differences. This lack of consensus also reflects the lack of common definitions for some characteristic parameters relevant to pulsating heat pipes, thus hindering technical communication and a comparison of results coming from different research groups.

This vision paper, starting from the thematic special issue published in Applied Thermal Engineering, is firstly an invitation to all the members of the Heat Pipe scientific community to promote the use of common standards and contribute to the construction of a shared platform. Moreover, it aims at providing a fair picture of the current knowledge of PHPs, focussing on the solved and still unsolved issues, on the most interesting applications and on the possible directions for future research activities in this field.

2 Current knowledge, open issues and challenges

From the very beginning, the academic world has been fascinated by the dichotomy between the complex nature of the two phase non equilibrium thermofluid dynamic phenomena occurring inside the PHP [3][4], and its simple structure: a capillary channel evacuated and partially filled with a working fluid, where one side is in contact with a hot source (i.e., an evaporator) and the opposite end is in contact with a cold source (i.e., a condenser). The great potential in terms of industrial application, implementation, versatility and performance [5] is immediately perceivable as the PHP could possibly solve a wide range of thermal problems that goes from the thermal control of critical elements and heat dissipation [6] to the heat recovery [7],[8]. On the other hand, the industry has always been sceptic mainly due to the intrinsic chaotic nature of the PHP dynamics and the consequent lack of robust and reliable predictive tools that hinders a systematic and consistent design. Nowadays more and more companies are approaching the subject in their R&D departments (i.e., ABB®, Airbus, Boyd®, Thales®, Boeing®, Fujicura®, just to quote the multinational corporations) [9]-[11] but there is only one PHP manufacturer on the market (Thermavant®) [12],[13] at least to the authors' knowledge.

A multi-scale approach is needed to understand what are the most crucial issues that hinder PHP technological readiness in several fields of application: at the macroscale level they concern the device transient behaviour, especially the start-up phase[14],[15], local dry-outs, also known as thermal crises or instabilities [16], and the quantitative definition of PHP operational limits [13]. These aspects are linked to a number of physical phenomena occurring at the microscale level that are not fully understood, such as:

a) the liquid evaporation at the triple line (i.e., the liquid/vapour meniscus line in contact with the inner tube surface at the start-up) [17][18];
b) the characterization of the thin liquid film that surrounds the vapour plugs in different dynamic conditions (thickness, instability etc) [11];
c) the dynamic effects (viscous, inertial) on the rupture of the liquid/vapour menisci and the consequent stability of the slug flow regime [19],[21]; and,
d) the detection and characterization of the non-equilibrium thermodynamic states and their role in the heat transfer mechanism [22][23].

The first book on PHPs, recently published by Professor Ma [24], one of the most active scientists in the field, and one of the cofounders of Thermavant®, contains a complete and detailed survey of the available works in the literature up to 2014, and also provides dispersed information on the PHP modelling, simulation and design in the above-mentioned situations. In the last years the number of articles on PHPs presented to the international heat pipe conference (IHPC) and to international journals became comparable to the most known and assessed sintered heat pipe and loop heat pipe technologies. This led to the first scientific meeting devoted specifically to the PHP: the international symposium on oscillating/pulsating heat pipes (ISOPHP, KAIST, Daejeon, Korea, 2019 September 25-28, Chairs: Sung Jin Kim, Sameer Khandekar, Hongbin Ma, Marco Marengo).

The present article presents a special focus to the following topics: the flat-plate PHP (FPPHP) assessment; the advancements in PHP modelling and simulations; the flow stabilization techniques; the non-conventional fluids subdivided into fluid mixtures, self-rewetting fluids, nanofluids; the cryogenic applications, the space application and finally the newest frontier of flexible PHPs.

2.1 Flat plate pulsating heat pipes

Pulsating heat pipe technology has been firstly proposed by Akachi in the tubular assessment [1][2] also known as the closed-loop pulsating heat pipe (CLPHP) but the channels can be embodied in solid continuous substrates of different shapes, such as flat plates, from here the acronym of flat-plate pulsating heat pipe (FPPHP). Usually, the flow path is milled on a substrate which is then covered by a second layer and then sealed. Alternatively, the flow path and the substrate can be directly obtained by mean of additive manufacturing techniques with very different materials, from plastics [25] to titanium alloys [26].

The FPPHP assessment seems identical to the tubular PHP in terms of channel topology but involves more heat transfer phenomena, such as the transverse thermal conduction between adjacent channels and a non-circular channel cross-section (i.e., square or rectangular). These features deeply affect the thermofluidics: a tubular PHP and a flat-plate PHP with a similar design, similar boundary and operating conditions, provide rather different outcomes in terms of flow regimes and thermal performance as also shown by a recent experimental comparison by Takawale et al. [27]. It is worth mentioning here that even though in this case the tubular PHP exhibits better thermal performance than FPPHP, it would be misleading to generalize such statement. In general transverse heat conduction can promote the extension of a local dry-out to the adjacent channels thus increasing the risk of a complete stopover. Researchers proposed to increase transverse conduction by introducing grooves between the channels, but it does not seem to be sufficient and further study should be devoted to the subject [28],[29].

As thoroughly explained by Ayel et al. [30] in their very exhaustive review paper on FPPHPs published in this special issue, this assessment offers the opportunity to develop peculiar geometries especially tailored for the thermal management problem thanks to the emerging additive manufacturing techniques. Furthermore, it is more suitable than the tubular assessment in terms of miniaturization [31]. The review by Ayel et al. also thoroughly discusses the physical phenomena occurring in FPPHPs with a focus on capillary flows in square/rectangular channels which is actually the other main difference with respect to the tubular assessment. It is worth to mention here indeed that transparent FPPHP assessments can be obtained in a relatively easier way with respect to the tubular layout and usually allow full visual inspection, offering wider opportunities of phenomenological investigations [32]. In this case, due to the unavoidable presence of sealings or plastic materials that are permeable to non-condensable gases, the long-term operation is overlooked in favour of the physical investigation. As shown by Arai and Kawaji [25] in a paper included in the present issue, the flow visualization images allow to evaluate the flow pattern and two-phase flow parameters such as vapour-slug lengths, velocity, and passing frequency, and to clarify the relationship between the oscillating flow and thermal performance during the PHP operation.

Another paper published in this special issue by Odagiri et al. [33] presents a complete (i.e., involving both experiments and modelling) three-dimensional (3-D) heat transfer analysis of an aluminium FPPHP obtained by direct metal laser sintering. Results explain the combined effects of thermofluidics and thermal diffusion in the casing plate on the surface temperature distribution.

Given the above reported state-of-the-art, the future challenge is to develop reliable FPPHPs that may fit complex 3-D geometries, or even directly embedded in the structures of modern heat transfer systems, with large heat load capability and stable operation, ideally independent from orientation, ranging from miniaturized assessments (i.e., electronic portable devices) to large heat recovery systems (i.e., solar panels or collectors).

2.2 PHP modelling and simulations

Since the late 1990s the scientific community devoted its efforts to model the PHP complex thermohydraulic behaviour with different strategies. So far in the literature, six main approaches can be found: continuum wave propagation (CWP) [34]-[36], spring-mass-damper (SMD) modelling [37],[38], the artificial neural networks (ANNs) [39]-[41], empirical correlations [40][42], CFD models [43],[44], 1-D dynamic models [45]-[47].

Historically, the first two approaches (i.e., CWP, SMD) put the platform for a better understanding of the PHP hydrodynamics but they do not consider the solid containment. Empirical correlations could be useful for a broad determination of the PHP operational limits but they are also characterized by a high uncertainty. ANN models, if well trained, could be powerful design tools for the steady state conditions but does not allow to infer about the physics (i.e., conservation and constitutive equations) of the involved phenomena. CFD models are often oversimplified in order not to lose their sustainability in terms of computational time. By the time being the 1-D dynamic approach seems to be the best compromise between physical characterization and simulation time.

For most of the above-mentioned approaches, the experimental validation is carried out for the pseudo steady state on a single performance parameter (i.e., equivalent thermal resistance VS heat load) or on a single hydrodynamic aspect (i.e., pressure wave oscillation frequency).

Dr. Nikolayev contributed to this special issue with a thorough and rigorous review of the state-of-the-art of PHP physical phenomena and modelling tools [48], that summarizes the most important advances done so far in the literature to fill the gaps mentioned in Section 2. First, the local physical phenomena occurring at the single liquid slug/vapour plug level are described, then the modelling of the single branch PHP is claimed to be a necessary first step towards the PHP understanding and model validation. Finally, multiturn PHP modelling options are reported and discussed. The analysis shows that, among the different modelling approaches (i.e., semi-empirical correlations, machine learning algorithms, 2-D and 3-D direct numerical simulations), the PHP 1-D dynamic simulation is the most reliable in terms of prediction capability and the most sustainable in terms of computational time. Nevertheless, 2-D and 3-D tools can be used to investigate the local heat transfer phenomena occurring at the microscale level and, once validated, exploited by 1-D dynamic models. At present, the liquid film dynamic modelling [18] is one of the most critical aspect that is starting to be implemented by the most updated codes in the literature [45]-[47], nevertheless, the author suggests that each numerical model should be validated not only with the overall evaporator temperature behaviour observed experimentally but with more detailed local data. In this regard, the paper by Rouaze et al. [49] published in this special issue resumes the last updated version of the variable thickness wedge film model firstly proposed by Professor Thome's research group [50]. The code has been experimentally validated on several parameters in pseudo steady state conditions and proved its ability to predict the local temperature gradient as well as flow regimes transition in horizontal orientation.

With respect to FPPHP assessments, the work by Odagiri et al. [33], already mentioned in the previous section, presents an advanced numerical model that accounts for the combined effects of 3-D thermal diffusion in the substrate and the thermofluid behaviour in the channels, as well as the effect of the liquid film thickness and of the active cavity radius for boiling. Despite the model is only partially validated, it provides valuable information on the generation of moving hot spots and overheating with respect to the evaporator average temperature.

To become complete and reliable design tools, the above-mentioned models still need to be validated in transient conditions. This process has been recently initiated by Abela et al. [51] with a validation of the code developed by Dr. Nikolayev [45] against the transient experimental data of a CLPHP tested in microgravity conditions. The code is able to quantitatively catch the evolution of many local parameters during the start-up period.

On the basis of the above reported survey, the major challenge for PHP numerical codes is to be able to predict the transient operation and, most important, the operational limits (i.e., start-up and dry-out conditions). Furthermore, models need to eliminate "ad hoc" fitting parameters and, ideally, introduce only general tuning parameters with a physical meaning that allow the user to ideally cover the widest possible set of conditions.

2.3 Flow stabilization techniques

When the PHP is fully activated (i.e., the flow motion is present in all the channels) and the heat load is within the operational range, the temperature temporal trends usually stabilize around a constant value maintaining a randomly variable component. This stable condition, generally called “pseudo steady state”, may result both from a pure oscillating flow regime or from an impulsive unidirectional flow regime. The second is preferable since it is often more efficient than the pure oscillating flow and reduces the occurrence of local dry-out phenomena. For a standard PHP the stable operation is affected by the interplay of several parameters such as the filling ratio, the orientation, the number of heated zones, the initial vapour and liquid phase distribution, the power input level. Literature often reports that the stable working ranges, in terms of heat input power, are extremely variable depending on the variation of the above-mentioned parameters.

As such dependence represents a drawback from the applicative point of view, researchers are investigating on alternative methods and geometries to enhance the flow stabilization. For example, the operation of planar PHPs becomes acceptably independent of the inclination angle by increasing the number of heated zones and cooled zones [52]-[53][54]. It is worth mentioning that researchers often refer, inappropriately, to the number of turns instead of the number of heated and cooling section as demonstrated by the experiment recently carried out by Okazaki et al. [55] on a large single loop PHP with ten heated/cooled zones and presented in this special issue.

However, increasing the number of heated portions in a planar geometry result in larger device dimensions, not always applicable in case of geometrical constraints. For ground applications, 3-D layouts (i.e., nonplanar layouts) are indeed preferable to the planar ones when both orientation independence and compactness are needed as shown by Pagliarini et al. [56]. This method guarantees that the gravity driving, even a small one, is always present in the flow direction and this is beneficial for all the orientations.

In any case, it is well known from the literature that a small number of heated portions hinders the PHP stable operation in the horizontal [57] and top heated mode (i.e., evaporator above the condenser). So, if the number of heated sections cannot be increased, two main paths have been chosen by scientists to enhance and stabilize the flow motion:

a) introduce non-symmetrical boundary conditions such as, uneven channels dimension/shape [58]-[60] uneven heating patterns [61],[62], uneven channel surface wettability [63]-[66]; and,

b) equip the system with local fluidic passive subsystems, such as check valves and Tesla valves. It is worth mentioning that the inventor himself already mentioned check valves in his patents [1][2].

Among the non-symmetrical condition methods, the uneven channel dimension/shape seems the most promising both for the tubular [58] and flat plate [59] PHPs. This technique is relatively easier to implement on the FPPHP, as the dual-dimension channel is engraved on the plate. Markal et al. [60] proposed one of the most effective layouts consisting in an asymmetric channel enlargement in the evaporator section which can have a performance that is nearly orientation independent at the optimum filling ratio. A fair physical analysis of the thermofluidic phenomena supported by the visualization analysis is also provided.

The uneven local heating condition can be quite effective too as recently shown by Lim and Kim [62], although in real applications it is not always possible to tailor the evaporator lengths to optimize the performance. The internal tube surface treatments are more complex to obtain, especially for the tubular assessment, and some doubts remain on their durability.

Check valves introduce a certain level of complexity too but they are also more reliable and efficient as described in the paper published in the present issue by Ando et. al [67]. The transparent layout allows to unequivocally infer that, among the different CV layouts, the one where check valves are located closer to the condenser section is preferable both in terms of start-up reliability and of steady-state performance.

Tesla-type valves does not contain any secondary element (i.e., fluid stoppers, springs and so forth) and promote the fluid circulation in the system but it is not clear whether they are able to stabilize the flow motion when the system is not assisted by gravity [68],[69].

It is worth mentioning that recently some studies have combined 3-D geometries with the above-mentioned fluid subsystems [70],[71]. In these cases, it is difficult to separate and characterize the two effects, thus the outcome is more valuable in terms of overall performance evaluation rather than in terms of phenomenological understanding.

2.4 Complex fluids

A very broad literature is available on PHPs filled with pure fluids. The effects of thermodynamic and thermophysical properties (i.e., density, viscosity, surface tension, thermal conductivity, heat capacity, latent heat and so forth) on the thermal behaviour of PHPs has received significant attention [3],[4],[24]. Figures of merit based on the above-mentioned properties and experimental findings have been also developed for fluid selection [48],[72].

Recently, research has focussed on the use of mixtures [7] or the addition of particles (i.e., nanofluids) [73] for enhancing PHP performance or widening working/operating ranges in terms of heat input capabilities (i.e., lower start-up thermal powers, higher critical heat fluxes).

2.4.1 Fluid mixtures

Most of the fluid mixtures investigated so far are zeotropic mixtures (i.e., components have different boiling points). Various pure components with complementary fluid properties are chosen and tested at different ratios looking for the existence of synergistic effects. For instance, the components with relatively low latent heat, low surface tension and high $(\mathrm{d}p/\mathrm{d}T)_{\mathrm{sat}}$ (i.e., alcohols, acetone) could help triggering the PHP start up at lower heat input levels, while the other component (i.e., water) could have a positive effect when the heat flux increases towards the critical level: the higher surface tension helps maintaining the slug flow regime and the higher latent heat copes for the higher heat input capability. Actually, the above-mentioned effects have been experienced both on a tubular PHP [74] and a flat-plate PHP [75] when tested in vertical orientation. On the other hand, the FPPHP tested in horizontal orientation stably worked when filled with pure fluid, while it did not operate at all when charged with mixtures [75].

In their work, Xu et al. [76] showed that similar results can be obtained with immiscible binary mixtures of water and hydroflorethers. These authors presented results for several mixing ratios, heat loads and inclinations but did not test their FPPHP in horizontal operation. This test would have been interesting to understand whether also these mixtures only offer advantages when the PHP is gravity assisted, or not.

So far, there are no models available to predict the PHP behaviour operated with mixtures probably due to the inherent complexity and non-linearity of multicomponent two-phase conservation equations and the complex interaction with other parameters such as the filling ratio and orientation. The development of semiempirical correlation could be helpful at least to provide design guidelines or to be used as subroutines of more complex models.

2.4.2 Self-rewetting fluids

A particular class of mixtures referred to as self-rewetting fluids (SFR), which are based on a small mass fraction of long-chain alcohols (i.e., hexanol, heptanol, butanol) diluted in water, has been also proposed [77],[78]. The addiction of alcohol (0.1 to 7% in mass) results in a non-monotonic trend of the surface tension with the fluid temperature: there exists a temperature range where the surface tension is an increasing function of the fluid temperature. In the above-mentioned temperature range, the inverse Marangoni effect is supposed to move the vapour bubbles from the hot zone to the cold zone and to recall the liquid slugs from the condenser and rewet the evaporator. By the time being preliminary results show modest performance enhancements in the gravity assisted mode [79], while promising outcomes have been found on the thermal response in microgravity conditions [80].

Systematic experimental studies monitoring the local fluid temperature and concentration still need to be performed to complete our knowledge of the effect of SFR on PHP performance.

2.4.3 Nanofluids

Nanofluids are colloidal dispersions obtained by adding solid particles with the sizes of nanometre (typically < 100 nm) to base fluids. The addition of small particles to the working fluid aims at increasing the effective thermal conductivity of the solution and consequently enhance the overall heat transfer mechanism. On the other hand, the increase of dynamic viscosity may hinder such enhancement especially at high particle contents.

Recently, Xu et al. [76] performed a very accurate literature review on the use of nanofluids in PHPs reporting that many hypotheses have been drawn to understand the thermal conductivity enhancement mechanism (i.e., Brownian motion, interfacial layering, clustering, ballistic and diffusive phonon transport, thermophoretic effect, near-field radiation). These theories brought to contradictory results after several attempts of experimental validation, thus concluding that the exact heat transfer mechanisms at the microscopic level are still unclear.

It is indeed still controversial whether the PHP performance enhancement reported by many experimental works are instead brought by particle deposition on the internal tube surface which may increase the wettability and may create more nucleation sites. However this could be checked by monitoring the PHP performance in time with the same experimental conditions: if there is an improvement, this may be due to the clustering of nano particles. Since surface wettability tuning is an effective approach to promote and stabilize the flow motion (see Section 2.3), the use of nanofluids in this direction could be a more affordable method for CLPHPs rather than complex surface treatments.

The other debated issue concerning nanofluids is their long-term stability. Among the different methods reported in the literature (i.e., surfactant addition, surface functionalization, pH control, ultrasonication and homogenization) functionalized nanoparticles seem a particularly promising solution for maintaining a low viscosity. For example, the surface of multiwalled carbon nanotubes (CNTs) can be treated to prepare uniform and stable nanofluids [81].

The work by Zhou et al. [82] published in this special issue, shows the experimental results obtained by a CLPHP filled with a zeotropic aqueous ethanol solutions of CNTs. A comparison with baseline cases (pure fluid with CNTs or binary mixture without CNTs) would have been helpful to separate the effect of the binary mixture from the effect of the CNTs. Thus, the outcome is more valuable in terms of overall performance evaluation rather than in terms of phenomenological understanding.

On the basis of the above state-of-the-art, a future challenge relating to the employment of non-conventional fluids concerns the identification of sustainable, economic, predictable and reliable solutions capable of inducing enhancements in PHP operation (i.e., independence on orientation, larger heat load capability, better heat transfer performance). Due to the inherent complexity of having different chemical species in the working fluid, particular effort should be devoted to analytical and numerical studies, also for the development of predictive tools.

2.5 Cryogenic applications

The low temperature heat transfer field, also known as cryogenics (i.e., fluid temperatures below 120 K), is gaining more and more interest in the scientific community due to the fast advancements of applications such as the cooling of superconducting magnets or heat dissipation in space environment (i.e., thermal radiators). On the other hand, distributing the heat fluxes on wide and typically complex surfaces in these conditions, is still a technological challenge. Thanks to its relatively simple structure and versatile embodiment, PHPs seem perfect candidates [8]. Due to the intrinsic complexity of the experimental assessments in low temperatures environments (i.e., material compatibility, thermal insulation etc), the research in the field applied to PHPs is relatively recent. The experimental work by Jiao et al. [83] dates back to 2009 on a horizontal CLPHP filled with nitrogen, the device is actually able to transfer a considerable amount of heating power (up to 380 W) with respect to other works performed later on. Natsume et al. [84] presented a study on a vertical gravity assisted CLPHP filled with Nitrogen, Neon and Hydrogen, showing that it could be possible to reach equivalent thermal conductivity values up to 18 kW/mK, thus improving the performance of superconducting magnets cooling systems.

The research team lead by Dr Baudouy proposed a breakthrough experiment on a metre-scale PHP, filled with nitrogen and tested stably for seven hours in horizontal position [85]. The characterization has been completed with different working fluids (neon, argon) and different filling ratios (from 30% to 70%) and published in the present special issue by Barba et al. [86]. Results reveal that the best performance is obtained at low filling ratios (i.e., below 50%) for all the fluids which is in line with the results obtained with PHPs tested at higher temperatures ranges: when the device is not assisted by gravity, it works better at lower filling ratios [87]. Further confirmation is provided by results obtained with a gravity assisted cryogenic PHPs filled with helium [88] and nitrogen [89], where the device shows the best performance and stability at around 70% filling ratio.

The research team lead by Prof Pfotenhauer focussed on the investigation of helium [88] and hydrogen [90] CLPHPs in vertical bottom heated mode, reporting remarkable equivalent thermal conductivities, especially when the device is filled with helium [88]. In this special issue Pfotenhauer et al. [91] raised the issue that in a practical application of PHPs in a superconducting magnet, the path between the cryocooler and the magnet shall likely consist of both horizontal and vertical sections ("L" profile) and proposed an analysis on the effect of the vertical to horizontal aspect ratio on the thermal performance of CLPHP charged with helium and hydrogen. As expected, the thermal performance increases with the aspect ratio.

On the basis of the above survey, the cryogenic PHP has already reached a fair TRL, but probably the future will witness further investigation on the heat transfer length limits, especially of helium and hydrogen PHPs. The main challenge for this application is indeed to develop extra long/wide PHPs competing with the loop heat pipe technology which is actually capable of transporting heat at tens of metres in anti-gravity conditions [92].

2.6 Space applications

The absence of capillary structures (grooves, porous wicks, screen meshes etc) together with the ability to work without the gravity field assistance suits well with the design requirements of space thermal control systems. Moreover, the possibility to adapt to 3-D shapes and cover wide surfaces may cover the gaps left by the grooved heat pipe and the loop heat pipe technologies that have already been implemented successfully in many actual space applications since the late 1960 [93].

For this reason, starting from the first years of the new millennium, many research groups focussed on the PHP thermohydraulic characterization in microgravity conditions, which is quite fascinating but very difficult to reproduce on earth. Nowadays, many methods are available to obtain a weightless environment. Starting from the shortest to the longer microgravity period duration: drop tower, parabolic flights, sounding rockets, suborbital flights, space stations and satellites. Despite almost all the above-mentioned experimental platforms are provided by the space agencies, the tests cell is often more complex and expensive with respect to the ones developed for ground characterizations.

Zero gravity experiments have been performed by many teams all over the world [94]-[97]. In particular, the Canadian team led by Professor Kawaji, supported by the Japanese Space Agency (JAXA), has been the first investigating the thermal response of FPPHPs by means of parabolic flights [98],[99] at least to the authors' knowledge. The experimental results suggest that the PHP can operate under reduced gravity. The Italian team lead by Professor Marengo supported by the European Space Agency (ESA) confirmed this outcome on a tubular PHP showing that for a planar geometry the operation of a capillary PHP to micro-gravity is similar to the horizontal operation on ground [100]. The Japanese team lead by Professor Nagai and supported by JAXA, has been the first to test an FPPHP on orbit with long duration experiment starting from 2012 showing that the thermal performance is comparable to the one obtained with ground tests without any degradation for almost four years [101]. Recently, the American Airforce Research Laboratory tested a FFPHP without check valves on orbit for 780 days, confirming that the PHPs experienced no significant hysteresis effects and performed successfully in six-week long continuous operation [102][103].

The absence of buoyancy forces experienced by the fluid in weightless conditions offered the hint to develop a new concept of a large diameter PHP which actually behaves as a hybrid between a two-phase loop thermosyphon in the presence of a gravity field, and a PHP in microgravity conditions, and allow to reduce viscous losses and to increase the heat load capability. Experimental campaigns supported by ESA show that this hybrid system actually works as a loop thermosyphon on ground and switch to the PHP mode as soon as the microgravity occurs [104],[105]. In any case, since the flow regime is also affected by inertial and viscous effects, these aspects needs to be investigated in more detail and with a long time microgravity duration. To this aim, an international team composed by most of the above-mentioned research groups is working with the ESA to test and characterize a large diameter PHP on the International Space Station (ISS) in 2024. It is worth mentioning that the long term and controlled microgravity condition on the ISS, offers a great opportunity for the further investigation/comprehension of fundamental physical phenomena and for the development and validation of numerical codes.

Since the capillary PHP equipped with check valves seems a robust efficient and reliable solution for the space applications, the literature has recently focussed on the design of actual spacecraft thermal control systems such as thermal straps [106] and deployable radiators [107].

Given the above state-of-the-art, the most interesting future challenge involves the further development of high-power hybrid loop thermosyphon/PHPs and fully passive deployable PHPs.

2.7 Flexible pulsating heat pipes

The absence of porous wicks or any other capillary structure allows the PHP assessment to be shaped or bended with a degree of freedom considerably higher than the other members of the heat pipe family. This feature opens to a wide variety of pioneering applications such as foldable heat dissipators in electronic devices [108], flexible or deployable heat transfer elements for space applications [109][110]. Two main paths can be found in the literature to develop flexible PHPs: one focusses on the use of thin plastic substrates, normally FPPHPs, covered with a metallic coating; the other relies on the use of metallic tubular structures. Regarding the plastic PHPs, it is worth to mention that the use of flexible copper clad laminates avoids the permeation of non-condensable gases and leakage, thus guaranteeing a long-term reliability up to 2000 days [111].

When the PHP needs to be operated in extreme environments (i.e., in space, at high or low temperatures), the metallic tubular PHP assessment is preferable. The paper comprised in the present issue by Iwata et al. [109] shows the vibration tests performed on a micro-oscillating heat pipe equipped with check valves during its operation, demonstrating that the dynamic stiffness is less than that of the graphite thermal strap used for space application. In general, for the metallic substrate the flexibility is limited to the elastic deformation so, to obtain if a high degree of foldability, mechanical stratagems, such as spring shapes, need to be implemented as suggested by Bacciotti et al. [110]. Interestingly, the authors propose a spring shaped PHP that can be unfolded by means of an external thermomechanical actuator made of a relatively new material known as shape memory alloy (SMA) that exhibit extraordinary elongations thanks to the solid/solid phase transformation occurring at low temperatures.

On the basis of the above survey, one of the main challenges for future research is to develop adaptable flexible and durable PHP structures on different scales (i.e., from miniature to metre lengths). In this context, the relation with the material sciences will be closer than ever.

3 Outlook and future challenges

The pulsating heat pipe is a youngest member of the heat pipe family, and has been attracting the attention of the scientific community since the early 1990s due to the complex non-equilibrium thermodynamics, posing challenging questions that still need to be fully understood by scientists. Nevertheless, after about thirty years of world-wide experimental and numerical studies, the main working principles and the effect of several governing parameters, such as the geometry, the heat load, the orientation, the working fluid, the filling ratio, on the thermal performance in pseudo-steady-state conditions, have been figured out.

The effort made by the scientific community to characterize the PHP governing phenomena brought the PHP to a high level of technological readiness in the electronic cooling field, confirming that the PHP is not only a promising candidate for the thermal management of heat transfer systems but a concrete emerging reality in the industrial world.

Actual predictive tools for the dynamic simulation of both CLPHP and FPPHP reached a certain level of completeness and physical detail and some models have been partially validated against experimental data on multiple parameters.

Fundamental research is currently focussing on the better understanding of the physical phenomena at a microscopic level so as to master the PHP modelling of the most critical working phases of the PHP (i.e., start-up, dry-out). In the near future, the findings of base research need to be correctly modelled and codes need to be updated. The multiparametric dynamic quantitative validation of such codes by means of systematic experimental investigation is one of the most crucial challenge that will provide engineers with more robust and reliable design tools.

Meanwhile, many experiments aim at verifying the possible strategies to make the PHP operation more stable and predictable or to improve the PHP performance and working ranges (i.e., flow stabilization techniques, non-conventional fluids). Proof-of-concepts have been shown in a variety of applications, from the cooling of superconducting magnets (i.e., cryogenic field), to the development of thermal radiators for satellites (i.e., space field), from the thermal energy recovery in solar panels, to the cooling of portable electronic device.

At present, investment is focussed on electronics cooling and towards the development of miniaturized devices with complex shapes and possibly foldable or deployable structures. Due to a growing attention paid to environmental issues and sustainability, future investments will likely focus on thermal energy recovery and thermal energy storage, where PHP technology may play an important role. In this context, a key challenge for future research is to develop adaptable flexible and durable PHP structures over a range of scales (i.e., from miniature to the metre lengths), for which the links with the material sciences will be fundamental.

Advisory board

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Professor Sauro Filippeschi, Associate Professor, University of Pisa, Italy. Email: sauro.filippeschi@unipi.it. Role: expert on experimental analysis of physical phenomena in pulsating heat pipes in extreme environments (space conditions, low/high accelerations, low temperatures).

Professor Sameer Khandekar, Full Professor and Head of the Mechanical Engineering Department, Indian Institute of Technology Kanpur (IITK), India. Email: samkhan@iitk.ac.in. Role: main expert on experimental analysis of physical phenomena, working principles and performance.

Professor Sung Jin Kim, Full Professor and Director of the Center for Flexible and Thin Superconductors, Korea Advanced Institute of Science and Technology (KAIST), Republic of Korea. Email: sungjinkim@kaist.ac.kr. Role: main expert on testing and development of novel PHP applications (miniature, flexible devices).

Dr. Vadim Nikolayev, Director of Research at the University Paris-Saclay and the Alternative Energies and Atomic Energy Commission of France (CEA), 91191 Gif sur Yvette Cedex, France. Email: vadim.nikolayev@cea.fr. Role: main expert on the theoretical and numerical analysis of physical phenomena, multiscale modelling and simulations.

Dr. Luca Pietrasanta, Process Development and Simulation Engineer, Highview Power, UK. Email: luca.pietrasanta@highviewpower.com. Role: main Guest Editor's assistant, management and organization.

Mr. Brenton Taft, Program Manager, Spacecraft Component Technology at Air Force Research Laboratory (AFRL), 3550 Aberdeen Ave SE, Kirtland AFB, NM 87117, USA. Email: brenton.taft@spaceforce.mil. Role: expert on the design, development and technological advancement of PHPs for ground and space applications.

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