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A review on heat transfer characteristics of cryogenic heat pipes

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Abstract

Heat pipes are broadly applied for thermal management of devices with high heat flux. Due to the dependency of their efficient operating range on the boiling point of the working fluids, employing special types of fluids is necessary to have applicable heat pipes at very low temperatures. Hydrogen, neon and nitrogen are among the most attractive working fluids for heat pipes in order to reach efficient heat transfer in cryogenic conditions. According to the reviewed studies on cryogenic heat pipes, similar to the medium or high-temperature heat pipes, their thermal performance depends on different factors such as filling ratio, input power, structure and type of heat pipe and working fluid. Employing appropriate fluids, applicable for the required operating temperature, provides heat pipes with high effective thermal conductivity in cryogenic conditions. The effective thermal conductivity of the cryogenic heat pipes is several orders of magnitudes higher than that of the conductive metals in the similar temperature which makes them as desirable thermal management devices for low-temperature applications such as cooling superconductors. In this paper, a comprehensive review is carried out on the researches focused on the cryogenic heat pipes and the factors influencing their heat transfer features to provide a useful and applicable reference for the future studies with relevant topics. This review study is categorized based on the type of heat pipes: conventional heat pipes, pulsating heat pipes and thermosyphons (gravity-assisted heat pipes). The reviewed studies have demonstrated that the operating fluid and heat load have substantial role in the performance of heat pipes. Finally, some recommendations for future studies are provided to reach further enhancement in the performance of cryogenic heat pipes.

Keywords Heat pipe · Cryogenics · Working fluid · Thermal resistance · Two-phase heat transfer

Introduction

Heat transfer enhancement is the main subject of several studies in the field of thermal engineering [1, 2]. Heat pipes (HPs) are a type of heat transfer appliances with high thermal conductivity owing to their two-phase heat transfer process [3–5]. These devices are very attractive options for the cases that require high heat transfer rate at low-temperature difference and limited space. HPs are employed in various systems for thermal management such as electronic equipment, fuel cells and PV panels [6–9]. As well as high- and medium-temperature applications, HPs can be employed at very low temperature, cryogenic conditions, in the case of filling them with appropriate fluids [10, 11]. Generally, the main parts of HPs are heat sink and heat source which are known as evaporator and condenser sections, respectively [12, 13]. Besides the mentioned main parts, adiabatic section can be added where there is a gap between the indicated sections of the HPs. Operating heat transfer principles of all

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kinds of HPs is based on the evaporation and condensation of the fluid used in their structure, while there are some differences in the regime of fluid and the driving force of working fluid circulation inside HPs which are explained in the next section. Depending on the required application, operating conditions and the restrictions regarding the space, the dimensions and type of HP are selected.

Conventionally, HPs are utilized for medium or high-temperature applications [14–16]. For instance, Alizadeh et al. [8] used pulsating HP for cooling PV panels and observed its efficient performance in reducing the cell temperature. In another study, Ramezanizadeh et al. [17] numerically analyzed the utilization of thermosyphon in air–water heat exchanger and concluded that using thermosyphon can improve the heat transfer rate up to 135% in comparison with employing the copper tube with the same dimensions. This enhancement in capacity of heat transfer was owing to the two-phase heat transfer. Shirzadi et al. [18], used miniature HPs for thermal management of fuel cell and concluded that by employing the HPs, the required power for thermal management of the fuel cell can be reduced, which resulted in higher overall efficiency of the system composed of thermal management unit and fuel cell. In another research, Arab et al. [19] used an extra-long pulsating HP in a solar water heating system and observed its efficient heat transfer in this medium.

As well as high- and medium-temperature conditions, efficient heat transfer devices are needed for low- temperature cases. There are various chemical processes which took place at very low temperatures [20–22], and some of them applied in this condition such as magnetized pure electron plasma require efficient cooling and thermal management [23, 24]. The majority of the conventional thermal management approaches are not employable for this condition which necessitates development of new methods. In this regard, special types of thermal mediums are required with ability of potent heat transfer in low-temperature operating conditions. Employing cryogenic HPs is an efficient option for reliable thermal management and heat removal at very low temperatures.

Heat pipe is one of the thermal devices with two-phase working principles with applicability in cryogenic conditions. Prior to filling HPs, its inner volume is evacuated in order to reduce the inner pressure and facilitate the evaporation of the fluid inside it to have more appropriate two-phase heat transfer. Moreover, non-condensable gases will be evacuated, leading to easier circulation of fluid inside the HPs. In all types of HP, received heat in the heat source causes working fluid evaporation, which can be occurred even in low temperatures due to its very low inner pressure [25, 26]. The evaporated fluid converts into the liquid by dissipating heat in the heat sink (condenser). This fluid returns to the heat source and this cycle continues, that results in continuous efficient two-phase heat transfer. The classification of the HPs is generally based on the mechanism of liquid return from heat sink to heat source.

In conventional or wick HPs, the capillary force, provided mainly by wick structure, is the main driving force to return liquid from the condenser to the evaporator [27, 28]. In these HPs, applied structure for capillary force influences the fluid motion; consequently, thermal performance of HP will be affected. The sensitivity of these HPs to orientation is the lowest among all types of HPs, which makes them applicable for no or low-gravity conditions. As well as type of fluid, filling ratio, heat load and dimensions, which are key factors for all types of HPs, employed capillary structure can remarkably influence the thermal performance of conventional HPs. Wick structure, which is applied to provide capillary force in conventional HPs, is a porous structure which can be made of some materials including copper, nickel and aluminum with various sizes of pore. These wicks are installed in the inner surface of HPs by employing metal foams or felts [29]. In addition, fibrous materials such as ceramics can be used as wick. The pore size of these materials is small compared to the previous ones. Little stiffness of these structures is their main disadvantages which makes crucial, in some cases, to use metal mesh as a support. In addition to the mentioned ones, carbon fibers have attracted attentions in recent years since they have high capillary pressure due to the existence of longitude grooves on the surface. By using carbon fibers as wick structure, it is possible to construct HPs with improved heat capacity. In selection of wick structure, different factors must be considered, while operating fluid properties is one of the most important ones. The most conventional types of wick used in HPs are sintered powder metals, wire screen mesh and grooved tube [29].

Thermosyphons, also known as gravity-assisted heat pipes, are applicable in different systems including solar systems and heat exchangers. Thermosyphon is defined as circulating fluid system that is driven by thermal buoyancy force [30]. In thermosyphons, gravity plays the key role and for its efficient working, it is crucial to have evaporator at lower position compared with condenser. Since the density of fluid in liquid state is higher than vapor, the condensed fluid in heat sink returns to the heat sources by gravity; while the vapor phase of the fluid moves upward owing to its lower density compared with the liquid. In comparison with the other types of HPs, the simplest structure of thermosyphons is their main advantages; however, their great sensitivity to the gravity restricts their utilization in horizontal and near horizontal orientations.

Pulsating HPs (PHP) are made of tube with very small diameters, which consists of several turns, and the evaporator and condenser sections are located on the turns. Due to the small diameter of tube and capillary action, liquid slugs and vapor plugs are formed. In PHPs, pressure instabilities account for liquid motion [31]. These HPs have several turns and applying heat load to them results in pressure difference in the turns, which provides the driving force for fluid circulation in the PHP. There are two main types of PHPs known as closed loop PHP and open loop PHP. In the first type, two ends of bended tube are connected to each other while in the later one, the ends are separated [32]. The main advantages of PHPs are their miniature size, makes them appropriate for utilization in limited spaces. The sensitivity of the PHPs to orientation is higher compared with wick heat pipes, while it is lower in comparison with thermosyphons. The schematic of various kinds of HPs is shown in Fig. 1. Depending on the type of HPs, each one is appropriate for special applications. Conventional HPs are favorable in the cases of no- or micro-gravity condition owing to its lower sensitivity to the direction of gravity force. PHPs are more attractive for small-scale and compact devices,

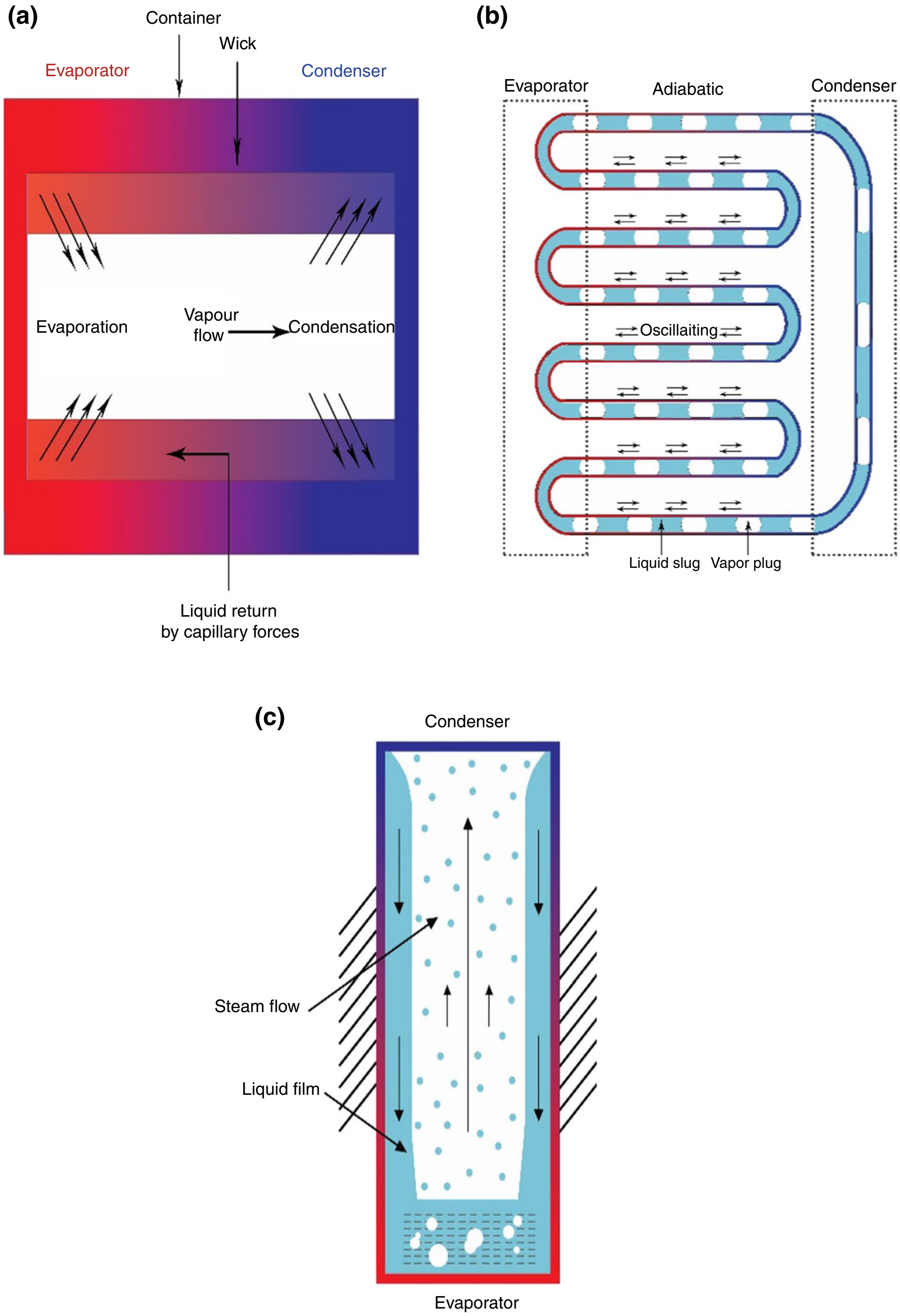

Fig. 1 Schematic of **a** wick HP **b** PHP and **c** thermosyphon [17, 36, 37]

and thermosyphons are favorable for the cases with high heat flux. The performance of HPs is under influence of several factors like the inclination angle, operating fluid, type of HPs, the utilized material, filling ratio and applied heat load [33–35]. In addition to the above-mentioned HPs, there are some other types such as rotating heat pipes, as shown in Fig. 2; however, since these HPs have not been used in cryogenic conditions, they are not discussed here. Furthermore, loop HPs have been considered as another main type of HPs, while in this study, these types are discussed in conventional type section. In Table 1, the advantages and disadvantages of the mentioned HPs are represented.

Despite there are several review articles on medium or high-temperature HPs, cryogenic ones have been considered in lower extent. Moreover, the majority of the published works are not up to date, while the present work covers the relevant studies in recent years. In addition, the current works consider all types of cryogenic HPs including gravity-assisted, pulsating and wick kinds. In addition, some suggestions are provided based on the outcomes of the reviewed works and knowledge of the authors.

Wick HPs

Conventional HPs utilize tube, or plate with channel, to contain the working fluid. In these HPs, wick structure must be used to provide capillary forces to return the condensed fluid to the heat source of the HPs. Conventional HPs can be used alone or in loop HPs (LHPs) [38]. Different fluids with low boiling temperatures, such as nitrogen, helium and hydrogen, must be applied the HPs to achieve efficient heat transfer in cryogenic conditions [39, 40]. For instance, Kown et al. [41] performed a study on a conventional HP, with stainless steel mesh wick, and employed nitrogen as the operating fluid. According to their results, by using the HP it was possible to achieve effective thermal conductivity equal to 24 kW/m K, which is much higher than the conductive metals such as copper. It was concluded that the high effective thermal conductivity of cryogenic HPs makes them efficient medium for thermal management of high-temperature superconductors. Similar to the medium-temperature HPs, exceptional performance of cryogenic HP was due to the two-phase thermal phenomenon inside it which causes several orders of magnitude increase in effective thermal conductivity compared with the tube without any fluid.

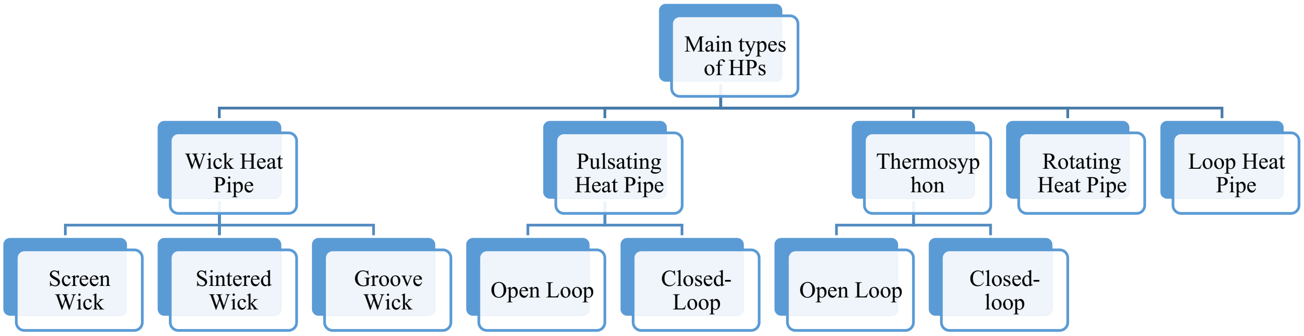

Fig. 2 Main types of heat pipes

Table 1 Advantages and disadvantages of various HPs

Type of HPs	Advantages	Disadvantages
Wick HPs	Low sensitivity to orientation	Complex structure due to wick structure
	High heat transfer capacity	
	Possibility of being used in loop HPs	
Pulsating HPs	Moderately low sensitivity to orientation	Relatively low heat transfer capacity compared with other types
	Compactness	
	Relatively simple structure compared with wick HPs	
Thermosyphons	High heat transfer capacity	High sensitivity to orientation
	Simple structure	

The performance of HPs can be influenced by their structure and other factors. Generally, it is preferred to use structures facilitate the fluid circulation inside the tube, which would result in lower thermal resistance and enhanced heat transfer capacity. Sangpab et al. [42] investigated the effect of flattening and bending, as shown in Fig. 3, on the thermal behavior of a wick HP. The radius of bending in their study was 21 mm, and four angles, include 0, 30°, 60° and 90°, were tested. Their results indicated that both bending and flatting of the HP led to increment in the thermal resistance. Increase in thermal resistance in the case of bending was attributed to the deformation of the wick and obstruction of liquid flow, while deterioration in heat transfer of the HP in the case of flattening was attributed to wick structure collapse and consequently liquid path broken. According to these results, it can be concluded that by changing the inner structure of the HPs in a way that facilitate liquid motion, more desirable performance can be reached.

Wick HPs can be used in LHPs as shown in Fig. 4. In LHPs, capillary forced is developed in the wick of evaporator in order to circulate the operating fluid in a loop [43, 45]. In comparison with conventional HPs, LHPs have modified structure. In LHPs, the wick structure is locally installed, the line of liquid and vapor transport are separated and inverted evaporator is used [43]. LHPs are able to have high heat transfer rate for long distance, even in antigravity conditions [46]. Depending on the applications and restrictions, different configurations for LHPs have been proposed and used. Various architectures have been proposed to cool systems based on the working principles of LHPs [47, 48]. Bai et al. [44] designed a nitrogen-charged LHP with auxiliary loop for realizing the supercritical start-up. Several thermocouples were used in their setup in order to measure the temperatures of various locations of the LHP as shown in Fig. 5. The tubes were made of steel, while the wick of the HPs was made of nickel powder. Their results showed that in the case of applying heat load lower than 2 W to the secondary evaporator, the primary evaporator was not able to be cooled down to the lower temperature of nitrogen critical point,

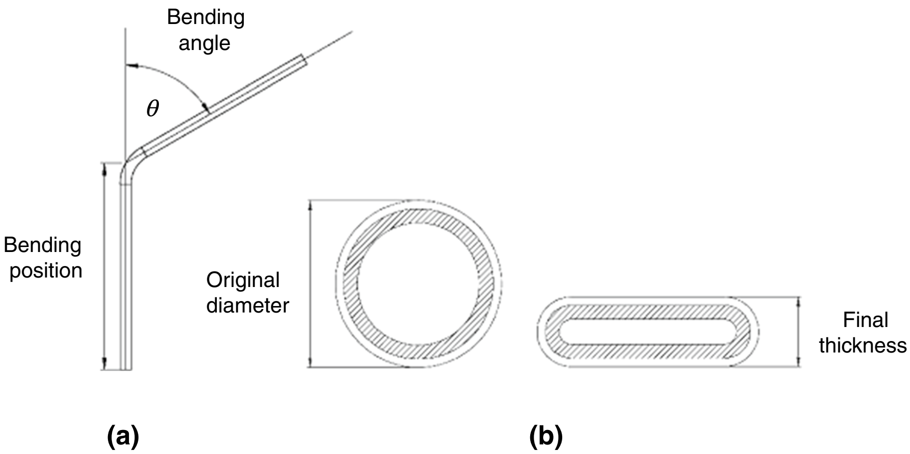

Fig. 3 Structure of wick HP with **a** bending and **b** flattening investigated by Sangpab et al. [42]

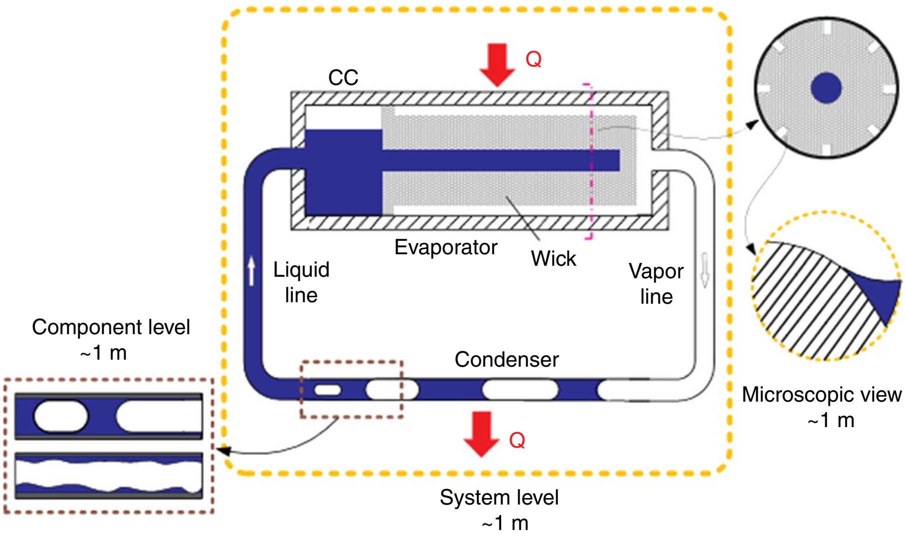

Fig. 4 Structure of LHP investigated by Wang et al. [43]

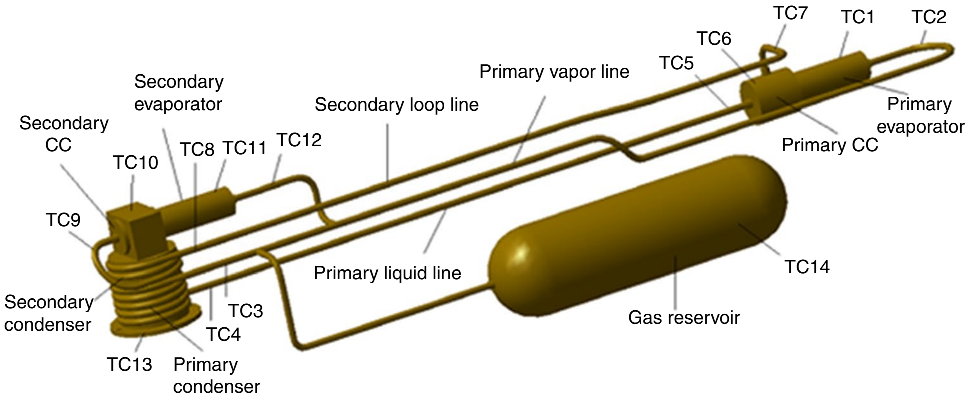

Fig. 5 Schematic of the LHP with installed thermocouples (TCs refer to the points that thermocouples are used for temperature measurement) investigated by Bai et al. [44]

which was attributed to the impact of heat input from the surrounding atmosphere and inability of the LHP in realizing the supercritical start-up in this condition. On the other hand, in the case of heat load equal to 3 W, the LHP was able to realize the supercritical start-up. Further increase in the heat load resulted in acceleration in the temperature reduction of the primary evaporator. Therefore, it can be expressed that the start-up phenomenon of cryogenic LHPs is dependent on the heat load which is similar to LHPs used in medium-temperature working conditions.

Orientation and component layout are among the other factors influencing the performance of cryogenic LHPs. Mo et al. [49] performed an experimental research on a cryogenic LHP filled with nitrogen in three orientations including horizontal, vertical and vertical-reverse in order to analyze the impact of inclination angle on its heat transfer capacity. It was observed that in horizontal and vertical-reverse orientations, the heat transfer capacity of the cryogenic LHP was up to 12 W, while in the vertical mode, its value increased to approximately 20 W. Increase in the heat transfer capacity of the cryogenic LHP in vertical mode was attributed to the gravity assistance in liquid motion. Indeed, in vertical orientation the gravity acts as a secondary driving force, in addition to the capillary force provided by the wick, which remarkably increases the heat transfer capacity. In another study [50], a miniature LHP with the same configuration shown in Fig. 5 was tested in different modes. It was observed that connecting the secondary loop line to the middle or top of the primary compensation chamber resulted in higher heat transfer capacity compared with the case it was connected to the bottom of compensation chamber. These results demonstrate that configuration of the cryogenic LHPs must be considered in design procedure in order to have efficient cooling system. In addition to the mentioned ones, some other factors affect the performance of cryogenic LHP. For instance, Lee et al. [51] applied a pressure reduction reservoir in a nitrogen-filled LHP and investigated effect of fluid charging pressure on the performance of the LHP. They found that increase in the pressure causes higher thermal resistance, attributed to the increase in saturation temperature.

Pulsating HPs

Similar to wick HPs, employing fluid with very low boiling temperature makes PHPs proper for cryogenic applications [52]. Hydrogen is one of the most conventional fluids utilized to fill cryogenic PHPs [53]. Sun et al. [54] experimentally investigated that the heat transfer ability of a cryogenic PHP consists of two turns under various working conditions. Their analysis on the filling ratio revealed that its optimum value was dependent on the applied heat. At high heat input, higher than 2.8 W, the PHP showed better thermal performance in filling ratios between 30 and 55%, while reduction in the applied heat to lower than 1 W led to more appropriate performance of the PHP in 10% filling ratio. Higher filling ratios in increased heat load are required since the rate of evaporation in heat source increases; consequently, in low filling ratios there is no adequate liquid in the evaporator to continue two-phase heat transfer. Similar to conventional PHPs, it was observed that increase in the heat load resulted in enhancement in thermal performance, which means lower thermal resistance. By increasing the thermal load in the evaporator section, the rate of evaporation will be increased, which means improvement in overall heat transfer coefficient, while there is a limitation in the heat load increase due to the possibility of dry-out occurrence. The measured effective thermal conductivity of the tested cryogenic PHP was in the range of 30,000–70,000 W/mK, which is remarkably higher than that of the conductive metals such as copper, indicating the efficient performance of the hydrogen-filled PHP for cooling in cryogenic conditions. Moreover, it was observed that by increasing the temperature of heat sink, improvement in the thermal performance is achievable.

In addition to hydrogen, other fluids with appropriate boiling temperatures for cryogenic conditions such as nitrogen and neon are applicable in cryogenic PHPs [55]. In the experimental study performed by Jiao et al. [56], nitrogen was employed as the operating fluid in a cryogenic PHP. The experimental setup was evaluated in horizontal orientation and 48% filling ratio. According to the represented results, as it was expected, increase in the applied heat from 22.5 to 321.8 W led to reduction in the thermal resistance from 0.256 to 0.112 K W^{-1}. Moreover, comparing the amplitude of temperature difference between the evaporator and condenser revealed that it would be decreased by increasing the heat load due to the increase in the fluid velocity inside the tubes. Indeed, by increasing the heat load, more powerful driving force will be provided for the working fluid which will increase its speed inside the tube. In another study [57], nitrogen was used to fill a PHP with one meter length in horizontal direction. In this study, the temperature of heat sink was kept constant at 75 K. Their experimental results showed that the increase in the heat load led to an increase in the amount of vapor in the evaporator section and liquid in the condenser part.

Similar to the conventional PHPs, the filling ratio and condenser temperature influence on the performance of cryogenic ones. For medium-temperature PHPs, filling ratios in the range of 40% and 60% have shown the most appropriate performance in the most of the cases, while this optimal filling ratio can be different for cryogenic PHPs [31]. For instance, Liang et al. [58] experimentally investigated the impacts of heat sink temperature and filling ratio on a closed loop PHP charged with neon. Six different filling ratios between 15.3 and 51.5% were tested to find the most appropriate one for heat transfer. Their findings revealed that at low heat inputs, 15.3% filling ratio led to the highest thermal conductivity; however, the dry-out phenomenon, where the temperature of the evaporator rises quickly and the pressure decreases [59], occurred at low temperatures for this filling ratio as shown in Fig. 6. In addition, it was observed that the increase in the temperature of the condenser part resulted in increment in effective thermal conductivity. Improvement in the thermal performance of the cryogenic PHP by increasing the temperature of condenser was attributed to variation in thermophysical properties of the operating fluid such as reduction in the dynamic viscosity and increase in saturation pressure gradient which facilitated the fluid motion inside the PHPs. As it was mentioned, dry-out occurrence is an unfavorable for the PHPs. In this condition, the thermal performance of the PHPs deteriorates and their thermal resistance sharply increases. This phenomenon can be prevented by increasing the number of turns and fluid inventory. In a study conducted by Li et al. [60], two PHPs, one of them with 48 turns and the other one with 8 turns, were charged with helium. As shown in Fig. 7, increase in number of turn resulted in lower effective thermal conductivity, while the dry-out phenomenon occurred at higher heat load, which was attributed to the increased amount of the fluid in the PHP. Moreover, by increasing the number of turns, the share of each turn of the overall heat load decreases, this phenomenon leads to reduction in the driving force of fluid oscillation, which means a decrease in the heat transfer coefficient; however, the possibility of dry-out is decreased.

In addition to the filling ratio, the orientation of PHPs influences on their performance [61]. The inclination angle of the PHPs influences on both maximum heat transfer capacity and thermal resistance [62–64]. Generally, the performance of the PHPs is better in vertical or near-vertical orientations due to gravity assistance, in addition to the pressure instabilities inside the tube, in fluid return from the heat sink to the evaporator [33]. Fonseca et al. [65] assessed the impact of gravity and filling ratio on the thermal resistance of a cryogenic PHP filled with nitrogen. The PHP was thermally investigated in filling ratios between 10 and 40% and in horizontal and vertical

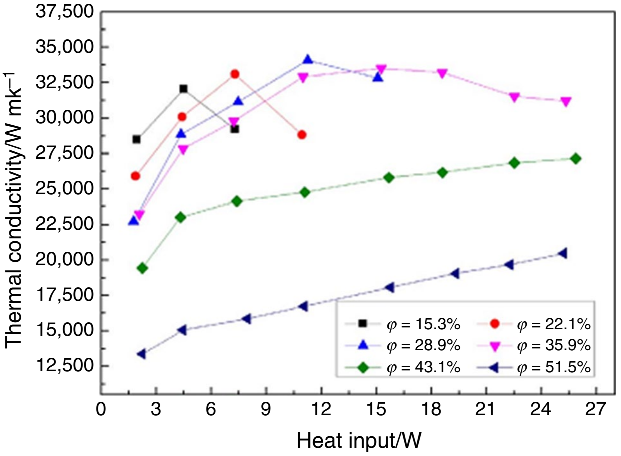

Fig. 6 Effect of filling ratio and heat load on effective thermal conductivity of neon-filled PHP investigated by Liang et al. [58]

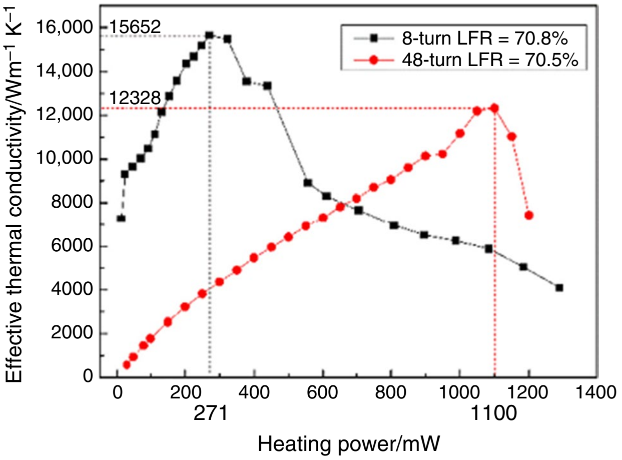

Fig. 7 Impact of number of turn and heat load on the effective thermal conductivity of cryogenic PHP investigated by Li et al. [60]

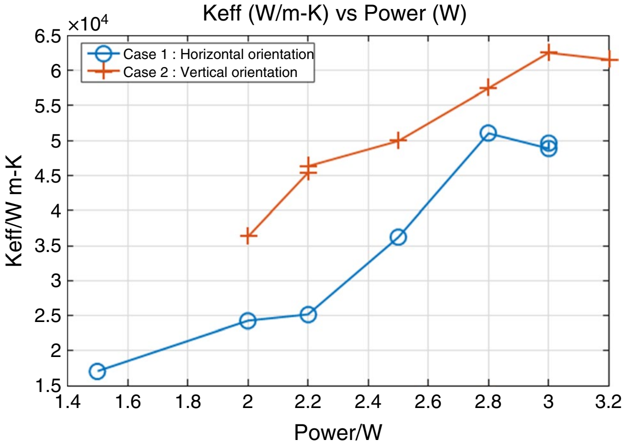

Fig. 8 Effective thermal conductivity of the nitrogen-filled cryogenic PHP in horizontal and vertical orientations investigated by Fonseca et al. [65]

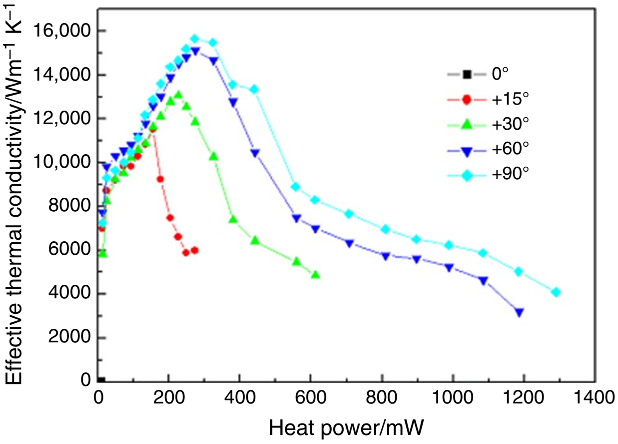

Fig. 9 Effect of inclination angle and heat load on the thermal conductivity of helium-charged PHP investigated by Xu et al. [66]

orientations. According to their outcomes, the filling ratios around 20% led to the highest effective thermal conductivity. Moreover, it was observed that changing the orientation of the PHP from horizontal to vertical could remarkably increase its effective thermal conductivity for different heat loads as shown in Fig. 8. Similar behavior was observed for the cryogenic PHPs filled with other working fluids. For instance, the effect of inclination angle on the thermal behavior of a cryogenic PHP charged with helium was investigated by Xu et al. [66]. In their study, the inclination angle increased from 0 to 90° in order to find its impact on the effective thermal conductivity and heat transfer capacity. As shown in Fig. 9, the increase in inclination angle resulted in higher effective thermal conductivity. In addition, it was observed that by increasing the inclination angle from 0° to 90°, the maximum heat transfer increased from 0.273 to 1.29 W, which indicates remarkable impact of inclination angle on the heat transfer capacity of the investigated cryogenic PHP. Increase in heat transfer capacity of PHPs in vertical orientation can be attributed to more available liquid in evaporator section due to the assistance of gravity in returning fluid from condenser to evaporator.

Working fluid, as one of the most important parameters, is another factor influencing the effective thermal conductivity. Studies have shown that thermophysical features of working fluid such as the surface tension, thermal conductivity and dynamic viscosity are among the most important ones play role in PHPs performance [67]. In a study carried out by Natsume et al. [68], neon and hydrogen were utilized to charge a PHP. The measured effective thermal conductivities of the tested PHPs were in the ranges of 5100–19,500 $\mathrm{Wm^{-1}\,K^{-1}}$ and 2200–11,500 $\mathrm{Wm^{-1}\,K^{-1}}$ for the neon- and hydrogen-charged ones, respectively [68]. Moreover, according to the experimental results, a correlation was proposed to predict the heat flux of the cryogenic PHPs based on the inclination angle, Prandtl, Karman and Jacob numbers. In addition to the thermal conductivity of cryogenic PHPs, their operating temperature is influenced by their working fluid [69]. In another research [70], three fluids including neon, hydrogen and nitrogen were tested in cryogenic PHPs, where the working temperature ranges for the mentioned fluids were 26–34 K, 17–27 K and 67–91 K, respectively. In these cases, the effective thermal conductivities of the PHPs were 1000–8000 $\mathrm{Wm^{-1}\,K^{-1}}$, 500–3500 $\mathrm{Wm^{-1}\,K^{-1}}$ and 5000–18,000 $\mathrm{Wm^{-1}\,K^{-1}}$, for the PHPs with 0.788 mm inner diameter and filled with neon, hydrogen and nitrogen, respectively. It was observed that higher effective thermal conductivity was achievable by increasing the inner diameter of the PHP. Improvement in the thermal performance of the PHP by increasing the inner diameter of the tube was attributed to changes in hydrodynamic and thermal properties of two-phase flow pulsation which was dependent on the diameter.

As well as the tube, flat plates with inserted channels for fluid motion can be used as PHP. In this condition, the hydraulic diameter of the channels must be in the appropriate range to have behavior similar to the PHPs composed of tube. Similar to medium-temperature applications [71], these kinds of PHPs can be used for cryogenic conditions. Natsume et al. [72] experimentally studied the heat transfer capacity of a flat plate PHP by using hydrogen, nitrogen and neon as working fluids. It was observed that employing flat plate PHPs was an efficient method for thermal management in cryogenic operating conditions. In addition, they concluded that the type of charging fluid had a noticeable impact on the effective thermal conductivity. In the cases of using nitrogen, neon and hydrogen, the effective thermal conductivities of the PHP were approximately 3500 $\text{Wm}^{-1}\,\text{K}^{-1}$, 2500 $\text{Wm}^{-1}\,\text{K}^{-1}$ and 850 W/K, respectively.

Thermosyphon

Thermosyphons, or gravity-assisted HPs, have the simplest structure among other types of HPs. These thermal devices consist of a tube, or a plate with channels for fluid motion, and partially charged by an operating fluid [73, 74]. Similar to other mentioned HPs, thermosyphons are able to operate in cryogenic conditions. Studies have shown that the effective thermal conductivity of cryogenic thermosyphons could be up to 200–500 times of copper tubes, which means it appropriateness for cryogenic thermal management [75]. Abdel-Bary et al. [76] tested a cryogenic thermosyphon charged with hydrogen. In their setup, the wall of thermosyphon was coated with a thin layer of gold to minimize the radiative heat transfer. The temperatures of the various parts of thermosyphon were measured at two conditions, with and without 20 layers of super insulation. The highest effective thermal conductivities of the tested thermosyphon were around 37,650 and 35,300 $\text{Wm}^{-1}\,\text{K}^{-1}$ in the cases of using the insulation and without insulation, respectively. By comparing these values of effective thermal conductivity with the corresponding values of metals, exceptional performance of thermosyphons in cryogenic conditions is revealed.

The operating range of all thermosyphons, including cryogenic ones, is influenced by various factors. In a study performed by Nakano et al. [77], a nitrogen-filled thermosyphon was experimentally investigated under different conditions to analyze its operating range. In their study, the temperature of the condenser sections varied in the range of 60.1 K and 121.7 K. It was observed that low temperature of condenser section led to high-temperature difference between the heat source and heat sink as shown in Fig. 10, which was attributed to formation of solid nitrogen which covered the inner surface of the condenser. In addition, it was found that there was an optimal temperature for condenser section to achieve the minimum thermal resistance. Their experimental results revealed that the operating limit of the cryogenic thermosyphon can be predicted based on the existing analytical models on the basis of flooding limit.

As well as single fluid, the mixture of two or more fluids has been tested in various HPs. Binary fluids, consisting of two different materials, are used in HPs as the working fluid to make them appropriate for wider ranges of applications, improve their performance, etc. [79, 80]. For instance, by using fluids with high boiling temperature as one of the components of the binary fluids, the start-up occurrence will be observed at higher heat loads. Similar to medium- and high-temperature HPs, binary fluids can be applied in cryogenic applications. Long et al. [56, 57] charged a cryogenic thermosyphon with N_2Ar as the working fluid. Different compositions of the binary fluid were tested in the thermosyphon in order to assess the impact molar fraction. It was observed that increasing the share of Ar in the mixture led to increase in the required heat for dry-out condition. However, high or very high fraction of Ar in the mixture limited film boiling of the nitrogen. Moreover, it was observed that at high heat loads, higher than 120 W, the thermal resistance of the thermosyphon became independent of the composition of the mixture which was due to the intensive boiling inside the thermosyphon. Thermal resistance of the thermosyphon versus heat load in different compositions of the mixture is represented in Fig. 11 [57]. In addition to the working fluid, filling ratio influences on the operating limit of the cryogenic thermosyphons. According to a study conducted by Long

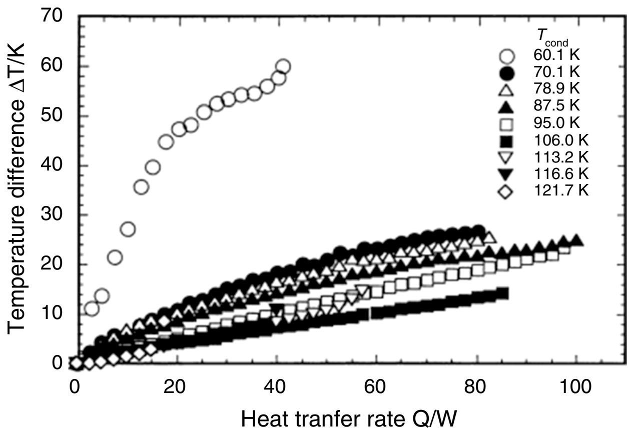

Fig. 10 Temperature difference vs heat input for various condenser temperature of cryogenic nitrogen-filled thermosyphon investigated by Nakano et al. [77]

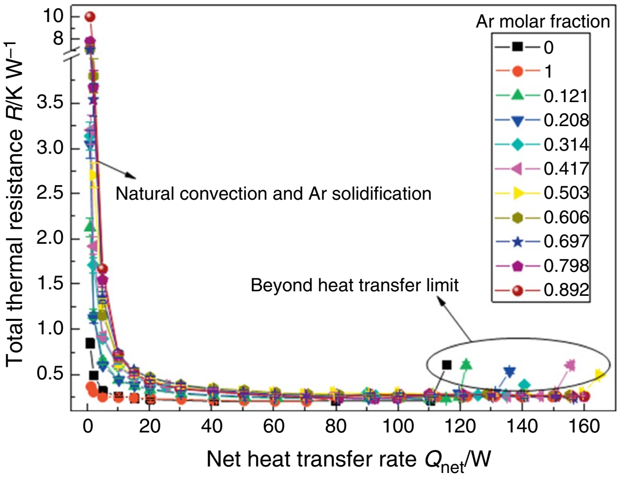

Fig. 11 Thermal resistance vs heat load for the thermosyphon with binary fluid investigated by Long et al. [78]

et al. [81] on a helium-filled thermosyphon, the increase in the filling ratio results in the dry-out occurrence at higher heat loads.

Different configurations of thermosyphons can be applied for cryogenic applications. For instance, Lee et al. [82] utilized a thermosyphon with two evaporators, as shown in Fig. 12, in cryogenic condition. In their study, liquid nitrogen was used for charging the thermosyphon. In steady state condition, 0.64 K temperature difference was observed between the two evaporators which was attributed to conductive thermal resistance of the tube in adiabatic section; however, the overall temperature difference was 1.59 K for heat load of 10.6 W which indicated that the high heat transfer ability of the tested configuration for cryogenic applications. The efficient thermal behavior of this thermosyphon makes them appropriate for thermal management of high-temperature superconductors which are separated in vertical direction.

In Table 2, summaries of the researches focused on the cryogenic HPs are listed.

Recommendations for future studies

In the previous sections, the studies carried out on the thermal investigation of cryogenic HPs were represented; however, there are some ideas which can be performed in order to have further improvement in the heat transfer characteristics of these HPs.

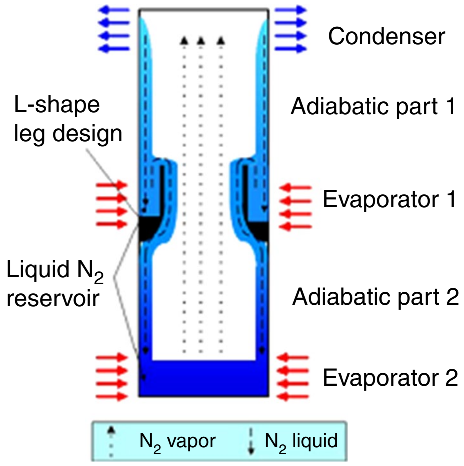

Fig. 12 Schematic of dual-evaporator nitrogen-filled thermosyphon investigated by Lee et al. [82]

For the conventional HPs, the impact of types and materials of wick structure has not been considered in the studies. Due to the dependency of capillary force, and as consequence the performance of conventional HPs, on the wick features, more investigations and studies are required to gain better insight. For instance, the pore size of wick structure and the material used for their installation on the inner surface of the tube should be considered in future relevant researches. By varying the mentioned factors, the provided capillary force would be varied and the performance of the cryogenic HPs will be affected. In addition, different shapes of wick, with novel architecture, can be used in the cryogenic HPs to find more proper ones. For instance, Khalili et al. [27] fabricated a new type of sinter wick, named one-third wick, in a LHP and observed enhanced thermal performance compared with annularly sintered wick. These types of wick can be tested in cryogenic HPs to reach lower thermal resistance. In addition, other types of capillary structures such as grooves and meshes can be used in these HPs to compare heat transfer ability and evaluate the potentials of improving thermal performance by using these structures.

In PHPs, different ideas have been proposed in recent years to improve the thermal performance. For instance, Ebrahimi et al. [83] connected the channels of a flat plate PHP to make the circulation of the working fluid easier. It was observed that the employed method was applicable to increase the effective thermal conductivity of the PHP. This method would be useful for cryogenic PHPs. In addition, since the operating principle of the PHP is based on pressure instabilities, using the structures with ability to make the fluid more instable would be applicable. In order to achieve it, the size of channels and tubes in a PHP can be different [84]. Moreover, the effect of orientation should be more investigated on the performance of both PHPs and thermosyphons. Finally, binary and ternary mixtures, which are used in moderate and high-temperature HPs, can be applicable for the cryogenic ones in order to widen their operating range. Till now, just one study was performed on the application of binary fluid in a cryogenic thermosyphon, while these mixtures can be used to charge cryogenic PHPs and conventional cryogenic HPs. In cases of using binary or ternary fluids in cryogenic HPs, the limitations related to the operating conditions, such as boiling temperature, must be considered. Finally, visualization of the cryogenic heat pipes which is

Table 2 Summary of the results of studies conducted on cryogenic HPs

References	Type of heat pipe	Working fluid	Key findings
Kown et al. [41]	Conventional HP	Nitrogen	High effective thermal conductivity, more than 24 $kWm^{-1} K^{-1}$ was achievable
Sangpab et al. [42]	Conventional HP	Nitrogen	Increase in thermal resistance by bending and flattening of the HP
Bai et al. [44]	LHP	Nitrogen	A minimum heat load is required for realizing the supercritical start-up in a LHP with auxiliary loop
Zhao et al. [47]	LHP	Nitrogen	Unsteady operation at low heat loads due to the initial thermal capacitance of the units
Mo et al. [49]	LHP	Nitrogen	Increase in heat transfer capacity of the LHP by changing its orientation from horizontal and vertical-reverse to vertical
Bai et al. [50]	LHP	Nitrogen	Connecting the secondary loop line to the middle or top of the primary compensation chamber, compared with its bottom, resulted in higher heat transfer capacity
Lee et al. [51]	LHP	Nitrogen	Increase in the charging pressure led to higher thermal resistance
Fonseca et al. [65]	PHP	Nitrogen	Higher effective thermal conductivity of the PHP in vertical mode compared with horizontal
Li et al. [61]	PHP	Nitrogen	Higher effective thermal conductivity of the PHP in vertical orientation compared with horizontal and vertical-reverse
Sun et al. [54]	PHP	Hydrogen	The cryogenic PHP had effective thermal conductivity. (In the range of 30,000 and 70,000 $Wm^{-1} K^{-1}$)
Jiao et al. [56]	PHP	Nitrogen	Reduction in thermal resistance from 0.256 to 0.112 K/W by increasing the applied heat from 22.5 to 321.8 W
Bruce et al. [57]	PHP	Nitrogen	Up to 85 $kWm^{-1} K^{-1}$ effective thermal conductivity was achievable
Liang et al. [58]	PHP	Neon	Increase in effective thermal conductivity of the PHP by increasing the condenser temperature
Xu et al. [66]	PHP	Helium	Increase in maximum transferred power from 0.273 to 1.29 W by increment in the inclination angle from 0° to 90°
Liang et al. [59]	PHP	Neon	Sharp increment in temperature and reduction in pressure in the case of dry-out onset
Natsume et al. [68]	PHP	Neon and hydrogen	Effective thermal conductivities of the PHP were in the ranges of 5100–19,500 $Wm^{-1}K^{-1}$ and 2200–11,500 W/m.K for the neon- and hydrogen-charged ones
Li et al. [62]	PHP	Helium	Filling ratio and orientation affect the maximum heat transfer rate and effective thermal conductivity
Natsume et al. [70]	PHP	Neon, hydrogen and nitrogen	Effective thermal conductivities in the ranges of 1000–8000 $Wm^{-1} K^{-1}$, 500–3500 $Wm^{-1} K^{-1}$ for hydrogen and 5000–18,000 $Wm^{-1} K^{-1}$, nitrogen-filled PHPs
Mito et al. [69]	PHP	Neon, hydrogen and nitrogen	Dependency of operating temperature on working fluid
Sun et al. [67]	PHP	Hydrogen and helium	Appropriate filling ratio of the cryogenic PHPs depend on their operating temperature
Natsume et al. [72]	Flat plate PHP	Neon, nitrogen and hydrogen	Among the three tested fluids, applying nitrogen led to the maximum effective thermal conductivity
Abdel-Bary et al. [76]	Thermosyphon	Hydrogen	The effective thermal conductivity of the HP reached up to 376.5 W/cmK
Nakano et al. [77]	Thermosyphon	Nitrogen	Operating limit of the thermosyphon can be predicted based on the flooding limit
Bolozdynya et al. [75]	Thermosyphon	Nitrogen	The tested thermosyphon was appropriate for efficient heat transfer in temperature range of 80–120 K
Long et al. [78]	Thermosyphon	Helium	Increase in required heat load for dry-out occurrence by increment in the filling ratio
Long et al. [81]	Thermosyphon	Ar-nitrogen	Operating range of the thermosyphon is broadened by employing binary mixture
Lee et al. [82]	Dual-evaporator thermosyphon	Nitrogen	Appropriate heat transfer capacity for thermal management of high-temperature superconductors

performed in medium-temperature ones [85, 86], by using appropriate transparent material for the tubes, would provide more useful and addition insight into the phenomena occur.

Conclusions

In the current article, the research works conducted on various types of cryogenic HPs including pulsating heat pipes, wick heat pipes and thermosyphons are reviewed. The most important findings are:

1. Different fluids with low boiling temperatures are applicable in different types of cryogenic HPs; however, nitrogen, hydrogen, neon and helium are among the fluids which are used in larger extent.
2. Compared with the conductive metals, cryogenic HPs have shown several orders of magnitude higher effective thermal conductivity at the same working conditions, attributed to the two-phase heat transfer mechanism.
3. Despite much lower operating temperature of cryogenic HPs, their behavior and working principles are similar to medium or high-temperature HPs and their performance is dependent on several factors including filling ratio, working fluid and structure.
4. Similar to conventional HPs, low heat load may not provide adequate driving force for their efficient performance; on the other hand, high heat loads can lead to unfavorable phenomena such as dry-out.
5. The performance of the cryogenic HPs is more appropriate in vertical or near-vertical orientations compared with horizontal due to assistance of gravity in fluid return from condenser to evaporator.
6. Operating range of the cryogenic HPs depends on the properties of working fluid, orientation, filling ratio, etc.

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References

1. Khan SM, Kaneez H. Numerical computation of heat transfer enhancement through Cosserat hybrid nanofluids using continuous Galerkin-Petrov method. Eur Phys J Plus. 2020;135(2):135:1-135:19. https://doi.org/10.1140/EPJP/S13360-020-00226-W.
2. Malvandi A, Ganji DD, Kaffash MH. Magnetic field effects on nanoparticle migration and heat transfer of alumina/water nanofluid in a parallel-plate channel with asymmetric heating. Eur Phys J Plus. 2015;130(4):130:1-130:21. https://doi.org/10.1140/EPJP/I2015-15063-Y.
3. Ahmadi MH, Sadeghzadeh M, Raffiee AH, Chau K. Applying GMDH neural network to estimate the thermal resistance and thermal conductivity of pulsating heat pipes. Eng Appl Comput Fluid Mech. 2019;13:327–36. https://doi.org/10.1080/19942060.2019.1582109.
4. Vijayakumar M, Navaneethakrishnan P, Kumaresan G, Kamatchi R. A study on heat transfer characteristics of inclined copper sintered wick heat pipe using surfactant free CuO and Al_2O_3 nanofluids. J Taiwan Inst Chem Eng. 2017;81:190–8. https://doi.org/10.1016/J.JTICE.2017.10.032.
5. Hoseinzadeh S, Sahebi SAR, Ghasemiasl R, Majidian AR. Experimental analysis to improving thermosyphon (TPCT) thermal efficiency using nanoparticles/based fluids (water). Eur Phys J Plus. 2017;132:197. https://doi.org/10.1140/epjp/i2017-11455-3.
6. Ramezanizadeh M, Alhuyi Nazari M, Ahmadi MH, Açıkkalp E. Application of nanofluids in thermosyphons: a review. J Mol Liq. 2018;272:395–402. https://doi.org/10.1016/J.MOLLIQ.2018.09.101.
7. Ramezanizadeh M, Nazari MA, Ahmadi MH, Lorenzini G, Kumar R, Jilte R. A review on the solar applications of thermosyphons. Math Modell Eng Probl. 2018;5:275–80. https://doi.org/10.18280/mmep.050401.
8. Alizadeh H, Ghasempour R, Shafii MB, Ahmadi MH, Yan W-M, Nazari MA. Numerical simulation of PV cooling by using single turn pulsating heat pipe. Int J Heat Mass Transf. 2018;127:203–8. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2018.06.108.
9. Ramezanizadeh M, Alhuyi Nazari M, Hossein Ahmadi M, Chen L. A review on the approaches applied for cooling fuel cells. Int J Heat Mass Transf. 2019;139:517–25. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2019.05.032.
10. Alhuyi Nazari M, Ahmadi MH, Ghasempour R, Shafii MB. How to improve the thermal performance of pulsating heat pipes: a review on working fluid. Renew Sustain Energy Rev. 2018;91:630–8.
11. Xu D, Liu H, Gong L, Xu X, Li L. A novel pre-cooling system for a cryogenic pulsating heat pipe. Phys Procedia. 2015;67:687–91. https://doi.org/10.1016/J.PHPRO.2015.06.116.
12. Gandomkar A, Saidi MH, Shafii MB, Vandadi M, Kalan K. Visualization and comparative investigations of pulsating Ferro-fluid heat. Appl Therm Eng. 2017. https://doi.org/10.1016/j.applthermaleng.2017.01.068.
13. Zamani R, Kalan K, Shafii MB. Experimental investigation on thermal performance of closed loop pulsating heat pipes with soluble and insoluble binary working fluids and a proposed correlation. Heat Mass Transf. 2018. https://doi.org/10.1007/s00231-018-2418-z.
14. Mohammadi M, Taslimifar M, Haghayegh S, Hannani SK, Shafii MB, Saidi MH, et al. Open-loop pulsating heat pipes charged with magnetic nanofluids: powerful candidates for future electronic coolers. Nanoscale Microscale Thermophys Eng. 2014;18:18–38. https://doi.org/10.1080/15567265.2013.787570.
15. Khalili M, Shafii MB. Investigating thermal performance of a partly sintered-wick heat pipe filled with different working fluids. SCIENTIA IRANICA. 2016;23:2616–25.
16. Kargar Sharif Abad H, Ghiasi M, Jahangiri Mamouri S, Shafii MB. A novel integrated solar desalination system with a pulsating heat pipe. Desalination. 2013;311:10–206. https://doi.org/10.1016/J.DESAL.2012.10.029.
17. Ramezanizadeh M, Alhuyi Nazari M, Ahmadi MH, Chau K. Experimental and numerical analysis of a nanofluidic thermosyphon heat exchanger. Eng Appl Comput Fluid Mech. 2019;13:40–7. https://doi.org/10.1080/19942060.2018.1518272.

18. Shirzadi N, Roshandel R, Shafii MB. Integration of miniature heat pipes into a proton exchange membrane fuel cell for cooling applications. Heat Transfer Eng. 2017;38:1595–605. https://doi.org/10.1080/01457632.2016.1262722.
19. Arab M, Soltanieh M, Shafii MB. Experimental investigation of extra-long pulsating heat pipe application in solar water heaters. Exp Thermal Fluid Sci. 2012;42:6–15. https://doi.org/10.1016/J.EXPTHERMFLUSCI.2012.03.006.
20. Liu B, Zhang M, Yang X, Wang T. Simulation and energy analysis of CO_2 capture from CO_2-EOR extraction gas using cryogenic fractionation. J Taiwan Inst Chem Eng. 2019;103:67–74. https://doi.org/10.1016/j.jtice.2019.07.008.
21. Song C, Kitamura Y, Li S. Optimization of a novel cryogenic CO2 capture process by response surface methodology (RSM). J Taiwan Inst Chem Eng. 2014;45:1666–76. https://doi.org/10.1016/j.jtice.2013.12.009.
22. Chuang YY, Wang JJ, Chao PY, Tsai CT, Tsai YC, Chen WC, et al. Evaluation of on-stream industrial CO_2 adsorbent in air pretreatment for cryogenic production of oxygen. J Taiwan Inst Chem Eng. 2018;84:41–8. https://doi.org/10.1016/j.jtice.2017.12.030.
23. Dubin DHE, O'Neil TM. Thermal equilibrium of a cryogenic magnetized pure electron plasma. Phys Fluids. 1986;29:11. https://doi.org/10.1063/1.865987.
24. Darr SR, Camarotti CF, Hartwig JW, Chung JN. Hydrodynamic model of screen channel liquid acquisition devices for in-space cryogenic propellant management. Phys Fluids. 2017;29:017101. https://doi.org/10.1063/1.4973671.
25. Faghri A. Heat pipe science and technology. Abingdon on Thames: Taylor & Francis; 1995.
26. Gandomkar A, Kalan K, Vandadi M, Shafii MB, Saidi MH. Investigation and visualization of surfactant effect on flow pattern and performance of pulsating heat pipe. J Therm Anal Calorim. 2020;139:2099–107. https://doi.org/10.1007/s10973-019-08649-z.
27. Khalili M, Shafii MB. Experimental and numerical investigation of the thermal performance of a novel sintered-wick heat pipe. Appl Therm Eng. 2016;94:59–75. https://doi.org/10.1016/j.applthermaleng.2015.10.120.
28. Savino R, Paterna D. Marangoni effect and heat pipe dry-out. Phys Fluids. 2006;18:118103. https://doi.org/10.1063/1.2397586.
29. Zohuri B. Heat pipe design and technology modern applications for practical thermal management. 2nd ed. Berlin: Springer; 2016.
30. Japikse D. Advances in thermosyphon technology. Adv Heat Transf. 1973;9:1–111. https://doi.org/10.1016/S0065-2717(08)70061-3.
31. Mohammadi M, Mohammadi M, Ghahremani AR, Shafii MB, Mohammadi N. Experimental investigation of thermal resistance of a ferrofluidic closed-loop pulsating heat pipe. Heat Transf Eng. 2014;35:25–33. https://doi.org/10.1080/01457632.2013.810086.
32. Faghri A. Review and advances in heat pipe science and technology. J Heat Transf. 2012;134:123001. https://doi.org/10.1115/1.4007407.
33. Heydarian R, Shafii MB, Rezaee Shirin-Abadi A, Ghasempour R, Alhuyi NM. Experimental investigation of paraffin nano-encapsulated phase change material on heat transfer enhancement of pulsating heat pipe. J Therm Anal Calorim. 2019;137:1603–13. https://doi.org/10.1007/s10973-019-08062-6.
34. Wang XW, Wan ZP, Tang Y. Thermodynamic and experimental study on heat transfer mechanism of miniature loop heat pipe with water-copper nanofluid. Phys Fluids. 2018;30:027102. https://doi.org/10.1063/1.5010244.
35. Salort J, Riedinger X, Rusaouen E, Tisserand JC, Seychelles F, Castaing B, et al. Turbulent velocity profiles in a tilted heat pipe. Phys Fluids. 2013;25:105110. https://doi.org/10.1063/1.4824852.
36. Sureshkumar R, Mohideen ST, Nethaji N. Heat transfer characteristics of nanofluids in heat pipes: a review. Renew Sustain Energy Rev. 2013;20:397–410. https://doi.org/10.1016/J.RSER.2012.11.044.
37. Daimaru T, Yoshida S, Nagai H. Study on thermal cycle in oscillating heat pipes by numerical analysis. Appl Therm Eng. 2017;113:1219–27. https://doi.org/10.1016/J.APPLTHERMALENG.2016.11.114.
38. Guo Y, Lin G, Bai L, Bu X, Zhang H, He J, et al. Experimental study on the supercritical startup of cryogenic loop heat pipes with redundancy design. Energy Convers Manag. 2016;118:353–63. https://doi.org/10.1016/J.ENCONMAN.2016.04.022.
39. Eggers PE, Serkiz AW. Development of cryogenic heat pipes. J Eng Power. 1971;93:279. https://doi.org/10.1115/1.3445564.
40. Zhang H, Wang S, Wang J. Experimental study on boiling flow of liquid nitrogen in inclined tubes-Velocities and length distributions of Taylor bubbles. J Taiwan Inst Chem Eng. 2009;40:431–8. https://doi.org/10.1016/j.jtice.2008.12.004.
41. Kwon DW, Sedwick RJ. Cryogenic heat pipe for cooling high temperature superconductors. Cryogenics. 2009;49:514–23. https://doi.org/10.1016/J.CRYOGENICS.2009.07.005.
42. Sangpab N, Kimura N, Terdtoon P, Sakulchangsatjatai P, Kammuang-lue N, Murakami M. Combined effect of bending and flattening on heat transfer performance of cryogenic sintered-wick heat pipe. Appl Therm Eng. 2019;148:878–85. https://doi.org/10.1016/J.APPLTHERMALENG.2018.10.099.
43. Wang H, Lin G, Bai L, Fu J, Wen D. Experimental study on an acetone-charged loop heat pipe with a nickel wick. Int J Therm Sci. 2019;146:106104. https://doi.org/10.1016/J.IJTHERMALSCI.2019.106104.
44. Bai L, Lin G, Zhang H, Miao J, Wen D. Experimental study of a nitrogen-charged cryogenic loop heat pipe. Cryogenics. 2012;52:557–63. https://doi.org/10.1016/J.CRYOGENICS.2012.07.005.
45. Bugby D, Marland B, Stouffer C, Kroliczek E. Across-Gimbal and miniaturized cryogenic loop heat pipes. AIP Conf Proc. 2003;654:218–26. https://doi.org/10.1063/1.1541297.
46. Bai L, Zhang L, Lin G, He J, Wen D. Development of cryogenic loop heat pipes: a review and comparative analysis. Appl Therm Eng. 2015;89:180–91. https://doi.org/10.1016/J.APPLTHERMALENG.2015.06.010.
47. Zhao Y, Yan T, Liang J. Experimental study on a cryogenic loop heat pipe with high heat capacity. Int J Heat Mass Transf. 2011;54:3304–8. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2011.03.056.
48. Mo Q, Liang J. Operational performance of a cryogenic loop heat pipe with insufficient working fluid inventory. Int J Refrig. 2006;29:519–27. https://doi.org/10.1016/J.IJREFRIG.2005.10.011.
49. Mo Q, Liang JT. A novel design and experimental study of a cryogenic loop heat pipe with high heat transfer capability. Int J Heat Mass Transf. 2006;49:770–6. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2005.08.010.
50. Bai L, Lin G, Zhang H, Miao J, Wen D. Effect of component layout on the operation of a miniature cryogenic loop heat pipe. Int J Heat Mass Transf. 2013;60:61–8. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2013.01.011.
51. Lee J, Kim D, Mun J, Kim S. Heat-transfer characteristics of a cryogenic loop heat pipe for space applications. Energies. 2020;13:1616. https://doi.org/10.3390/en13071616.
52. Bonnet F, Gully P, Nikolayev V. Development and test of a cryogenic pulsating heat pipe and a pre-cooling system. AIP Conf Proc Am Inst Phys. 2012;1434:607–14. https://doi.org/10.1063/1.4706970.
53. Liu Y, Deng H, Pfotenhauer J, Gan Z. Design of a hydrogen pulsating heat pipe. Phys Procedia. 2015;67:551–6. https://doi.org/10.1016/j.phpro.2015.06.074.

54. Sun X, Li S, Jiao B, Gan Z, Pfotenhauer J. Experimental study on a hydrogen closed-loop pulsating heat pipe with two turns. Cryogenics. 2019;97:63–9. https://doi.org/10.1016/J.CRYOGENICS.2018.10.010.
55. Han X, Ma H, Jiao A, Critser JK. Investigations on the heat transport capability of a cryogenic oscillating heat pipe and its application in achieving ultra-fast cooling rates for cell vitrification cryopreservation. Cryobiology. 2008;56:195–203. https://doi.org/10.1016/J.CRYOBIOL.2008.02.006.
56. Jiao AJ, Ma HB, Critser JK. Experimental investigation of cryogenic oscillating heat pipes. Int J Heat Mass Transf. 2009;52:3504–9. https://doi.org/10.1016/j.ijheatmasstransfer.2009.03.013.
57. Bruce R, Barba M, Bonelli A, Baudouy B. Thermal performance of a meter-scale horizontal nitrogen pulsating heat pipe. Cryogenics. 2018;93:66–74. https://doi.org/10.1016/J.CRYOGENICS.2018.05.007.
58. Liang Q, Li Y, Wang Q. Effects of filling ratio and condenser temperature on the thermal performance of a neon cryogenic oscillating heat pipe. Cryogenics. 2018;89:102–6. https://doi.org/10.1016/j.cryogenics.2017.12.002.
59. Liang Q, Li Y, Wang Q. Experimental investigation on the performance of a neon cryogenic oscillating heat pipe. Cryogenics. 2017;84:7–12. https://doi.org/10.1016/J.CRYOGENICS.2017.03.004.
60. Li M, Li L, Xu D. Effect of number of turns and configurations on the heat transfer performance of helium cryogenic pulsating heat pipe. Cryogenics. 2018;96:159–65. https://doi.org/10.1016/J.CRYOGENICS.2018.09.005.
61. Li Y, Wang Q, Chen S, Zhao B, Dai Y. Experimental investigation of the characteristics of cryogenic oscillating heat pipe. Int J Heat Mass Transf. 2014;79:713–9. https://doi.org/10.1016/j.ijheatmasstransfer.2014.08.061.
62. Li M, Li L, Xu D. Effect of filling ratio and orientation on the performance of a multiple turns helium pulsating heat pipe. Cryogenics. 2019;100:62–8. https://doi.org/10.1016/J.CRYOGENICS.2019.04.006.
63. Rahman ML, Mir F, Nawrin S, Sultan RA, Ali M. Effect of fin and insert on the performance characteristics of open loop pulsating heat pipe (OLPHP). Procedia Eng. 2015;105:105–12. https://doi.org/10.1016/j.proeng.2015.05.017.
64. Rahman ML, Chowdhury M, Islam NA, Mufti SM, Ali M. Effect of filling ratio and orientation on the thermal performance of closed loop pulsating heat pipe using ethanol. AIP Conference Proceedings, vol. 1754, AIP Publishing LLC; 2016, p. 050011. https://doi.org/10.1063/1.4958402.
65. Fonseca LD, Miller F, Pfotenhauer J. Experimental heat transfer analysis of a cryogenic nitrogen pulsating heat Pipe at various liquid fill ratios. Appl Therm Eng. 2018;130:343–53. https://doi.org/10.1016/J.APPLTHERMALENG.2017.11.029.
66. Xu D, Li L, Liu H. Experimental investigation on the thermal performance of helium based cryogenic pulsating heat pipe. Exp Thermal Fluid Sci. 2016;70:61–8. https://doi.org/10.1016/j.expthermflusci.2015.08.024.
67. Sun X, Pfotenhauer J, Jiao B, Fonseca LD, Han D, Gan Z. Investigation on the temperature dependence of filling ratio in cryogenic pulsating heat pipes. Int J Heat Mass Transf. 2018;126:237–44. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2018.05.147.
68. Natsume K, Mito T, Yanagi N, Tamura H, Tamada T, Shikimachi K, et al. Development of cryogenic oscillating heat pipe as a new device for indirect/conduction cooled superconducting magnets. IEEE Trans Appl Superconduct. 2012. https://doi.org/10.1109/TASC.2012.2185029.
69. Mito T, Natsume K, Yanagi N, Tamura H, Tamada T, Shikimachi K, et al. Achievement of high heat removal characteristics of superconducting magnets with imbedded oscillating heat pipes. IEEE Trans Appl Supercond. 2011;21:2470–3. https://doi.org/10.1109/TASC.2010.2100356.
70. Natsume K, Mito T, Yanagi N, Tamura H, Tamada T, Shikimachi K, et al. Heat transfer performance of cryogenic oscillating heat pipes for effective cooling of superconducting magnets. Cryogenics. 2011;51:309–14. https://doi.org/10.1016/J.CRYOGENICS.2010.07.001.
71. Alizadeh H, Alhuyi Nazari M, Ghasempour R, Shafii MB, Akbarzadeh A. Numerical analysis of photovoltaic solar panel cooling by a flat plate closed-loop pulsating heat pipe. Sol Energy. 2020;206:455–63. https://doi.org/10.1016/j.solener.2020.05.058.
72. Natsume K, Mito T, Yanagi N, Tamura H. Development of a flat-plate cryogenic oscillating heat pipe for improving HTS magnet cooling. Phys Procedia. 2013;45:233–6. https://doi.org/10.1016/J.PHPRO.2013.05.010.
73. Cieśliński JT. Effect of nanofluid concentration on two-phase thermosyphon heat exchanger performance. Arch Thermodyn. 2016;37:23–40. https://doi.org/10.1515/aoter-2016-0011.
74. Faegh M, Behshad M. Experimental investigation of a solar still equipped with an external heat storage system using phase change materials and heat pipes. Desalination. 2017;409:128–35. https://doi.org/10.1016/j.desal.2017.01.023.
75. Bolozdynya AI, Dmitrenko VV, Efremenko YV, Khromov AV, Shafigullin RR, Shakirov AV, et al. The two-phase closed tubular cryogenic thermosyphon. Int J Heat Mass Transf. 2015;80:159–62. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2014.09.001.
76. Abdel-Bary M, Abdel-Samad S, Elawadi GA, Kilian K, Ritman J. A thin gold coated hydrogen heat pipe-cryogenic target for external experiments at COSY. Cryogenics. 2009;49:192–7. https://doi.org/10.1016/J.CRYOGENICS.2009.01.003.
77. Nakano A, Shiraishi M, Nishio M, Murakami M. An experimental study of heat transfer characteristics of a two-phase nitrogen thermosyphon over a large dynamic range operation. Cryogenics. 1998;38:1259–66. https://doi.org/10.1016/S0011-2275(98)00109-X.
78. Long ZQ, Zhang P. Heat transfer characteristics of thermosyphon with N2–Ar binary mixture working fluid. Int J Heat Mass Transf. 2013;63:204–15. https://doi.org/10.1016/j.ijheatmasstransfer.2013.03.042.
79. Patel VM, Gaurav MHB. Influence of working fluids on startup mechanism and thermal performance of a closed loop pulsating heat pipe. Appl Thermal Eng. 2017;110:1568–77. https://doi.org/10.1016/j.applthermaleng.2016.09.017.
80. Cui X, Qiu Z, Weng J, Li Z. Heat transfer performance of closed loop pulsating heat pipes with methanol-based binary mixtures. Exp Thermal Fluid Sci. 2016;76:253–63. https://doi.org/10.1016/J.EXPTHERMFLUSCI.2016.04.005.
81. Long ZQ, Zhang P. Experimental investigation of the heat transfer characteristics of a helium cryogenic thermosyphon. Cryogenics. 2013;57:95–103. https://doi.org/10.1016/J.CRYOGENICS.2013.04.006.
82. Lee J, Ko J, Kim Y, Jeong S, Sung T, Han Y, et al. Experimental study on the double-evaporator thermosiphon for cooling HTS (high temperature superconductor) system. Cryogenics. 2009;49:390–7. https://doi.org/10.1016/J.CRYOGENICS.2009.04.004.
83. Ebrahimi M, Shafii MB, Bijarchi MA. Experimental investigation of the thermal management of flat-plate closed-loop pulsating heat pipes with interconnecting channels. Appl Therm Eng. 2015;90:838–47. https://doi.org/10.1016/J.APPLTHERMALENG.2015.07.040.

84. Kwon GH, Kim SJ. Operational characteristics of pulsating heat pipes with a dual-diameter tube. Int J Heat Mass Transf. 2014;75:184–95. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2014.03.032.
85. Asirvatham LG, Wongwises S, Babu J. Heat transfer performance of a glass thermosyphon using graphene-acetone nanofluid. J Heat Transfer. 2015;137:111502. https://doi.org/10.1115/1.4030479.
86. Yoon A, Kim SJ. Characteristics of oscillating flow in a micro pulsating heat pipe: fundamental-mode oscillation. Int J Heat Mass Transf. 2017;109:242–53. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2017.02.003.