



## Review

## Heat pipe based systems - Advances and applications



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## ABSTRACT

Heat pipes are becoming increasingly popular as passive heat transfer technologies due to their high efficiency. This paper provides a comprehensive review of the state-of-the-art applications, materials and performance of current heat pipe devices. The paper is divided into four main parts; low temperature heat pipes, high temperature heat pipes, thermal modelling of heat pipes and discussion. The low and high temperature sections present an extended list with suitable working fluids and operating temperatures, along with their compatibility with casing materials. Furthermore, the sections focus on some of the most widespread industrial applications, such as solar, nanoparticles, Rankine cycles, nuclear, thermoelectric modules and ceramics, in which heat pipe technologies offer many key advantages over conventional practises. The third part of the paper consists of a thorough analysis of the thermal modelling side of heat pipes. Internal and external thermal modelling techniques, theories and methodologies are presented in this section, for various applications such as non-Newtonian fluids, nanofluids, solar, geothermal, automotive, hybrid storage and nuclear systems. The final part of the paper discusses the limitations of heat pipes and the reasons why they are not implemented in more aspects of our lives. Operational limitations, cost concerns and the lack of detailed theoretical and simulation analysis of heat pipes are some of the point covered in this section. Finally, some of the recent and future developments in the field are discussed.

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Nomenclature		$\xi$	area ratio
$A$	surface area ( $m^2$ )	$\varepsilon$	exergy efficiency
$C_p$	specific heat capacity of water ( $J/kg.K$ )	<i>Subscripts</i>	
$\dot{E}$	energy rate per unit area ( $W/m^2$ )	$a$	ambient
$\dot{E}_X$	Exergy ( $W/m^2$ )	$c$	collector
$G$	Solar irradiation per unit area ( $W/m^2$ )	$e$	electrical
$\dot{m}$	mass flow rate ( $kg/s$ )	$PV$	photovoltaic panel
$P_{max}$	electrical output ( $W$ )	$PV/T$	photovoltaic/thermal panel
$Q$	thermal heat output ( $W$ )	$sun$	sun, solar radiation
$T$	temperature ( $K$ )	$th$	thermal
$t$	time ( $s$ )	$w, i$	cooling water inlet
		$w, o$	cooling water outlet
<i>Greek Symbols</i>			
$\eta$	efficiency		

## 1. Introduction

Heat pipes are recognised as one of the most efficient passive heat transfer technologies available. A heat pipe is a structure with very high thermal conductivity that enables the transportation of heat whilst maintaining almost uniform temperature along its heated and cooled sections. In general, heat pipes are passive thermal transfer devices able to transport large amounts of heat over relatively long distances, with no moving parts, using phase-change processes and vapour diffusion. The main structure of a heat pipe consists of an evacuated tube partially filled with a working fluid that exists in both liquid and vapour phases. Fig. 1 represents the basic steps of operation of heat pipes.

The addition of heat pipes within systems allows a full utilisation of the thermal superconductor property by allowing a high heat transfer rate, making the system ideal for a number of industries and applications. The basic operation is a continuous cycle. The working fluid is located at the bottom of the pipe; the addition of a heat source allows the liquid pool to evaporate. The difference in densities between the vapour and fluid, allows the vapour to reach the cool condenser section. The difference in wall temperature causes the vapour to condensate and releasing the latent heat, allowing the fluid to return to the liquid pool located in the evaporator, by the influence of gravity (thermosyphons) or by some sort

of capillary wicking structure (wicked heat pipes), as shown in Fig. 2.

The generalisation of heat pipes is a broad subject covering many applications ranging from low temperature cryogenic applications to high temperature applications. The implementation of heat pipes are commonly applied in the following scenarios:

- For heat transfer applications, where efficient heat transfer with small temperature differences is the primary purpose

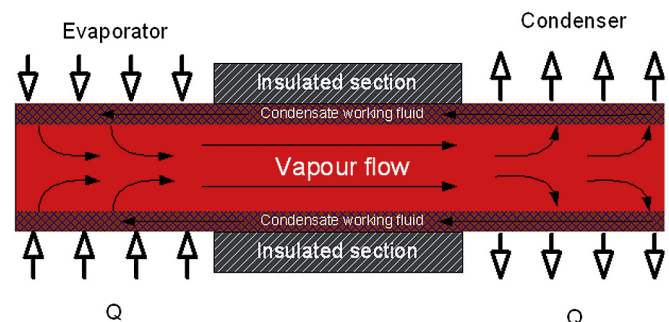


Fig. 1. Heat pipe working cycle [1].

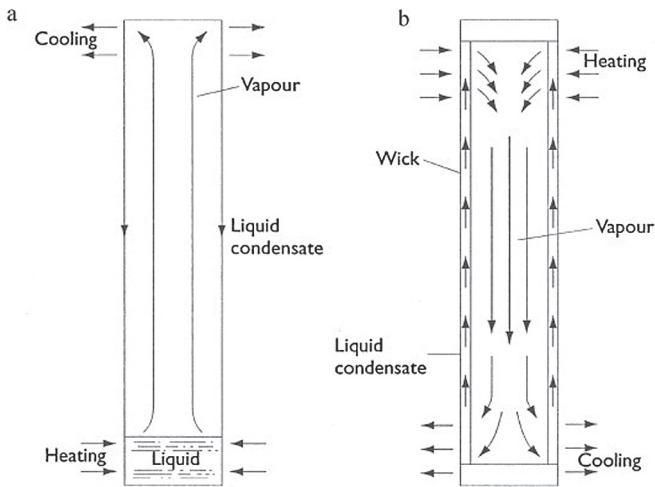


Fig. 2. Structure of thermosyphons (a) and wicked heat pipes (b) [2].

- For isothermal applications, where reduction of pre-existing temperature gradients of a body and operation with isothermal surfaces is the primary purpose
- For temperature control applications, where the heat pipe controls the temperature of a body
- For heat flux transformation applications, where heat from a high heat flux at the evaporator is transformed to a lower heat flux at the condenser

Many reviews have been formed providing a generalisation of technologies in one specific area with the identification of optimum operating conditions and potential limitations. Although the operating conditions and limitations have been identified, the same technology has not been tested and applied in an industrial application, or lacks validation. Chan et al. [3], investigated the different types of wicks alongside different types of heat pipes. The study itself was primarily based on experimental, with minimal discussion around validation methods. The lack of validation within review paper does not fully identify the optimum conditions for certain wick and heat pipe types. The paper proposes the study of alternative shapes, but similarly the experimentation is scarce, but the initial result indicates potential for expansion. The study identifies the most current application around oscillating and rotating heat pipes, which can be applied in multiple sectors ranging from low temperature heat pipes and engine coolant systems. The overall findings present the infinite possibilities but the lack in validation around these topics poses an issue, especially with the development of hybrid technology. Similarly Bai et al. [4], presented a review under cryogenic heat pipes, the paper highlights the key issues with closed loop heat pipes (CLHP) and the lack of availability regarding the system. The review proposes systems which maximise the performance of each CLHP system with the consideration of supercritical start up. The proposal of new configurations allows the identification of potential systems to be implemented in specific cryogenic uses, opening a new range of possibilities in a notoriously difficult industry. Technological advances such as nanofluids increases the complexities due to the metallic particles. Both nanofluids and heat pipes are relatively new technologies, with an increasing amount of experiments and validation occurring [5,6]. It is evident that the utilisation of heat pipes can be applied in a range of applications ranging from nuclear to low temperatures but the available literature identifies the lack of progression into an industrial application.

The following review identifies the current technology

occurring in both high and low temperature applications alongside the progression into industrial systems. The paper also highlights the current CFD methods used to validate the systems alongside technological limitations that are affecting the technological advances and subsequently the industrial application.

## 2. Low temperature

Pharmaceutical, food processing, biotechnology, chemical and medical industries rely on preserving their materials under extremely low temperatures. Red blood cells and platelets can be transfused after years of storage, artificial insemination, banking of cells and tissues, bone marrow transplantation, in-vitro fertilization, facilitated transport of cells and tissues, food and seed storage and many more applications are nowadays possible with cryogenic preservation. As a principle, the colder the better, thus industries are challenging the heat transfer community to provide solutions to enable systems that can run reliably at extremely cold temperatures. Theoretically, a heat pipe can operate at any given temperature, as long as the operation temperature is between the triple and the critical points of the working fluid utilised. Both of these state points refer to the pressure-temperature curve of a matter and they are defined as follows: the triple point of a matter refers to the state where the three phases (vapour, liquid, solid) of a substance coexist, while the critical point is the end point under which the liquid and vapour phases of a matter can coexist.

### 2.1. Working fluid considerations

Cryogenic heat pipes consider any heat pipe system which can operate at temperatures below  $-70^{\circ}\text{C}$ , while low temperature heat pipes have a typical operating temperature between  $-70$  and  $270^{\circ}\text{C}$ . The working fluid can be either an organic fluid with short carbon chains such as methanol and ethanol, or other commonly used fluids like ammonia, acetone or water.

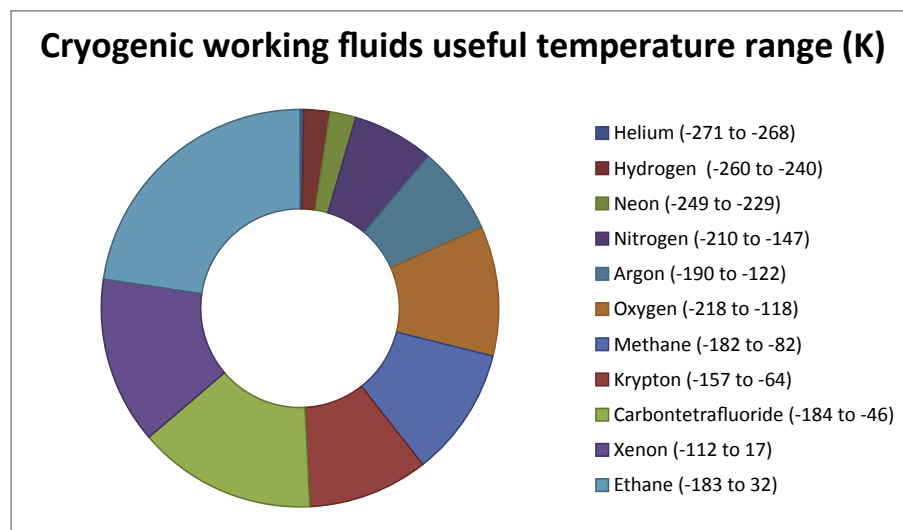
Any type of heat pipes can be used for low or cryogenic applications. Depending on the working fluids charged, cryogenic heat pipes can operate in a specific low temperature range, as shown in Table 1, which contains a list of the most commonly, used working fluids of heat pipes for cryogenic and low temperature applications, with some of their key thermal properties. As stated above, the operational temperature range of a heat pipe varies between the triple and the critical points of the working fluid used. The thermal conductivity of the heat pipe is defined by the evaporation and condensation properties of the working fluid. Table 1 also contains the latent heat of vaporization (LHV) values of the selected working fluids.

Figs. 3 and 4 illustrate how broad the useful temperature ranges of working fluids available for cryogenic and low temperature applications are, respectively, as it was previously presented in Table 1. Comparing the two figures, it is obvious that the lowest the required operational temperatures are the fewer the available choices of working fluids are. Especially Helium and Neon are described from the shortest useful operation range comparing to the rest cryogenic working fluids, while the low temperature working fluids provide more or less the same broad range of temperatures.

The selection of the working fluid determines the thermal performance of the heat pipe. For the desired operating temperature range several potential working fluids may exist, so other factors have to be taken into consideration in order to choose the most acceptable fluid for the given application. Parameters such as heat transfer capabilities, good thermal stability, wettability, optimum vapour pressure, high latent heat and the compatibility of the fluid with the case and wick material of the heat pipe play a significant

**Table 1**  
Properties of working fluids for cryogenic and low temperature applications [7–12].

	Fluid	T <sub>cp</sub> (°C)	T <sub>b</sub> (°C)	T <sub>tp</sub> (°C)	LHV (kJ/kg)
Cryogenic Applications	Helium (He)	−267.9	−268.9	−270.9	21
	Hydrogen (H)	−239.9	−252.7	−259.3	461
	Neon (Ne)	−228.7	−246	−248.6	86.3
	Nitrogen (N <sub>2</sub> )	−146.9	−195.8	−210	199
	Argon (Ar)	−122.3	−185.8	−189.3	162.3
	Oxygen (O <sub>2</sub> )	−118.5	−182.9	−218.3	213
	Methane (CH <sub>4</sub> )	−82.5	−161.7	−182.4	510.8
	Krypton (Kr)	−63.8	−153.2	−157.3	107.5
	Carbontetrafluoride (CF <sub>4</sub> )	−45.6	−127.9	−183.7	135.9
	Xenon (Xe)	16.6	−108.1	−111.7	96.3
	Ethane (C <sub>2</sub> H <sub>6</sub> )	32.3	−88.5	−183.2	489.4
Low Temperature Applications	Freon R22	96.1	−40.8	−157.4	233.7
	Freon R410a	72.8	−48.5	−73.1	256.7
	Propane (C <sub>3</sub> H <sub>8</sub> )	96.8	−42	−187.6	428
	Ammonia (NH <sub>3</sub> )	132.3	−33.2	−77.7	1369.5
	Freon R134a	100.9	−26.5	−103.3	215.9
	Freon R21	178.3	8.8	−135	239.4
	Freon R11	197.9	23.7	−111.1	181.3
	Pentane (C <sub>5</sub> H <sub>12</sub> )	196.7	36	−128.7	367.3
	Freon R113	214	47.6	−36.2	13.2
	Acetone (C <sub>3</sub> H <sub>6</sub> O)	235	56.2	−94.3	538.4
	Methanol (CH <sub>3</sub> OH)	239	64.6	−97.7	1100
	Ethanol (C <sub>2</sub> H <sub>6</sub> O)	241	78.3	−123	837
	Heptane (C <sub>7</sub> H <sub>16</sub> )	266.8	98.3	−90.6	318
	Water (H <sub>2</sub> O)	373.95	99.9	−0.05	2264.76
	Toluene (C <sub>6</sub> H <sub>5</sub> -CH <sub>3</sub> )	320	110.6	−95	351



**Fig. 3.** Useful temperature range of working fluids for cryogenic heat pipe applications.

role in the determination of the appropriate working fluid. The last factor has to be carefully considered as non-compatibility of materials can decompose the working fluid, which will lead to corrosion and chemical reactions of the non-condensable gases causing the failure of the heat pipe.

## 2.2. Material compatibility

Usually, metals are preferred as a construction material for the heat pipe casing due to their mechanical strength and high thermal conductivity, but recently silicon has been presented as the best material and an alternative to replace metals due to its simple fabrication process and compatibility with semiconductor devices. The use of polymer-based casings is highly attractive due to their flexibility and low cost. However, the most commonly used

container materials are copper, aluminium and stainless steel. Copper is preferred for operating temperatures between 0 and 200 °C, while aluminium is an ideal choice due to its weight advantages. Stainless steel casings cannot be used when water is chosen as the working fluid without reducing the operational performance of the heat pipe; progressively the water vapour reacts with the steel casing material and forms free hydrogen molecules, which manifest as a cold plug of gas accumulated at the condenser end, limiting the effective heat pipe length [13]. More details regarding the compatibility of working fluids and casing materials are given in Table 2.

Cryogenic heat pipes reported in the literature can be categorized into three types: thermosyphons [7,17–19], oscillating [2,20–24] and loop heat pipes [4,25–32]. However, only the investigation of oscillating and loop heat pipes has been widely

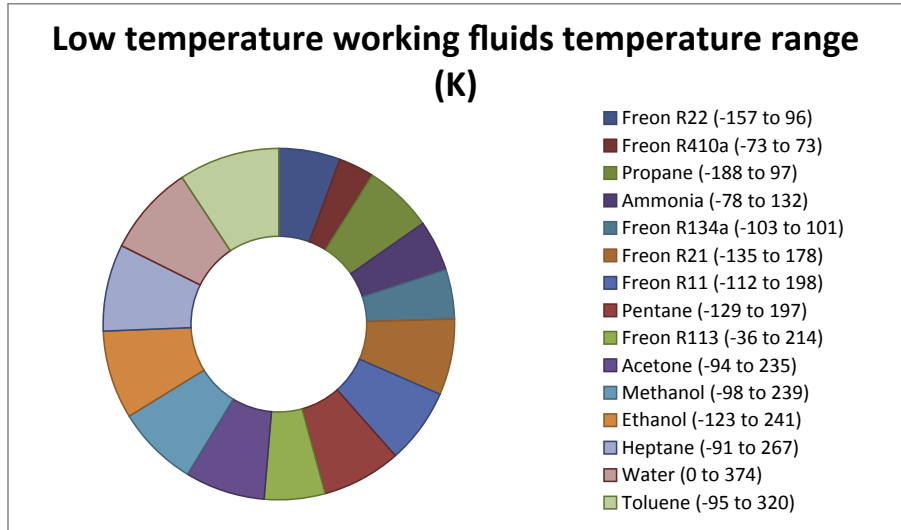


Fig. 4. Useful temperature range of working fluids for low temperature heat pipe applications.

Table 2  
Materials compatibility [12,14–16].

	Fluid	Casing Materials Compatibility					
		Metals				Elastomers	Polymers
		Aluminium	Copper	Stainless Steel	Ferritic Steels	Silicon	PTFE, PCTFE, PVDF, PA, PP
Cryogenic Applications	Helium (He)	✓	✓	✓	✓	✓	PCTFE, PVDF, PA
	Hydrogen (H)	✓	✓	✓	✓		✓
	Neon (Ne)	✓	✓	✓	✓		
	Nitrogen (N <sub>2</sub> )	✓	✓	✓	✓	✓	✓
	Argon (Ar)	✓	✓	✓	✓	✓	✓
	Oxygen (O <sub>2</sub> )	✓	✓	✓	corrosive in presence of moisture	✓	✓
	Methane (CH <sub>4</sub> )	✓	✓	✓	✓		PTFE, PVDF
	Krypton (Kr)	✓	✓	✓	✓		
	Carbontetrafluoride (CF <sub>4</sub> )	✓	✓	✓	✓		
	Xenon (Xe)	✓	✓	✓	✓		
Low Temperature Applications	Ethane (C <sub>2</sub> H <sub>6</sub> )	✓	✓	✓	✓		PTFE, PVDF
	Freon R22			✓			PTFE
	Freon R410a			✓			
	Propane (C <sub>3</sub> H <sub>8</sub> )		✓	✓	✓		✓
	Ammonia (NH <sub>3</sub> )	✓	corrosive in presence of moisture	✓	✓	✓	✓
	Freon R134a			✓			
	Freon R21	✓	✓	✓	✓		PTFE, PVDF
	Freon R11	✓		✓	✓		PTFE
	Pentane (C <sub>5</sub> H <sub>12</sub> )	acceptable					✓
	Freon R113		✓	✓	✓		PTFE, PVDF
	Acetone (C <sub>3</sub> H <sub>6</sub> O)	acceptable	✓	✓	✓		PTFE
	Methanol (CH <sub>3</sub> OH)		✓	✓	✓	✓	✓
	Ethanol (C <sub>2</sub> H <sub>6</sub> O)	acceptable	acceptable	✓	acceptable	acceptable	✓
	Heptane (C <sub>7</sub> H <sub>16</sub> )	✓	✓	✓	✓		PTFE, PVDF
	Toluene (C <sub>6</sub> H <sub>5</sub> -CH <sub>3</sub> )	✓	✓	✓	✓		✓

conducted in the literature, both theoretically and experimentally.

### 2.3. Applications

#### 2.3.1. Cryogenic oscillating heat pipes

Oscillating heat pipes (OHPs) operate on the principle of pressure and temperature changes occurring during the phase change of the working fluid, which creates a pulsating motion of liquid slug and vapour bubbles between the evaporator and the condenser. The advantage of OHPs is that the liquid and vapour flow is conducted in the same direction, without the need of a wick structure.

The OHP consists of a series of bundles in a serpentine configuration, with the ends jointed to the inlet (Fig. 5).

In general, the principle of OHPs is that the tube diameter should be small enough to allow the propagation of flow oscillations as shown by formula [21,23,34,35]:

$$d \leq 2 \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \tag{1}$$

where  $d$  is the tube inner diameter,  $\sigma$  is the surface tension,  $g$  is the gravitational acceleration, and  $\rho_l$  and  $\rho_v$  are the densities of the

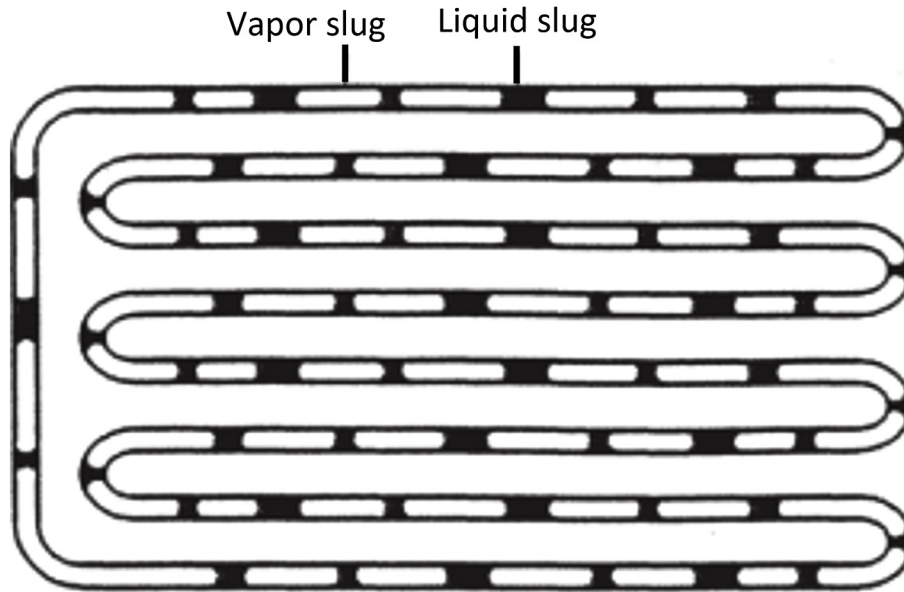


Fig. 5. Oscillating heat pipe [33].

liquid and vapour phase of the working fluid, respectively.

Oscillating heat pipes were invented in the early 90s and ongoing efforts have been made to implement the technology in the field of cryogenics. The first loop heat pipe working at liquid nitrogen temperatures (Cryogenic OHP) was presented in 1991, and Chandratilleke et al. [30] demonstrated in 1998 that loop heat pipes can be made to function at any cryogenic temperature, right down to 4 K ( $-269.15\text{ }^{\circ}\text{C}$ ).

Since then, a substantial amount of experimental studies has been conducted for OHP systems operating under room temperature, but research on cryogenic OHPs is highly limited. Parameters such as the internal diameter, the number of turns, the working fluid, the filling ratio, the heating method, the length ratio of heating to cooling section and the inclination angle of the system have been investigated by many researchers to determine their effect on the thermal performance of OHPs [34,36–43].

So far, successfully operated OHPs using hydrogen, neon or nitrogen have managed to achieve thermal conductivities of 500–3000 W/m-K, 1000–8000 W/m-K and 10,000–18,000 W/m-K, respectively [44,45]. The number of turns and the filling ratio of the working fluid seem to have a great influence in the thermal performance of OHPs [18,43–45].

The latest development of the technology is the addition of nano-particles or micro-particles into the base fluid, which seems to increase the heat transport capabilities of the system. This heat transfer enhancement derives from the oscillating motion of the particles, rather than their thermal conductivity [39,46–49].

### 2.3.2. Cryogenic loop heat pipes

The high heat transfer capacity, the ability to operate at any orientation, the ability to remove heat from several spatially separated sources, the distinct liquid/vapour transportation lines, but most importantly the controllability of loop heat pipes (LHPs) distinguish them as attractive two-phase heat transfer devices.

The configuration of LHPs is a closed circuit in which the vapour and liquid flow in different channels, and in addition to the evaporator and the condenser of the system. The system features a compensation chamber which regulates the redistribution of the liquid, as shown in Fig. 6.

During the operation of a LHP system part of the condenser is

filled with vapour, which transmits the heat output, and the remainder part is filled with liquid. At the same time, the compensation chamber is partially filled with liquid and saturated vapour, which allows the volumetric proportion to change according to the heat input. At the start of the LHP operation, as the heat input increases, the mass flow rate is increased and thus more liquid is pushed to the compensation chamber. As the process continues the amount of vapour increases, which decreases the sub-cooling of the returned condensate. In the last case, when the condenser is fully utilised and the liquid displaced is completely located in the compensation chamber, the LHP will operate at constant conductance.

The only difference of an ambient and a cryogenic LHP systems is that the latter has to involve a pressure reduction reservoir for safe system handling, as the filling pressure at room temperature may become dramatically large (typically in the range of 20–80 MPa) if no pressure reduction chamber is used [29].

To ensure the optimum performance of a cryogenic LHP (CLHP) system, the working fluid inventory has to occupy the compensation chamber at a proper level. However, for a given reservoir volume, the working fluid inventory imposes a limitation on the heat transfer capability of a CLHP when the inventory is less or greater than the optimal value, as the operating temperature and pressure will increase very quickly resulting in the reduction of surface tension and capillary pressure. Furthermore, other difficulties with CLHPs are that in order to start up a CLHP the working fluid must be first cooled below its critical temperature (i.e. nitrogen to about 126 K ( $-147.15\text{ }^{\circ}\text{C}$ )), until it condenses and saturates the evaporator wick [28].

Pereira et al. [50] tested three different cryogenic working fluids in a CLHP and achieved heat transfer rates of 20, 25 and 30 W, using argon, krypton and propane, respectively.

### 2.3.3. Cryogenic thermosyphons

The thermosyphon is a gravity-assisted heat pipe, in which the condensate returns to the evaporator driven by gravitational forces as the evaporator and the condenser are positioned with an inclination angle between them. The highest performance of the thermosyphons is achieved when they are oriented vertically, as the distance between their top and bottom is sufficiently large to set up

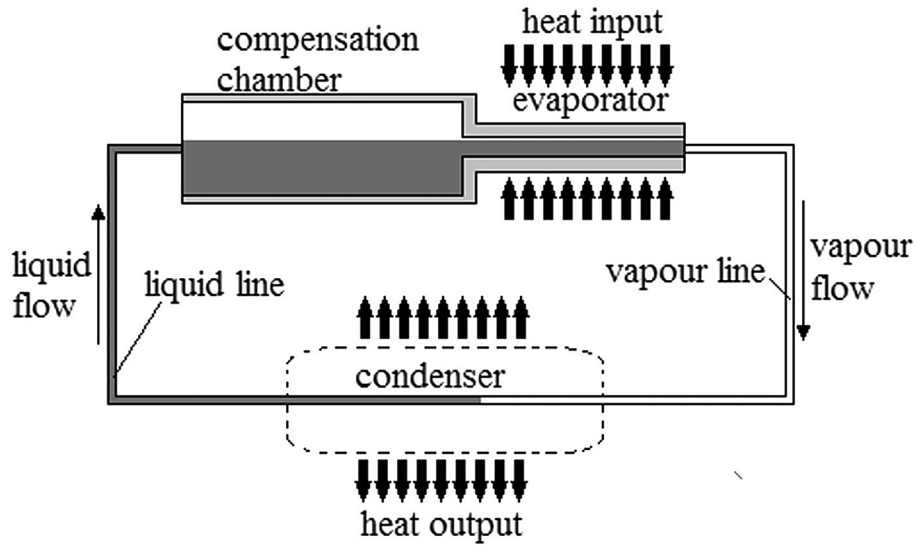


Fig. 6. Loop heat pipe [3].

the necessary natural convection flow (Fig. 7).

The research work on cryogenic thermosyphons is quite limited compared to other categories of low and ultra-low applications heat pipes.

Many researchers have focused their studies on identifying the heat transfer characteristics of cryogenic thermosyphons. The most popular apparatuses are copper as the casing materials and nitrogen, helium or argon as the working fluids. The temperatures achieved with these kind of systems were between 4 and 145 K ( $\approx -270$  to  $-130$  °C) [1,13,60,65,66]. *Bolozdynya et al.* [7] investigated the heat transfer capabilities of a cryogenic copper thermosyphon filled with nitrogen as the working fluid for a filling ratio (FR) of 3.2% and 6.5%. To provide the cooling effect, the condenser of the system was immersed into a free boiling liquid nitrogen pool. The system operated between the temperatures of 80–120 K ( $\approx -193$  to  $-153$  °C), while its heat transfer limit was 100 W. *Felder et al.* [57] charged helium into a neon thermosyphon to achieve more stable evaporator temperatures in the range of 24.6–44.4 K ( $\approx -248.55$  to  $-228.75$  °C). *Long and Zhang* [16] investigated the heat transfer performance of a helium cryogenic thermosyphon and the effect of the FR on the cooling down profile. They concluded that the cooling down process can be accelerated considerably if supercritical helium is used, with 1% FR [17].

Other researchers have focused their interest in expanding the operational temperature range of the cryogenic thermosyphons in order to accelerate the cooling process from room temperature to ultra-low temperatures. So far, two different approaches have been developed in that direction; the use of different fluids in separate thermosyphons and their structural combination [54–56], or the use of a single thermosyphon filled with a mixture of different working fluids [52,53,57–59]. The only consideration related to the first method is in limited space applications, where complex structures have to be compact [52]. In the technique of the binary working fluid mixture, concerns have been raised regarding the production of non-condensable gases in the working fluid mixture, the solidification of the working fluids, the operation near critical state and the fact that the operational temperatures of the working fluids have to overlap [60–62].

#### 2.3.4. Sorption heat pipes

Sorption heat pipes are a relatively new development in the field, which combine the advantages of the heat pipe technology

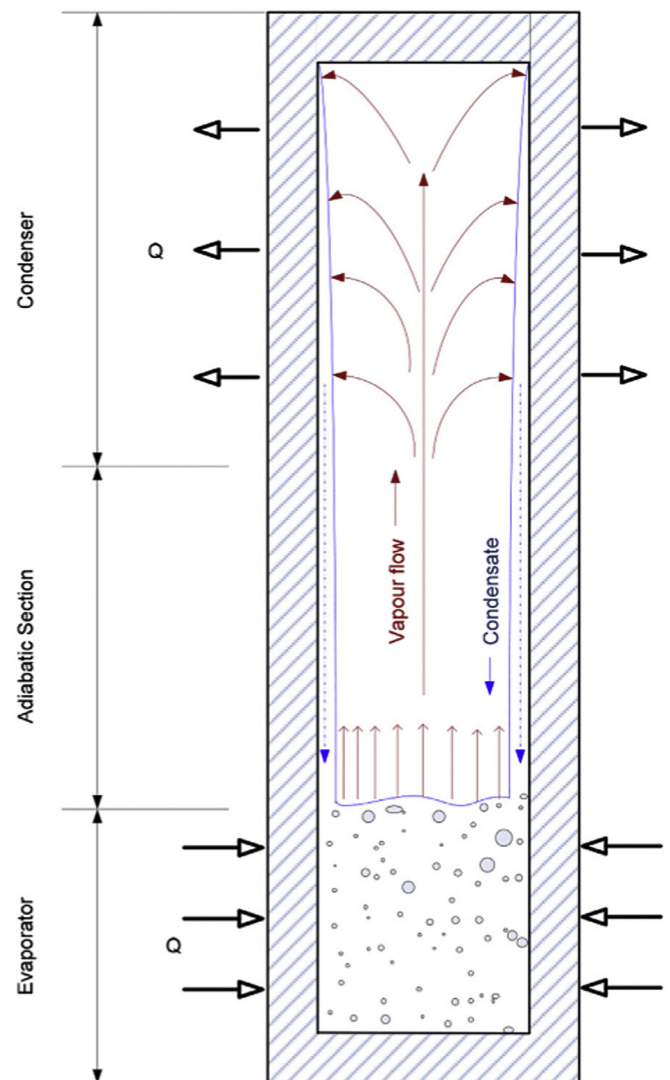


Fig. 7. Schematic of a thermosyphon [51].

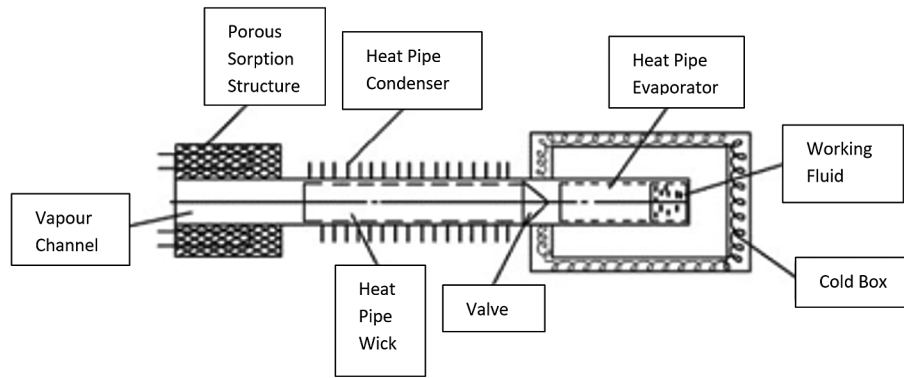


Fig. 8. Sorption heat pipe [63].

with sorption phenomena of a sorbent bed. The basic part of any sorption system is two linked vessels, one filled with adsorbent and refrigerant and the other one just with refrigerant. Sorption heat pipes use the same working fluid as sorbate and heat transfer media, while their typical configuration consists of a sorbent bed (adsorber/desorber and evaporator) at one end and a condenser and an evaporator at the other end, as shown in Fig. 8.

At the beginning of the cycle, the heat input desorbs the sorption structure; then, working fluid vapour is released from the porous media and condenses in the condenser section. The pressure difference between the hot and cold ends of the device drives part of the condensate through the valve towards the evaporator, and the remaining part of the liquid flows back to the sorbent bed driven by the capillary forces of the wick, where it enhances the heat and mass transfer phenomena. When no more heat is applied the working fluid accumulates inside the evaporator and the pressure in the sorbent bed decreases until it cools down. During the operation of the device the air inside the cold box is cooling, due to the cooling effect provided by the evaporator section of the heat pipe [64,65].

Sorption heat pipes find wide use in applications such as electronics cooling, thermal control devices for space and ground applications, and heat recovery [63–69].

### 3. High temperature

Heat pipes are utilised in high temperature applications due to their advantageous properties such as isothermal surfaces, which allow the heat pipe system to transfer high amounts of heat with a small temperature difference, high thermal conductivity, and each heat pipe working independently, therefore the failure of one heat pipe does not affect the operation of the whole system.

High temperature heat pipes are commonly employed in a variety of applications such as high temperature heat exchangers, nuclear and solar reactors, space reactors, and solar energy storage with phase change materials [70–75].

Conventional heat pipe heat exchangers (HPHE) have many advantages such as high thermal conductivity, high thermal effectiveness and minimum weight in comparison with conventional heat exchangers [76]. However, HPHE cannot be utilised in corrosive or high temperature media, and needs the consideration of the radiative heat transfer elements.

Jung and Boo [77] performed a numerical thermal modelling of a high temperature heat pipe heat exchanger under radiation. The heat pipe material was stainless steel charged with sodium. The study involved the effect of the heat transfer area and the Reynolds number ratio between the hot side and the cold side on the following parameters: inlet and outlet temperature, heat transfer

rate and effectiveness of the heat exchanger. Yoo et al. [78] previously conducted a similar experimental study which, when compared against the work of Jung and Boo [77], demonstrated that the theoretical model was validated by experimental results. To overcome the corrosion issue in high temperature waste heat recovery applications, Meisel et al. [79] presented a design of a multi-layer ceramic heat pipe used for high temperature heat pipe heat exchangers which can be employed in high corrosive and abrasive environments. A numerical model was developed to predict the axial heat transfer rate of the thermosyphon, and results agreed with the experimental data. Sodium was chosen as the working fluid and the case material was Inconel 600 clad with ceramic. A thermosyphon heat pipe and a wicked heat pipe were tested. It was observed that the performance of the heat pipe with capillary structure is better than the thermosyphon for the same conditions.

#### 3.1. Working fluid and casing considerations

To achieve the optimum performance of a heat pipe, the working fluid should be carefully selected. Alkali metals are generally used as working fluids for high temperature heat pipes [80]. The main properties that are taken into consideration for selection of the working fluid are: latent heat, melting and boiling point, vapour pressure, heat conductivity, wettability of the inner tube material wall and wick. The corrosion resistance of the tube material against the working fluid, and vapour and liquid working fluid viscosity [16,79]. Working fluids commonly used for high temperature heat pipes are listed in Table 3 [16]. A working fluid with higher surface tension is more favourable to achieve a higher capillary force, enabling a better wetting of the wick and pipe wall material; the flow resistance can then be reduced by selecting a working fluid which has a lower viscosity. However, selecting a working fluid with higher latent heat of vaporization minimises the required amount of working fluid, leading to a reduction in the pressure drop through the heat pipe [81].

However, there are some limitations for the operation of heat

Table 3  
Working fluids used in high-temperature heat pipes [16].

Working fluid	Melting point (K) at 1 atm pressure	Boiling point (K) at 1 atm pressure	Useful range (K)
Mercury	234.2	630.1	823–923
Caesium	301.6	943	723–1173
Potassium	336.4	1032	773–1273
Sodium	371	1151	873–1473
Lithium	453.7	1615	1273–2073
Silver	1234	2485	2073–2573



pipes such as continuum flow limit, sonic limit, capillary limit, entrainment limit, viscous limit and boiling limit, which need to be taken into consideration during the design process of the heat pipe [16,80,81]. One of the challenges of high temperature heat pipes is the corrosion which occurs as a result of the incompatibility between the working fluid and the shell case material. This incompatibility results in a chemical reaction, resulting in the production of non-condensable gases that dramatically affect the thermal performance of the heat pipe. The production of non-condensable gases can further accelerate the effects of corrosion, which reduces the life span of the heat pipe. The presence of non-condensable gases can be due to many factors such as inappropriate manufacturing methods. It is highly recommended to perform a high vacuum value when charging the heat pipe to prevent the presence of the oxygen gas and expand the life span of the heat pipe [82]. Compatible and incompatible materials for each working fluid are listed in Table 4 [3].

### 3.2. Applications

#### 3.2.1. Solar applications

The increase in energy demand and the fluctuating prices of oil and gas in addition to the global warming caused by CO<sub>2</sub> emissions have raised global concerns. The need for more efficient, sustainable, pollution free and renewable energy technologies is increasing. A promising and widespread solution is the use of solar energy, as it is readily available and its exploitation does not produce waste. Moreover, solar energy technologies such as PV panels and solar water heaters show a life span of 20–30 years and have low maintenance needs [83]. Solar energy can efficiently produce heat and electricity for domestic and industrial applications, by employing solar heaters (solar collectors, solar concentrators) and photovoltaic cells. However, conventional solar technologies experience some challenges which affect the performance of the systems. In flat solar collectors, the heat is absorbed by the flat plate and transferred to the water through the tubes wall. One major concern is the high hydraulic resistance of the working fluid, which requires a relatively high pump power to run system [84]. In addition, conventional solar panels cannot be applied in cold climates due to the freezing of water, which causes the rupture of collector tubes and results in mechanical failure of the system.

An efficient solution to overcome the former challenges is the use of heat pipes into conventional solar systems [85]. The implementation of heat pipes in solar collectors prevents the freezing and the backflow of the working fluid during night time. Thus, the heat pipe acts as a thermal diode which transfers the heat in only one direction [85,86]. As a result, more stable operating conditions are achieved [85]. In addition, heat pipes can increase the life expectancy of the solar system, due to the fact that it eliminates the freezing and corrosion phenomena occurring under low temperature environmental conditions [87–90]. Finally, by employing heat pipes in solar systems the hydraulic resistance of the heated fluid can be reduced by more than twice, due to the fact that the working fluid passes through the condenser part of the heat pipe only, instead of the whole structure [91].

Several types of heat pipes can be used in solar applications: thermosyphons, loop heat pipes, flat plate heat pipes and wicked heat pipes [86]. Wick structures are usually used in heat pipes to achieve a regular flow distribution of the working fluid in the evaporator.

In high temperature solar applications such as solar power plants, molten salt is used as a working fluid and as a heat storage material. Due to its high temperature freezing point, the intermittent availability of solar radiation and limited functional working hours per day, the fast response and isothermal surface of high temperature heat pipes are key features in these applications.

A novel heat pipe solar central receiver for a concentrated solar power tower was proposed by Liao and Faghri [73]. A numerical simulation was carried out to investigate the thermal performance of the heat pipe. The impact of the number of flow passes of the cooling fluid in the receiver tube and the concentrated heat flux density on the receiver efficiency and evaporator temperature were studied. The results obtained show that the proposed concept of heat pipe solar receiver can increase the daily operating duration of the receiver.

Yang et al. [92] presented and carried out an experimental study on a novel high temperature flat heat pipe receiver in a solar power plant. The heat pipe was filled with sodium as a working fluid. Thermal performance, start-up time characteristics, fast response, isothermal feature, effect of inclination angle, and effect of heat flux were investigated. It was noted that the thermal performance and start-up time are considerably influenced by inclination angle and heat input. Moreover, the flat heat pipe exhibited good temperature uniformity and excellent thermal conductivity.

Boo et al. [93] conducted an experimental study on loop heat pipes to transport thermal energy from a concentrated solar receiver to an Alkali metal thermal to electric converter (AMTEC). The heat pipe was charged with sodium at different filling ratios. It was noted that the fill ratio has an impact on thermal resistance, effective thermal conductivity, start up time and isothermal characteristics. Another solar application is the solar thermochemical reactor, which is considered as a special case of solar receiver. It utilises the concentrated solar energy to carry out a chemical reaction that produces hydrogen as a solar fuel from splitting the water [94].

Wang et al. [95] proposed a high temperature special-shaped heat pipe (HTSSHP) to be utilised in a thermochemical solar reactor. The HTSSHP is designed by coupling a flat plate heat pipe (FHP) as heat receiver and cylindrical heat pipes to transport the heat. Start-up characteristics, isothermal performance and thermal resistance were investigated experimentally. The flat heat pipe exhibited the potential of preventing the formation of hot spots on the absorber surface and the cylindrical heat pipe showed that it can improve temperature distribution in the reaction chamber. A later study conducted by Ma et al. [96] was carried out to improve the frozen start-up performance of the HTSSHP. Start-up characteristics were conducted under different inclination angles and heat fluxes. The HTSSHP exhibited successful performance at inclination angles between 0° and 45° and it was observed that start-up time is reduced with the increase of heat flux.

**Table 4**  
Compatible and incompatible materials with working fluids [16].

Working fluid	Compatible material	Incompatible material
Mercury	Stainless Steel	Molybdenum, Nickel, Tantalum, Inconel, Titanium, Niobium
Caesium	Titanium, Niobium, Stainless Steel, Nickel-based super alloys	
Sodium	Stainless Steel, Nickel, Inconel, Niobium	Titanium
Lithium	Tungsten, Tantalum, Molybdenum, Niobium	Stainless Steel, Nickel, Inconel, Titanium
Silver	Tungsten, Tantalum	Rhenium

Thermal energy storage is a significant factor in solar applications to provide a steady amount of heat energy and to expand the working period of the application. However, thermal energy storage materials have a low conductivity and the solidification/melting of these materials takes a long time. This has shown to be of great importance when employing heat pipes in thermal energy storage systems since heat pipes have high effective thermal conductivity and isothermal characteristics.

A specially configured high temperature heat pipe for solar energy storage systems was proposed by *Mahdavi et al.* [97]. Sodium was chosen as the working fluid due to its low vapour pressure at high temperatures. Heat transfer limits of the heat pipe were determined, which were caused by heat pipe geometry, working fluid, wick structure, and operational temperature. The effects of heat input, adiabatic section and thermal resistance were also investigated.

In medium temperature solar applications, many studies have been conducted on the performance of heat pipe evacuated tube collectors (ETC) [98–103] and flat solar collectors combined with heat pipes [84,91,104–106]. According to the literature, the thermal efficiency of ETC ranges between 65 and 80%, whereas the heat pipe flat solar collectors' thermal efficiency reaches up to 68% [86].

Heat pipes are also employed in photovoltaic/thermal applications (PV/T). A PV/T panel is a system which combines a conventional PV panel with heat pipes to produce electricity and thermal energy simultaneously [85,107]. The operational principle of PV panels is as follows: when the panel is subjected to solar irradiance, it absorbs the solar radiation and converts part of it into electricity and the remaining part into heat [88]. The efficiency of the panel depends on the operating temperatures and decreases with the increase of the temperature [108]. High operation temperatures reduce the PV panel's life span, due to the applied thermal stresses on the cells of the panel [109]. Water or air can be used as working fluids of the cooling system to reduce the temperatures of the PV/T panels and secure their nominal operation [83,110]. Thus, the system efficiency is enhanced, which can reduce the payback time of the installation [111].

Overall, the hybrid system of PV/T panels offers the following advantages in comparison to the generation of heat and electricity separately [112]:

- Increase of the energy produced per area unit, which leads to a reduction of the required space for the application
- Suitable for limited space applications
- Architectural uniformity of buildings
- Enhanced electrical efficiency

However, a conventional cooling cycle of air or water in the PV/T panels is not capable of maintaining uniform temperature distribution across the panel, which affects its efficiency [83,109]. This kind of system presents additional challenges in their applications as they cannot be integrated in roof installations and water cannot be used as working fluid in cold regions due to its freezing point [83,89]. PV/T panels may have a complex design but they offer key advantages [113]. The implementation of heat pipes in the system provides isothermal distribution of temperatures along the panel surface, which can be adjusted to the desired working temperatures [114]. The key characteristics of PV/T panels are the energy gain, energy efficiency, exergy efficiency and the operating temperatures. The performance of a PV/T panel can be evaluated based on its energy efficiency. The total efficiency of the system is the sum of thermal and electrical efficiencies, which are given by the following correlations based on the first law of thermodynamics as highlighted in equations (2)–(9) [115,116]:

$$\eta_{PV/T} = \frac{\int_{t1}^{t2} (A_c \dot{E}_{th} + A_{PV} \dot{E}_e)}{A_c \int_{t1}^{t2} G dt} \quad (2)$$

where:

$$\eta_{th} = \frac{\int_{t1}^{t2} A_c \dot{E}_{th}}{A_c \int_{t1}^{t2} G dt} \quad (3)$$

$$\eta_e = \frac{\int_{t1}^{t2} A_{PV} \dot{E}_e}{A_c \int_{t1}^{t2} G dt} \quad (4)$$

$$\xi = \frac{A_{PV}}{A_c} \quad (5)$$

As a result:

$$\eta_{PV/T} = \eta_{th} + \xi \eta_e \quad (6)$$

$$\eta_{th} = \frac{Q}{A_c G} \times 100 \quad (7)$$

$$\eta_e = \frac{P_{max}}{A_{PV} G} \times 100 \quad (8)$$

$$Q = \dot{m} \cdot C_p \cdot (T_{w,o} - T_{w,i}) \quad (9)$$

where  $\dot{E}_{th}$  is the thermal output power per unit collector area,  $\dot{E}_e$  is the electrical output power per unit cell area,  $\eta_{th}$  is the thermal efficiency of the collector,  $\eta_e$  is the electrical efficiency of PV cells,  $A_c$  is the collector area,  $A_{PV}$  is the PV cell area,  $G$  is the solar irradiation per area,  $P_{max}$  is the electrical energy output of PV cells,  $Q$  is the thermal energy output of the PV/T panel,  $\dot{m}$  is the mass flow rate of the cooling water,  $C_p$  is the specific heat capacity of water,  $T_{w,o}$ ,  $T_{w,i}$  are outlet and inlet water temperature, respectively, and  $\xi$  is PV cell packing factor, which is the ratio of PV panel area to the collector area as reflected in equation. Exergy demonstrates the maximum quantity of work that can be obtained in a specified environment. Exergy efficiency is the ratio of total exergy output to the total exergy input. The exergy efficiency of the system is given by the formula below, based on the second law of thermodynamics, as highlighted in equations (10)–(16) [115,116]:

$$\varepsilon_{PV/T} = \frac{\int_{t1}^{t2} (A_c \dot{E}_{Xth} + A_{PV} \dot{E}_{XPV})}{A_c \int_{t1}^{t2} G dt} \quad (10)$$

$$\varepsilon_{PV/T} = \varepsilon_{th} + \xi \varepsilon_e \quad (11)$$

$$\varepsilon_{th} = \frac{\dot{E}_{Xth}}{\dot{E}_{Xsun}} \quad (12)$$

$$\epsilon_e = \frac{\dot{E}X_{PV}}{\dot{E}X_{Sun}} \quad (13)$$

$$\dot{E}X_{th} = \dot{m} \cdot C_p \cdot \left[ (T_{w,o} - T_{w,i}) - T_a \ln \frac{T_{w,o}}{T_{w,i}} \right] \quad (14)$$

$$\dot{E}X_{PV} = \frac{P_{max}}{A_{PV}} \quad (15)$$

$$\dot{E}X_{Sun} = G \left( 1 - \frac{T_a}{T_{Sun}} \right) \quad (16)$$

where  $\epsilon_{th}$  is the thermal exergy efficiency,  $\epsilon_e$  is the electrical exergy efficiency,  $\dot{E}X_{th}$  is the thermal exergy output per unit collector area,  $\dot{E}X_{PV}$  is PV exergy output per PV cells area,  $\dot{E}X_{Sun}$  is the exergy of solar radiation per unit area,  $T_a$  is the ambient temperature (K) and  $T_{Sun}$  is the sun temperature ( $T_{Sun} = 5800$  K).

A substantial amount of research has been focused on investigating the performance of PV panels when they are combined with heat pipes, where the performance was evaluated by determining the working temperature of the heat pipe and the system. The focus of the research was to operate the PV panels at temperatures lower than 35 °C, cooling it with a heat pipe system and using the excess water in different applications. The operating temperature of the PV panels represents the temperature of the heat pipe evaporator. It should be noted that if the heat pipe does not reach a high operating temperature, the evaporator temperature will increase to reach an energy balance. The energy balance will continue until the thermal gain is equal to the heat transferred to the cooling fluid with the consideration of thermal losses. Different heat pipe PV/T designs have been presented in the literature. The designs can be categorized into two main types: cylindrical heat pipe heat exchangers and flat heat pipe heat exchangers.

Gang et al. [88] developed a novel flat plate heat pipe PV/T panel, consisting of nine copper heat pipes joined together at the back of an aluminium plate, using water as working fluid. The condenser section of the heat pipes was incorporated into a heat exchanger, as shown in Fig. 9. The thermal efficiency of this system was  $\eta_{th,PV/T} = 45.7\%$ , the electrical efficiency was  $\eta_{e,PV/T} = 10.2\%$ , the total efficiency was  $\eta_{total,PV/T} = 51.5\%$ , and the exergy efficiency was  $\epsilon_{PV/T} = 7.1\%$ . The thermal heat gain varied between 550.6 and 363.3 W/m<sup>2</sup>, and the electrical gain varied between 34.8 and 36.5 W/m<sup>2</sup>.

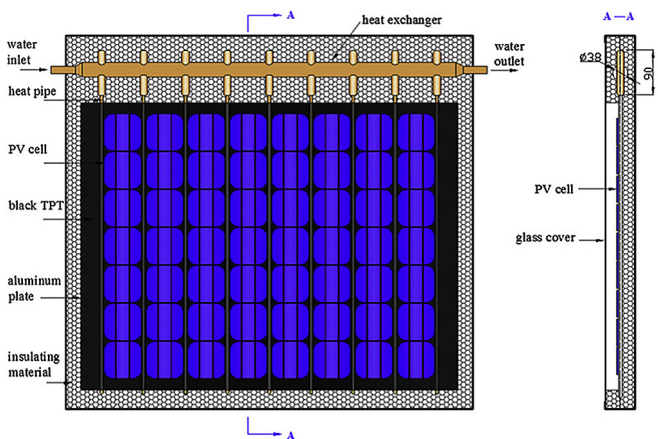


Fig. 9. HP-PV/T solar collector [88].

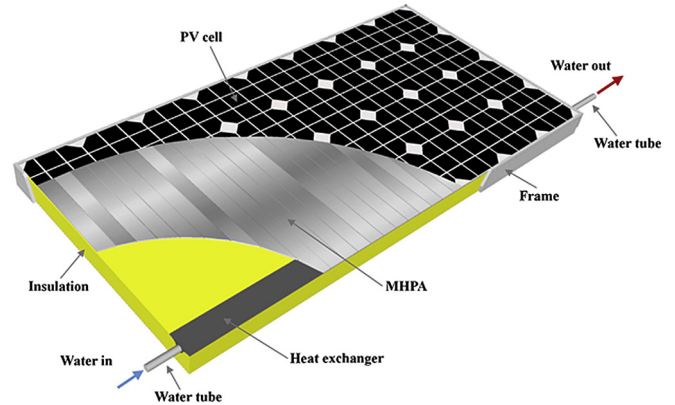


Fig. 10. Schematic of MHPA-PV/T module [89].

It should be noted that joining cylindrical heat pipes with PV panels creates the following disadvantages [89,117]:

- Increase of the thermal resistance and reduction of the contact area between the tubes and the panel, resulting in the development of non-uniform temperatures along the panel and reduction of the system efficiency
- Increase of the system design complexity, which increases the manufacturing cost

Deng et al. [89] conducted experiments with PV/T modules equipped with a micro heat pipe array (MHPA), in order to overcome the limitations of conventional heat pipes. Fig. 10 shows the construction of the modules, by which multiple parallel micro heat pipes are positioned in a flat aluminium plate and operate independently. Each heat pipe consists of many microgrooves which extend the surface area and enhance the evaporation and condensation heat transfer of the heat pipe. The thermal, electrical, and total efficiency of this investigation were respectively:  $\eta_{th,PV/T} = 19.9 - 37.8\%$ ,  $\eta_{e,PV/T} = 11.9 - 15.1\%$ ,  $\eta_{total,PV/T} = 35.6 - 50.8\%$ .

The key advantages of implementing MHPA with PV/T panels are as follows [89,118]:

- Increase of the contact area between the panel and the heat pipe, which reduces the thermal resistance of the system
- Enhanced heat transfer coefficient due to the larger heat transfer area of the heat pipe and the increased number of thin liquid films in the evaporator and condenser sections by the micro grooves
- Reduced hydraulic resistance as the cooling section consists of a plain smooth tube
- High reliability as hundreds of micro heat pipes run independently, thus in case of failure of one of the micro heat pipes the performance of system will not be affected
- Relatively low manufacturing cost, as the extrusion of aluminium is a low cost process. However, in the case of copper, the total cost increases due to the higher cost of the materials

Jouhara et al. [119,120] developed a novel flat heat pipe to be used as a building envelope material, shown in Fig. 11. The design of the panel consists of a cooling cycle in which the waste heat is transferred through the heat pipe to the cooling fluid. This novel method converts building envelope materials to energy-active components. The system absorbs heat from the ambient when there is no solar radiation, in addition to eliminating the possibility of freezing the working fluid of the heat pipe by selecting a suitable

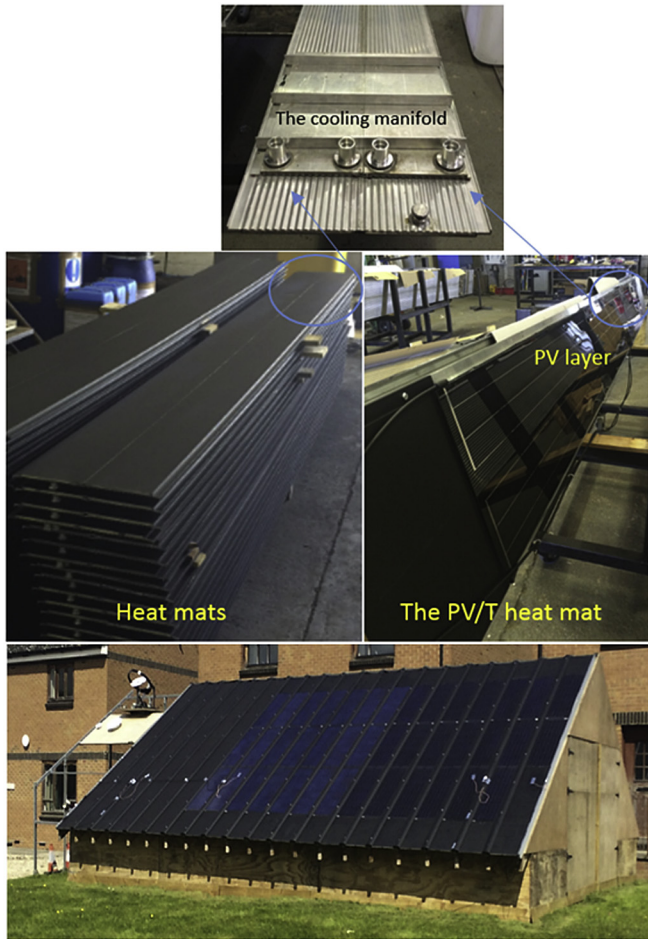


Fig. 11. PV/T heat mat module [120].

working fluid for this range of temperatures. The investigation tested a flat heat pipe with no PV and the results were compared to other flat heat pipes provided with PV panels. The reported data showed that the thermal efficiency of thermal flat heat pipe was  $\eta_{th} = 64\%$ , while it was  $\eta_{th,PV/T} = 49.4\%$  for the combined flat heat pipe with total thermal energy gain of  $2.49 \text{ kWh/m}^2$ . The electrical efficiency was  $\eta_{e,PV/T} = 7.0\%$  and the total efficiency was  $\eta_{total,PV/T} = 56.5\%$  with total electrical gain of  $0.35 \text{ kWh/m}^2$ . It was observed that cooling the PV/T panels enhanced the electrical efficiency by 15%.

Although the panel was not insulated from the top surface, the system showed a very good thermal efficiency.

Furthermore, several studies have been conducted to investigate the effect of cooling systems on the performance of PV/T panels, their operating temperatures and their electrical and thermal efficiencies [87–89,114,116,118,120–123]. According to the literature, the performance of the heat pipes is influenced by different factors such as the inlet temperature and mass flow rate of the cooling fluid, the PV cell covering factor, the spacing between heat pipes and the inclination of the heat pipes [88,114,124]. By increasing the flow rate of the cooling fluid, the efficiency and the energy gain of the PV/T panel are enhanced [88]. The increase of the cover factor results in higher electrical gain and enhanced total efficiency, while the thermal efficiency of the system decreases [88].

Hu et al. [124] studied the effect of inclination angles on wicked and wickless heat pipes. It was observed that the thermal performance of wickless heat pipes is strongly influenced by the

inclination angle, unlike the wire-mesh heat pipes. Moreover, the wickless heat pipe had a better performance when utilised with an inclination of  $20^\circ$  or more, while the wicked heat pipe should be used in inclinations up to  $20^\circ$ . The optimum performance of both types of heat pipes was at an inclination degree of  $40^\circ$ . According to the results reported in the literature [87,114,116,123,125], the thermal efficiency, electrical efficiency and exergy efficiency varied between the following ranges

$$\eta_{th} = 41.9\% \text{ to } 63.65\% \quad \eta_e = 9.4 - 15.1\%$$

$$\varepsilon_{PV/T} = 6.8\% \text{ to } 10.26\%$$

### 3.2.2. Nanoparticles

During the last decade, several investigations have been conducted regarding the viability of heat pipes charged with nanoparticles as a working fluid. The nanoparticles and the combined suspension fluid have been implemented to enhance the thermal capacity of the heat pipe. The majority of studies mainly focused on the investigation and the effects on heat transfer with a variation in nanoparticle composition.

Nanofluid heat pipes have been investigated with the effects of altering the filling ratio and the concentricity of nanoparticles. Table 5 shows the result of experiments achieved in the field of nanofluid heat pipes. The results highlighted an increase in the amount of energy transferred and a decrease of the thermal resistance compared to water-based heat pipes. The generalised results from the investigation highlight an increase of the heat transfer capability and an overall improved efficiency of the heat pipes system. However, when the concentration of nanoparticles is too high, the thermal resistance of the heat pipe rapidly increases. Ghanbarpour et al. [126] investigated the effect of an  $\text{Al}_2\text{O}_3$  nanofluid on a mesh heat pipe with a nanoparticle concentration of 5% and 10% of  $\text{Al}_2\text{O}_3$  in distilled water. For the 10% concentration of  $\text{Al}_2\text{O}_3$ , the thermal resistance of the heat pipe increased between 155% and 206%. The reason for this increase can be due to the coating made of nanoparticles. The issues associated with nanofluid coatings have been investigated by Stutz et al. [127]. The study was focused on the evaporation of nanofluids using  $\text{Fe}_2\text{O}_3$  nanoparticles. The results obtained from the experiments highlighted the coating effect of nanoparticles during the boiling phase. The heat transfer coefficient was lower compared to a system without nanoparticles due to the increase of thermal resistance. Bang and Heung Chang [128] investigated the boiling heat transfer characteristics of a fluid composed of alumina nanoparticles and water compared to a solution of water for a plain surface in a pool. They concluded that the addition of nanoparticles in pure water can cause a decrease of the pool nucleate heat transfer. On the other hand, the critical heat flux performance increased to 32%. If the critical heat flux performance is enhanced in a heat pipe, it can increase the temperature range of the heat pipe by postponing the transition boiling and the film boiling. The field of nanofluids is still in progress. Further experiments and simulations need to be done in order to quantify and validate the effectiveness of nanoparticles in heat pipes.

### 3.2.3. Thermosyphon Rankine Cycle

The Thermosyphon Rankine cycle is based on the same principle as the typical Rankine cycle which is used to generate power. The thermosyphon Rankine cycle is composed of a pipe sealed at both ends, containing a small amount of working fluid inside and a turbine to extract electrical power. The evaporator and the condenser are separated by a plate with two holes [134].

**Table 5**  
Nanofluid test results.

Nano fluid composition	Maximum thermal resistance decrease compared to deionized water based heat pipe (%)	Maximum Heat transfer capacity increase compared to deionized water based heat pipe (%)
Fly-ash/deionized water [129]	31.2%	/
Alumina/deionized water [129]	6.9%	/
Graphene and water [130]	21.6%	31.1%
Silicon Carbide and water [131]	30%	29%
Al <sub>2</sub> O <sub>3</sub> with water [126]	55%	
Magnesium Oxide with water [132]	18.1%	26%
Copper oxide with water [133]	23.83%	33%

When the temperature of the working fluid exceeds the saturation temperature in the pipe, the fluid vaporizes and the vapour then travel through a turbine and is cooled in the condenser section. The turbine is connected to a generator which will convert the rotation into an electrical signal [134]. The proposed design has been tested by *Nguyen* et al. [134]. The system was able to produce power when the condenser temperature was at 31.5 °C and the evaporator at 63 °C. The electrical power input to warm up the evaporator was 4.4Kw and the electrical output from the generator was 5.5 W. The global efficiency of the system was 0.125%, which is relatively low compared to the technical difficulties required to build the system. One of the main issues during this test was the vibrations caused by the rotation of the turbine. When the turbine reached the speed of 5000 rpm, vibration started to damage the bearing support.

*Ziapour* [135] investigated the performance of an enhanced Thermosyphon Rankine cycle using an impulse turbine. The proposed design was a loop type where the vapour and the liquid phase passages are separated (Fig. 12).

The simulations achieved by *Ziapour* [135] highlighted that the designed system had an efficiency of 2.854% (first law of efficiency) and 16.477% (second law of efficiency). The gap between the

efficiency calculated by *Nguyen* et al. [134] and the present simulation can be explained by the following issues: viscous losses of the wheel, the limited design of the blade rotor, the presence of leakage into the system, heat losses, bearing losses, leakage of vapour, temperature losses in the evaporator and condenser.

3.2.4. Nuclear applications

The actual shut down system in nuclear reactors is composed of a neutron absorber (rod assembly) [136]. The heat decay can be removed using passive safety systems or containment systems [137]. Both systems work together but each of them can be used separately. The rod assembly is also used to control the nuclear reaction within the nuclear reactor and, in case of emergency; the control rod will be dropped by gravity to stop the nuclear reaction and shutdown the reactor. However, the Fukushima and Three Miles Island accidents highlighted the limitations of this system. Indeed, the passive cooling system failed to remove the heat decay of the water contained in the reactor, which led to a fusion of the core, even after the depressurisation of the pressure vessel. A passive device that combines the functions of the current control rod assembly and the passive cooling systems could avoid such accidents in the future.

The heat pipe technology has been investigated in Refs. [138–140] as a passive heat transfer and a shutdown device for nuclear reactors. The hybrid heat pipe is used for two main functions. The first is to shut down the reactor under an accident condition, while the second is to evacuate the heat decay generated from the core after the shutdown. The hybrid heat pipe contains a neutron absorber (such as B<sub>4</sub>C) in the evaporator, which corresponds to the core of the nuclear reactor. The hybrid heat pipe must operate at high temperatures and pressure in a radioactive environment, and are located above the reactor pressure vessel. In case of emergency, the system will fall in the reactor by gravity, which

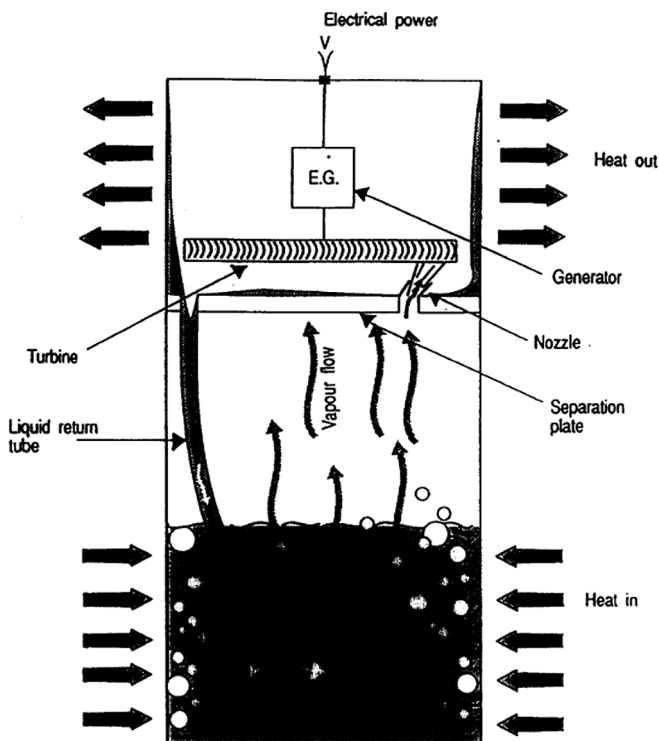


Fig. 12. Schematic of the first design of a Thermosyphon Rankine Cycle [134].

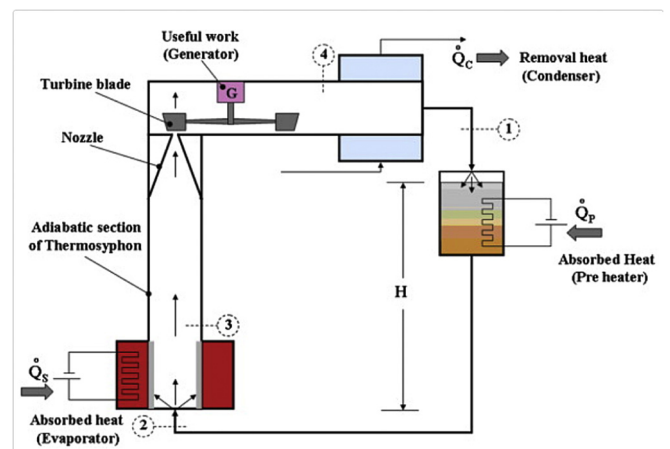


Fig. 13. Proposed design of a Thermosyphon Rankine cycle [135].

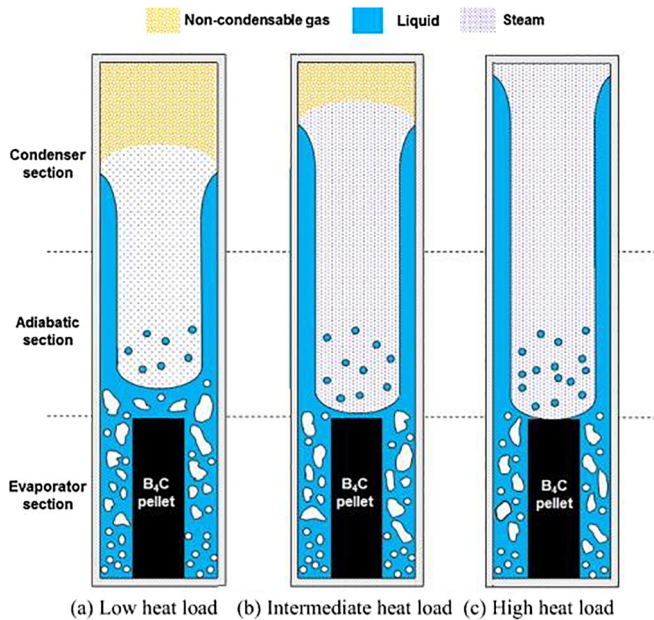


Fig. 14. Passive in-core cooling system using Hybrid Heat Pipes [208].

means that even if the energy system is shutdown, the passive cooling system can be activated. Fig. 13 shows a schematic of the proposed design (see Fig. 14).

Tests on hybrid heat pipes have been carried out by Jeong et al. [138] for advanced nuclear power plants. The results have demonstrated that the system is able to shut down the reactor and, at the same time, remove the heat decay from the nuclear pressure vessels. To validate the heat pipe analyses, Jeong et al. [138] performed a full-scale model at reactor condition. The hybrid heat pipe managed to transport 18.20Kw from the core to the outside. The time required to boil the water from the core was delayed by 13 min and the core uncover time by 5.4 h. The hybrid heat pipe has improved the cooling capacity of the passive in-core cooling system by approximately 2.5 times. Moreover, the hybrid heat pipe can be used as a passive in-core cooling system, but also as an in-core cooling system during core exploitation. Such a system could improve the safety of nuclear power stations, but it can also be used for space nuclear reactors [139]. In the space nuclear power application, the hybrid heat pipe has shown a remarkable heat transfer performance. The experiment carried out in Ref. [139] show that it managed to remove 82Kw/mK from the core.

Space power reactor heat pipe systems offer the potential of providing high power density and high reliability with the absence of solar power to meet the high power demand in space explorations and outposts [74]. By utilising heat rejection by heat pipes, failure of one heat pipe does not mean the failure of the whole heat rejection system. It also reduces the required space for cooling and the total mass of the system. Zhang et al. [81] designed and investigated a high temperature heat pipe radiator to be employed in a space power reactor. The heat pipe radiator was designed to overcome the disadvantages of the pumped loop radiator due to its isothermal characteristics, lower mass and high operational limits. The heat pipe radiator characteristics were analysed and compared with a pumped loop radiator using numerical calculations. The heat pipe was charged with potassium as the working fluid, wicked by a stainless steel wire-mesh, and the case material was Inconel.

### 3.2.5. Power generation using heat pipe thermoelectric module

The recovery of low grade waste energy is an important area to

investigate. In fact, because of the global warming and the energy price, the industrial sectors are looking for innovations to reduce energy consumption and greenhouse emissions in their processes. A number of investigations have been conducted on the use and implementation of thermoelectric modules coupled with heat pipe heat exchanger to extract and recover the heat from processes and transform it into electricity [141–143]. The thermoelectric module is a device that is able to transform heat to power. The system is based on the Peltier effect, which is the change in temperature at a junction between two semiconductors when a current passes through the junction [144]. The direction of the current determines the increase or decrease in temperature [144]. The system has the potential to generate electricity or heat depending on the input (Fig. 15).

The concept of power generation systems using heat pipes as a heat source and heat sink have been proposed and demonstrated by Remeli et al. [143]. The results obtained demonstrated the possibility of power generation using heat pipes as a heat sink between two counter-flow ducts (cold and hot air) and a thermoelectric module as an interface between two heat pipes as shown in Figs. 15 and 16.

The results show an electrical power output of 6.9 W for a heat transfer rate of 645 W. The efficiency is less than 1%, which is really poor for such a system especially because the price of a thermoelectric module is high compared to the output of this system.

Some solar applications using heat pipes coupled to a thermoelectric module to provide hot water and electricity have been investigated by Date et al. [141]. The thermoelectric module managed to produce 0.756Kw/h of electricity and the heat pipe handled to warm up a 300L tank up to 76 °C for a typical house with 5 m<sup>2</sup> of available surface. All the data were collected during peak sun hours, which is only when the system is at 100% of its solar radiation capacity. No experiment has been conducted during off-peak hours.

### 3.2.6. Ceramic industry

Ceramic components are defined as non-organic, non-metallic materials that are consolidated using heat. The solidification of ceramic-based products takes place in a high temperature kiln, usually for a prolonged duration. However, the application of high temperature heat is by definition an energy intensive process [146,147]. The energy consumption is reflected in the associated cost, and there is a clear indication that a significant percentage of the total production cost is for energy consumption [148]. Studies on energy saving and the quality of ceramic products have highlighted that the implementation of energy saving technologies is crucial in response to the worldwide energy crisis and

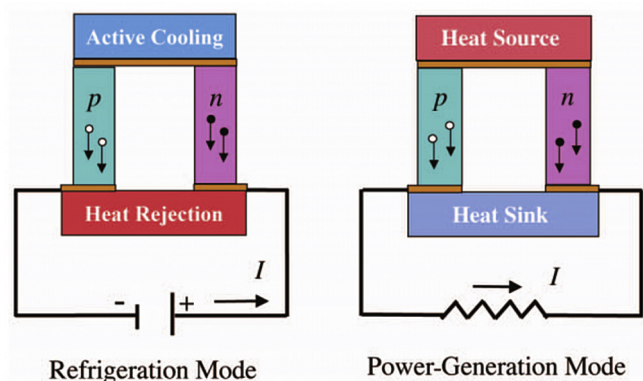


Fig. 15. Peltier thermoelectric couple [145].

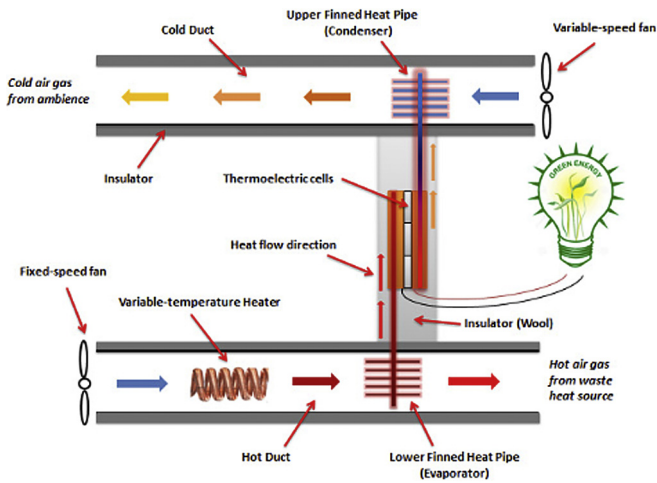


Fig. 16. Concept of power generation using heat pipe and thermoelectric module [145].

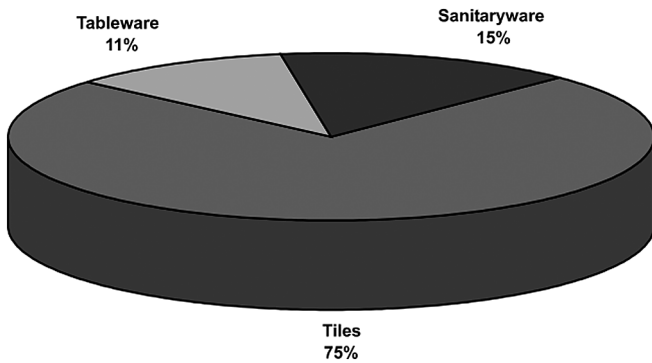


Fig. 17. European ceramics industry by energy consumption [152].

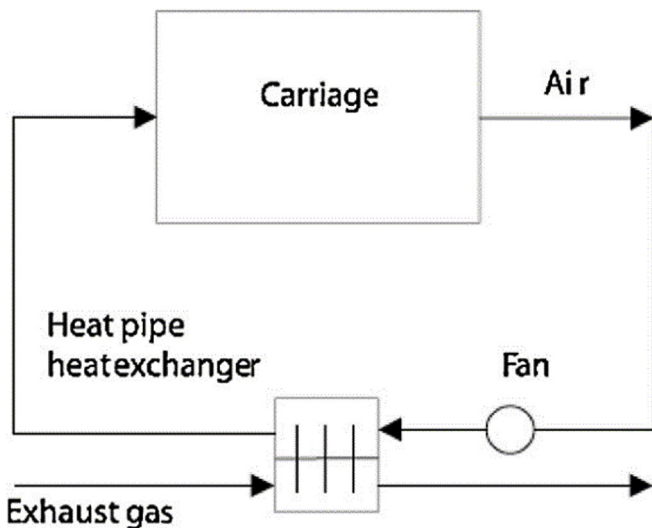


Fig. 18. Schematic of a heat pipe based waste heat recovery system.

environmental issues, but also for product quality and cost reduction [149–151].

The European ceramics sector is divided into two different sectors: “traditional ceramics” (wall and floor tiles, tableware and sanitary ware) and “advanced ceramics” (electronic ceramics,

technical ceramics, and bio ceramics) [152]. The tile ceramic industry is the largest sector within the traditional ceramics. Tile manufacture represents 75% of the total energy consumption, sanitary ware 15% and table ware 10% (Fig. 17).

A significant number of investigations have been conducted regarding the waste heat recovery from the kiln cooling stage. Those investigations have been summarised in Ref. [153].

Waste heat recovery using heat pipe based heat exchangers has been conducted in many industrial sectors but not the ceramic tile sector. *Srimuang and Amatachay* [2] have compiled a review of the applications of heat pipe heat exchangers for heat recovery in air-to-air waste heat recovery. They used three types of heat pipes; a conventional heat pipe, a two-phase thermosyphon, and oscillating heat pipes (Fig. 18). The use of heat pipes in waste heat recovery presents many advantages. The design of the heat pipe ensures there is no cross-contamination between the exhaust air and the air supply. The effectiveness of a heat pipe based heat exchanger is higher than that of a conventional heat exchanger. The heat pipe system tends to be more compact with fewer mechanical parts and minimal pressure drops. Such a system ensures a complete separation between the hot and cold flows and high reliability, with minimal need for maintenance [154].

#### 4. Thermal modelling simulations

The CFD modelling of the operation of heat pipes requires the use of a multiphase model to simulate the phenomena of boiling and condensation. One of the major difficulties in the modelling of this type of flow is the determination of the distribution of the liquid and the gas phases. The most popular numerical technique for this kind of problem is the Volume of Fluid (VOF) model, which is a surface-tracking technique designed for two or more immiscible fluids where the position of the interface between the fluids is of interest. The VOF model is based on the solution of a single set of momentum equations shared by the fluids, together with a volume fraction of each fluid in each computational cell. When a multiphase problem with mass exchange between the phases is considered, extra terms need to be applied in the mass conservation equations of both phases. Analogously, the heat of evaporation must be accounted for in the energy equation. The simulation of boiling and condensation using commercial CFD packages is possible by developing User-Defined Functions (UDFs) to consider these extra terms and linking them to the main hydrodynamic model equations. Other numerical solvers such as hybrid models, LES and DNS have been adopted in certain applications but are linked to certain restrictions with each application.

##### 4.1. Internal thermal modelling

*De Schepper et al.* [155] defined the fundamentals of modelling the interaction between homogeneous flows by stating the thermal properties of the working fluid. This allows the saturation temperature and latent heat to be defined, and will prompt a phase change once the fluid reach the desired temperature. A Eulerian–Eulerian approach was adopted in which the grid is fixed and the fluids are assumed to behave as continuous media. From the available Eulerian–Eulerian models in the literature, the VOF model was chosen. *De Schepper et al.* [156] developed a model to simulate the evaporation process of a hydrocarbon feedstock in a heat exchanger. They also used the VOF technique to simulate flow boiling including the phase change process, and proposed correlations to calculate the mass and heat transfer between the phases that were implemented in FLUENT through UDFs. The simulations were able to model the evaporation and boiling phenomena inside the convection section of a steam cracker, but the model was only

adopted for the convection section in a steam-cracking furnace and did not include the heat pipe system. *Alizadehdakhel et al.* [157] and *Fadhl et al.* [158] also considered the phase change process by implementing the appropriate source terms in the flow governing equations. These source terms, determining the mass and heat transfer between the liquid and vapour phases, have been linked to the main hydrodynamic equations of FLUENT by using UDFs. *Fadhl et al.* [159] studied the operation of a wickless heat pipe charged with two working fluids, namely R134a and R404a, and focused their study on their thermal performance during start-up and operation. The two-dimensional CFD results of *Fadhl et al.* [158,159] show that FLUENT with the VOF and UDFs can successfully model the complex two-phase flow phenomena inside the thermosyphon.

*Legierski et al.* [160] presented CFD modelling and experimental measurements of heat and mass transfer in a horizontal wickless heat pipe. They investigated the effectiveness of the heat pipe thermal conductivity in a transient state during start-up of the pipe operation and during temperature increases. The heat pipe adopted was 200 mm long with 4 mm diameter and 25 mm length for the evaporator and condenser. However, the authors did not consider the phase change from liquid phase to vapour phase in their CFD modelling, as well as condensation in the condenser section and pool boiling in the evaporator section. *Colombo and Fairweather* [161] simulated the effect of boiling flows using a Eulerian-Eulerian model, which provides more accuracy in this case due to the additional transport equations. The implementation of a complex model to a simple flow phenomenon allows the visualisation of bubble propagation, growth and interaction at the thermosyphon walls with the addition of coupled particle effects. *Alammar et al.* [162] simulated the effect of inclination ratio and fill ratio on thermosyphons in both low and high power operations. The simulation follows the work of *Noie* [163], the fundamental experimental studies surrounding fill ratio and evaporator aspect ratio using refrigerants. The study conducted by *Alammar et al.* [162] allows visualisation of increasing fill ratios at different inclination angles rather than in previously simulated vertical configurations. The study of high fill ratios allowed the visualisation of blockages, which results in a lower wall temperature. The inclination and fill ratios were incrementally increased using a series of time steps applied in a transient flow schematic. The simulation of higher fill ratio allows the observation of shock propagation at the wall, also known as water hammer. The appearance of water hammer is more prominent with a higher fill ratio as observed in the experimental work of *Negishi and Sawada* [164], which looked at the interactive influence of the inclination angle and the amount of working fluid upon the heat transfer performance of an inclined two-phase closed thermosyphon. The difference in fill ratios and working fluids highlights a difference in thermal performance [164].

*Jouhara et al.* [165] developed a three-dimensional CFD model and simulated the effect of geyser boiling, with clear observations being made about the propagation of pool boiling and the formation of vapour bubbles for both high and low power. The numerical techniques used in the geyser boiling simulation were an extension of the techniques previously developed by *Fadhl et al.* [159] to model multiphase properties of a wickless heat pipe, but now including the simulation of the condenser water jacket. The pool boiling behaviour was investigated for different working fluids, namely water and R134a. The effects of high and low power throughput on the characteristics of the geyser boiling have been investigated. The reported work focused on the flow visualisation of the two-phase flow during the operation of a wickless heat pipe. A transparent glass wickless heat pipe charged with water was used to observe and visualise the geyser boiling process.

*Kafeel and Turan* [166] modelled pulsed heat pipes and studied

the effect of different pulsed increases in heat input in the evaporator zone. They adopted a Eulerian model to simulate film condensation at the condenser zone, with a filling ratio of 30% of the evaporator zone. *Lin et al.* [167] developed a CFD model to predict the heat transfer capability of miniature oscillating heat pipes (MOHPs) using VOF and mixture models, and water as the working fluid. The effects of different heat transfer lengths and inner diameters at different heat inputs were used to analyse the heat transfer capability of MOHPs. A combination of VOF and a mixture model was used to simulate the oscillations. *Alizadehdakhel et al.* [157] reported on a two-dimensional model and experimental studies in which they investigated the effect of input heat flow and filling ratio of the working fluid on the performance of a two-phase closed thermosyphon, using water as the working fluid. *Annamalai and Ramalingam* [168] carried out an experimental investigation and CFD analysis of a wickless heat pipe using ANSYS CFX. They considered the region inside the heat pipe as a single-phase of vapour and the wick region as the liquid phase, and used distilled water as the working fluid. The predicted surface temperature along the evaporator and condenser walls and the vapour temperature inside the heat pipe were compared with the experimental data. *Xu et al.* [169] recently presented a CFD model for a thermosyphon based on the VOF, where the amount of mass transfer during the phase change process is controlled through a time relaxation parameter.

#### 4.2. External thermal simulations

The implementation of heat pipes plays a significant role in the thermal effectiveness of heat transfer systems. The implementation of heat pipe systems is highly dependent on the application and desired configuration of the heat pipes. *Jeong and Bang* [140] modelled the implementation of a hybrid heat pipe in the application of a dry storage unit within a nuclear power station. The simulations conducted compared the thermal properties of the system before and after the implementation of hybrid heat pipes. A homogeneous model was applied throughout the system. A selection of 2D simulations was produced; showing improved cooling properties associated with the implementation of a wickless heat pipe. A uniform heat distribution is evident through the systems, which contain reciprocating heat pipes. Reciprocating heat pipes have been modelled by *Chang and Lees* [170]. Reciprocating heat pipes allows them to sequentially reciprocate in line with the crank angle revolutions. The modelling of reciprocating engines requires a significant amount of UDFs as reciprocating movement models are not usually available in commercial CFD packages. External heat pipe systems have commonly been applied in waste heat recovery systems. *Ramos et al.* [171] modelled a heat pipe system in an air-to-water heat pipe based heat exchanger. The modelling of heat pipes within waste heat recovery systems is typically carried out as single pipe systems and rarely modelled in a complete heat exchanger schematic. The modelling of heat pipes in waste heat recovery implements certain assumptions to accurately produce a waste heat recovery model. The heat pipes are typically set as superconductors in the material boundary conditions, with associated boundary conditions such as thermal conductivity and adiabatic regions. The mass flow boundary condition at the inlet is assumed to be constant throughout the system. This could be slightly problematic when modelling complex geometries. The standard models used to simulate multiphase flow cannot model external flow simultaneously to the internal flow due to limitations within the available packages. With the thermal conductivity of the heat pipe being assumed as constant, the modelling of the multiphase aspect would be unnecessary for external flows.

The implementation of heat pipes in electrical systems was



originally developed by NASA for cooling small electrical devices, such as computers, to replace other components such as heat sinks and fans. *Choi et al.* [172] modelled a heat pipe within a CPU system acting as a heat sink. By implementing the Discrete Phase Model (DPM), the model can accurately simulate the recirculation zones and the cooling heat sink effect around the CPU. By modelling a cool sink through a Lagrangian based method, the individual particle trajectories can be traced, allowing for an accurate visualisation. *Calautit et al.* [173] modelled thermosyphons in a wind tower system; the modelling of micro and macroclimates surrounding the heat pipes was carried out by using a realizable  $k-\epsilon$  turbulence model. The modelling of natural convection does not require the complex process of multiphase modelling due to the assumptions of constant heat distribution around the thermosyphon. The wind tower system was simulated under steady state conditions, but the implementation of a transient flow regime would be necessary to represent the performance of the wind tower with the addition of thermosyphons. *Calautit and Hughes* [174] modelled the implementation of thermosyphons in a wind catcher application for natural ventilation applications. Similarly to previous studies, the modelling of the wind catchers was conducted under steady state conditions and contained both micro and macro climate conditions. The implementation of modelling techniques such as DPM would provide a more accurate simulation, allowing individual tracking data to be generated for each particle. Although DPM is a computationally intensive model, the individual tracking properties of particles can highlight potential improvements to the system to make it more effective.

### 4.3. Applications

The application of heat pipes allows a wide combination of modelling techniques to model factors such as granular structures and pulsations. The availability of commercial CFD packages depends on the applicability and implementation of the mathematical model.

#### 4.3.1. Non-Newtonian fluids and nanofluids

Nanofluids are commonly used in heat transfer applications due to their heat transfer enhancement properties [175]. Similar to the homogeneous flow modelling associated with conventional wickless heat pipes, the implementation of nanofluid-based heat transfer requires a model that can consider particle structures, such as a Eulerian-Granular Model. Recent advancements in the modelling of non-Newtonian nanofluids allows the fluid properties to be modelled like a Newtonian fluid, allowing similar properties whilst containing solid particles [168,169]. The modelling of nanofluids is a complex procedure due to the phase change experienced whilst modelling a nanofluid in addition to solid metal particles. Commonly, the modelling of nanofluids is primarily based on the idea that the nanofluid is acting as a single phase model. *Sidik et al.* [176] adopted a mixture model with the implementation of nanofluids, and followed the same assumption as any other granular flow. The assumption allows each phase to have its own velocity field and corresponding volumetric fraction, but allows the consideration of the influence of both phases. Similarly to the granular model, the mixture model allows an accurate visualisation of nanofluids in thermosyphons, but with each model there are associated limitations. *Mahdavi et al.* [177] modelled the implementation of nanofluids and the associated heat transfer characteristics for a laminar flow regime using both Lagrangian and Eulerian models. A comparison between the models was done through the use of thermal visualisation. The study was conducted through a pipe structure, but a thermosyphon has not been modelled in such fashion. The modelling of nanofluids in a heat

pipe system suggests that the heat flux is highly dependent on the properties of the solid metallic elements. The modelling of such fluids requires an approach that considers the effect of high loading and thermal properties of different metallic particles. Recent studies have experimented with the effects of high metallic particle loading in a heat pipe configuration, and the conclusions drawn from the study suggest an increase in heat flux with an increase in particle concentration.

The modelling of nanofluid-based heat pipes is highly limited due to the computational constraints and the complexities associated with particle settings within the model. The use of nanofluids in heat pipes is not limited to gravity-dependent structures, but it can also be applied through microchannels, wicked and oscillating heat pipes. As previously discussed, the modelling of oscillating heat pipes commonly needs the addition of UDFs to account for the oscillation frequency of the heat pipe. The addition of oscillations in conjunction with the modelling of thermal properties produced with nanofluids has not been simulated yet. Both nanofluids and oscillating heat pipes are relatively new technologies, with oscillating heat pipes commonly being implemented in cryogenic structures. The addition of nanofluids at low temperatures has been studied widely but is yet to be simulated.

*Liu and Li* [178] concluded the implementation of nanofluids in both oscillating, wicked and microchannels was beneficial, with observations being verified experimentally for an improved heat transport mechanism [179]. The implementation of the mixture model in a nanofluid-based heat pipe will provide an overview into the increase in thermal properties but, due to the limits in particle volume fraction, the model cannot be used in heavier particle flows, and can experience clumping and coagulant fluid properties [180]. The simulation of such fluids requires a model that allows heavy coupling between inter-particle, fluid-particle, particle-wall, and fluid-wall interactions. Models such as the Eulerian-Eulerian Granular Model allow the intermixing of fluid and particles. *Behroyan et al.* [181] modelled nanofluids through the dispersion model, as the particles in such a flow are more chaotic than represented in the granular and mixture model. The dispersion model is yet to be implemented in a thermosyphon application, but the implementation of the dispersion model in other heat transfer applications looks promising. *Salemi and Ali* [182] further builds on the work of the dispersion model with accurate results in comparison with experimental data. *Behroyan et al.* [181] and *Alawi et al.* [179] have investigated the implications of both Eulerian and Lagrangian coupled methods, but both investigations are missing the implication of nanofluids in a complete thermosyphon system. From previous observations, it is evident that both models require heavy coupling relationships to produce accurate results. The addition of  $Al_2O_3$ , CuO and  $TiO_2$  in a water suspension has not been implemented in a multiphase model to investigate the implication of nanofluids for modelling phenomena such as geyser boiling and water hammer. The modelling of nanofluids needs a significant amount of considerations before a full simulation model can be developed. Although nanofluids increase the thermal capacity, the primary function of nanofluids needs the particles to be suspended for the fluid to work effectively. The largest concern with modelling nanofluids is the modelling of adhesion on the heat pipe wall, as this in effect will increase the thermal resistance within the heat pipe and will compromise the operation. Adhesion is difficult to model due to the sticking properties of the particles and the unpredictable sticking locations. Other considerations need to be taken into account with nanofluids, which involve the effects of Brownian forces, particle size, particle shape, thermophoretic forces, etc. The forces themselves add complexities to the model that are not usually considered with similar particle flows, alongside the properties of the metallic elements. The required

considerations need a significant amount of coupling to define the flow regime within the heat pipe, and this itself is extremely complicated and computationally demanding. Although nanofluids seem like an obvious future for heat pipes, there is a significant amount of research work required until CFD modelling is fully viable.

#### 4.3.2. Solar thermal applications

The use of heat pipes in a solar thermal collector is the most common application of high temperature thermosyphons. The thermal absorption of a solar thermal collector is commonly done in a parabolic or flat heat pipe application. To further increase thermal conductivity within thermosyphon-based systems, metallic nanoparticles have been added due to their high thermal conductivity [183]. *Ghasemi and Ranjbar* [184] modelled the implementation of nanoparticles in a parabolic thermosyphon. Both water and an  $\text{Al}_2\text{O}_3$  mixture were simulated and compared. As previously modelled, the implementation of  $\text{Al}_2\text{O}_3$  had a significantly increased thermal conductivity compared to a simple water solution commonly used in water-based solar thermal collectors. Both the modelling of solar thermal collectors and a nanofluid working fluid are relatively new technologies and their combination is yet to be simulated. A high level of accurate experimental work exists around solar thermal collectors such as flat heat pipes compared to conventional water collectors, but these are yet to be simulated in a solar thermal application. Solar thermal heat pipe applications have not been simulated yet, as the heat pipe commonly adopted is a flat heat pipe. As this is a relatively new technology, simulations in the area are still very limited.

#### 4.3.3. Geothermal applications

The implementation of heat pipes geothermal applications allow the extraction of heat from a ground source to provide an alternative renewable technology [185]. The implementation of heat pumps allows the thermal system to act as a heat sink in warmer climates and a heat source in cooler months [186]. *Congedo et al.* [187] modelled three different geometric ground heat exchangers, and a series of simulations were conducted to investigate the thermal properties in both winter and summer applications. *Zhang et al.* [188] studied the thermal characteristics of a thermosyphon when implemented into a permafrost region. Typically, regions of permafrost are highly sensitive to climate change, thus changing the thermal performance of the implemented thermosyphon. Modelling in permafrost areas has only been conducted through numerical means, allowing an extended transient simulation but without identifying thaw regions. CFD models allow the simulation of the same transient conditions, but will identify thaw zones and areas of sub-soil pool formations. *Mu et al.* [189] implemented a heat pipe system within permafrost regions to prevent thawing. The investigation has only been conducted through theoretical models and physical experimentation. The CFD modelling based around thawing and a heat pipe is complex as there are no fundamental models to accurately model thawing whilst simultaneously modelling a cooling system. Both phenomena have been physically experimented but have not been simulated through a CFD model. The lack of simulation can be due to a number of factors such as commercial model constraints ranging from the lack of modelling tools to simulation time. Typically with permafrost modelling, the simulation itself requires a long simulation time to effectively model all the seasons. The simulation time needed can range from time scales reflecting the effect of years to decades. Simulations that require years face multiple issues ranging from old data obtained due to an ever changing environment to the physical storage of the simulation data.

An alternative geothermal application has been used in the

renewable energy sector. *Xu et al.* [190] proposed a simplified heat transfer model between a hydro-based heat exchanger system and fluid flow influenced solid rock fractures. Typically, the modelling of heat transfer between hot dry rock formations and thermosyphons needs the consideration of fractures within the rock formation, to identify possible water streams. Currently, the simulation of the propagation of cracks through formations remains a complex problem due to the significant number of variables and instabilities. The simplified model derives the production of potential cracks by using the conductivity of rock structures and the related properties of water. The model itself is relatively new, with the main issue being the prediction of cracks within structures. The identification and propagation of rocks can be done but the formation of cracks can prove to be problematic to the system. The prediction of cracks itself can be difficult and requires the integration of both FEA and CFD systems to model the crack and the flow profile. The biggest limitation in the proposed model is the prediction of when and where a crack will occur, especially because of the unpredictable nature of rock fractures. The addition of heat pipes in the system is an effective utilisation of the technology, due to the flexibility of the system, but the major difficulty in the system is the prediction of crack formation.

#### 4.3.4. Applications within the automotive industry

The implementation of heat pipes has an increasing application with hybrid vehicles, in particular the addition of flexible heat pipes in a battery cooling unit. The research around flexible heat pipes is highly noted within computer cooling technologies. The hybrid vehicle technology faces many issues regarding heat pipes, with the main concern surrounding the difficulties to reach the thermal requirements under different operation conditions. From a modelling perspective, simulations of heat pipe based heat sinks have been applied in the computer technology industry, but not in the hybrid vehicle industry. *Liu et al.* [191] simulated a flexible heat pipe under transient conditions with respect to the phase change process occurring within the heat pipe and suggested a design segmented system which is relatively successful, but the design itself seems problematic. Similarly to the designs observed in the computer cooling industry, the addition of more complex pipes and wick structures could significantly improve the operation. Complex heat pipes used for cooling of a CPU have proven to be more effective, as in theory the adaption of CPU style heat pipes seems like a good idea but the scalability of such a technology is the main limiting factor in conjunction with other variables such load conditions. The capacity of the battery under different load conditions with regards to the applicability is dependent on the application and usage of the battery unit. The development of hybrid systems using heat pipes using a flexible geometry, in conjunction with other technologies such as oscillations, could prove to be effective under multiple load conditions. *Qu et al.* [192], investigated the effectiveness of an oscillating pipe based thermal management system used within hybrid cars. Unlike traditional heat pipes, the proposed heat pipe was composed of a fluororubber compound with copper micro-grooves. From previous studies, the simulation of copper micro-grooves is well noted for their notorious capabilities in heat transfer performance. When added to an oscillating pipe, it is inevitable to experience an increase in performance. The physical modelling of flexible structures is the main issue in this type of application. As stated in the study, there are a number of variables that affect the performance of the heat pipe such as geometry deformation. A number of commercial codes exist to conduct both mechanical and fluid simulations simultaneously, but the oscillating functions add another level of complexity. The study itself has not been conducted with a CFD package, but possible hybrid systems exist with a substantial amount of research being

conducted into the accurate modelling of oscillating pipes and PCM in a range of applications. Greco et al. [193] numerically investigated the addition of heat pipes in a lithium ion based battery system. The system contains a lithium ion battery sandwiched between heat pipes acting as a cooling system. The simulations used a transient model to identify the cooling effects and improved performance of the system. The battery-heat pipe combination has also been observed through an electric vehicle perspective. Liu et al. [194] modelled a heat pipe in a hybrid vehicle system. A thermal model was implemented to simulate the heat generation and to allow the representation of both forced and natural convection. The technology around hybrid vehicles and effective battery units is relatively new. A significant amount of experimental work is being conducted on such systems, but with minimal CFD simulations. The simulation of such technology proves to be difficult under multiple load conditions and flexible oscillating heat pipes.

Research has been conducted on the addition of Phase Change Materials (PCM), with promising results to improve the efficiency of the heat sink. The study conducted by Zhao et al. [195] added PCM modules to the heat pipe structure, but similarly to the majority of studies conducted within this sector, is purely experimental. There is an alarming lack of CFD simulations regarding heat pipe based battery cooling units; this is evident in the lack of specialised commercial codes to accurately simulate such systems. Typically, the modelling of heat pipes and PCM currently requires a substantial amount of UDFs to describe the basic fluid and structural behaviour. The computational modelling surrounding this specific application faces a number of difficulties ranging from the lack of commercial codes to the accurate modelling of new technologies. Simulations can still be conducted by using open source software, but this is highly dependent on the programming knowledge of the user.

The addition of heat pipe technology is not limited to applications within battery units. Chang and Lees [170] implemented reciprocating thermosyphons into a jet entry flow regime. The application of reciprocating heat pipes allows the synchronised rotation of coolant cycles with the revolutions of the crankshaft. The results showed the effect of heat pulsation and the thermal implications at different crank angles and expansions of the jet. The modelling of reciprocating heat pipes is similar to that of oscillating and pulsating heat pipes. The modelling of reciprocating heat pipes is commonly defined by the crank angle of the crankshaft, and a UDF is necessary to define the rotations. The application of CFD modelling within the automotive industry regarding heat pipes is not limited, but is merely a case of a limited amount of flexibility within available commercial codes. The main difference between both studies is the vehicle type used: Chang and Lees [170] used a common engine, a relatively older technology compared to hybrid vehicles and heat pipes. The lack of simulations within hybrid technologies compared to reciprocating engines can be due to the combination of two relatively new technologies.

#### 4.3.5. Hydride storage

The addition of heat pipes used in metal hydride (MH) hydrogen storage is commonly used in conjunction with Proton Exchange Membrane Fuel Cells (PEMFC). The purpose of a metal hydride storage tank is to supply the PEMFC with hydrogen. The addition of heat pipes has been proposed to transfer heat from the fuel cell to the metal hydride. The process in which to separate the metallic elements from hydrogen requires an efficient exothermic-endothermic reaction. The implementation of hydrogen fuel cells has a high potential due to their high efficiencies and low emissions, making them a prime alternative in a number of applications. The research behind hydrogen fuel cells is growing but faces many issues such as pressurisation and related safety issues. Fuel cells can

be applied to a range of temperatures and densities. There is a large number of studies regarding the viability of heat pipes and the subsequent effects on disassociation. The addition of heat pipes has been widely experimentally investigated with a range of locations, sintered wicks and inclination angles to determine the optimum charging and discharging. Although there are a number of PEMFC studies regarding heat pipes, very few deal with CFD modelling. Tetuko et al. [196] highlighted the inaccuracies with numerically modelling PEMFC and metal hydrides alongside heat pipes; this study is one of many which validates the improved operation of the system with heat pipes. Unlike many other studies, Tetuko et al. [196] conducted the study in MATLAB compared to Liu et al. [197] who simulated the role of heat pipes and the effect of hydrogen charging rates. Both studies show good agreement with the addition of heat pipe for an improved disassociation, but the lack of modelling can be due to a number of reasons. Both technologies for heat pipes and PEMFC fuel cells are relatively new; although the reaction model has been available for a considerable amount of time, the aspect of disassociation is a complex process to model. Apart from the disassociation, further considerations need to be accounted for such as ideal gas laws, wick density properties, reaction equilibria, etc. The main issue with assumptions is the compromise between accuracy and the lack of commercial models. The majority of the simulation issues are primarily based around the reaction model with respect to the multiphase model. The influence of a multiphase system needs to be compromised in order to fully simulate the disassociation model within the reaction. Similarly to a multiphase model, there is only a limited amount of problems which the reaction model can simulate without the implementation of a UDF. The majority of investigations using the reaction model have implemented a UDF to describe the reaction of the disassociation with respect to the activation energy. Chung et al. [198] modelled heat pipes in a metal hydride hydrogen storage tank to reduce the dry-out rate in heat pipes. The implementation of a UDF allowed the definition of velocity, temperature distribution and hydrogen content in the storage unit, as well as the addition of a temperature-dependent viscosity to be modelled for the hydrogen element of the simulation. The simulations consisted of three separate geometries to investigate dry-out properties. The dry-out properties in heat pipes have been investigated in a generalised application but the investigation within PEMFC cells has not been investigated. The added complexity of the hydrogen disassociation plays a significant role in the dry out simulation and progression of PEMFC. The modelling of the dry-out properties allows further simulations of the influence of the fill ratio, in order to find the optimum performance and optimum charging rates.

#### 4.3.6. Nuclear

The modelling of energy storage has been carried out in hydrogen storage applications. Jeong and Bang [140] conducted a simulation of heat pipe storage tanks in a nuclear fuel generation application. Typically, the traditional function of such storage facilities is to implement natural convection to remove decaying heat but the method poses a risk for the potential of system failures. The implementation of heat pipes in a nuclear application exists as a wick structure. The heat pipe contains a neutron absorber core enclosed in a wick structure. The modelling behind hybrid heat pipe structures includes both a homogeneous and a reactive model, due to the radioactive materials coexisting within the metal cask. The domain surrounding the wicked core exists as a homogeneous model, whereas the wicked core contains a permeable surface which allows cooling. Pavlou et al. [199] modelled the implementation of a thermosyphon system in a cold neutron source system. Simulations of such a system were carried out by modelling an external hydrogen flow by using a RANS turbulence model, but

an internal multiphase model has not been applied. The modelling of nuclear heat pipes is very limited, with the majority of simulations being focused on single pipe structures. The modelling of nuclear reactions is a complex procedure with certain limitations such as reaction rates, decay and the material properties of the radioactive material. The modelling of radioactive materials is a difficult task with many considerations and properties depending on the location of the heat pipe structure. Ideally, the addition of heat pipes in a nuclear application should be applied in a cooling application or within a condenser, as observed in experimental tests and the few available CFD simulations; as the heat pipe is a passive structure, the risk of cross-contamination is minimal. Although the utilisation of heat pipes is vast, applications within a nuclear-based system have not been modelled. This can be due to a number of factors ranging from both technology limitations and lack of modelling resources. Similarly to many applications, the modelling of radioactive waste can be difficult to define, and can be possible with a UDF, but the thermal capacity of the fluid is unknown and requires vast amounts of testing before simulations can be carried out. As expected with other applications, nuclear applications will experience similar difficulties such as compromised models, lack of commercial models and lack of available data.

## 5. Discussion

Although the application of heat pipes is beneficial to many industries, the implementation of heat pipes is difficult with many factors needing to be considered. Effects such as cost, technology development and areas of application all play a large role in the commercial application of heat pipes. The reasons why heat pipe technology is not as widespread as it would be expected are associated with several heat transport limitations and high initial investment cost. Compared to conventional heat transfer methods, such as aluminium extrusions and cast heat sinks, heat pipes can have a higher initial cost, and this is the main reason why heat pipes are not recommended for applications where cooling can be performed by simple conductive heat sinks. Furthermore, heat pipes are subject to such limitations as sonic limits that mainly affect heat pipes which use liquid metals as working fluids. When the vapour velocity inside the heat pipe reaches the speed of sound in that vapour, the core of the heat pipe experiences a shock wave, which can cause mechanical failure of the device [13]. Viscous limits mainly affect heat pipes which are operating at low temperatures. When the vapour pressure difference between the evaporator and the condenser is lower than the viscous forces, the vapour cannot flow [200]. Dry-out limits affect heat pipes where the filling ratio is very small. When the amount of working fluid inside the heat pipe is not sufficient to circulate the vapour and liquid films continuously, dry spots appear on the evaporator and it fails to operate optimally [200–202]. Boiling limits affect heat pipes with large filling ratios and high radial heat fluxes. When the transition from nucleation to film boiling occurs, a sharp decrease in the heat transfer rate also occurs which can lead to mechanical damage to the device [203]. Flooding limits affect heat pipes with large filling ratios, high axial and small radial heat fluxes. Flooding occurs when the vapour velocity is high enough to prevent the liquid film flowing back to the evaporator. Liquid drops are then carried by the vapour to the condenser, creating a dry-out phenomena at the evaporator [203–205].

Heat pipes are prone to certain problems when exposed to high temperatures. The main issue facing high temperature heat pipes is corrosion, as a result of a chemical reaction between the case material and the working fluid inside the heat pipe. Additional corrosion can occur on the external surface of the heat pipe when the working fluid is corrosive. This requires more research and

development on the shell case material of heat pipes, to further increase the applicability of heat pipes. Flat heat pipes are commonly used in electronic cooling applications; however, a specific geometry is required such as a flat surface to ensure that there is a uniform temperature distribution capable of transferring high energy rates. Flat heat pipes have the same benefits as conventional heat pipes, but the recent development of different flat heat pipe geometries allowed operations exceeding the working temperature experienced within electronic modules. The flat heat pipe is a promising technology due to the flat sections, which can be combined with different types of condensers. The combination with PV/T panels and traditional heat pipes has previously been a cumbersome task. This in effect can reduce the manufacturing cost and increase the viability of mass production. The addition of PV/T overcomes the disadvantages of conventional heat pipes, where it converts the PV panels to an isothermal surface which expands their service life by eliminating the stress caused by temperature differences on the PV surface. The flat shape of the heat pipe makes it possible to combine this energy generating unit with building structures.

The addition of solar thermochemical reactors allows the operation at higher temperatures where there is a need for a heat transfer device. Solar thermochemical generators provide uniform temperature dissipation, and eliminate hot spots on the condenser and the evaporator sections. High temperature heat pipes with flat evaporator sections offer the potential to meet these requirements. The combination of a flat evaporator with cylindrical pipes in the condenser is a promising technology, which enhances the system performance due to the fast response to the change on heat energy input and short start-up time. The utilisation of Phase Change Materials (PCM) in solar thermal energy storage, due to their high latent heat, extends the operating period and provides the system with energy at a constant temperature. However, the main challenge with PCMs is the low thermal conductivity and the duration of the phase change. By employing heat pipes to transfer heat from solar radiation to the PCM during the charging period, and from the PCM during the discharge period, increases the efficiency and the performance of the system. The heat transfer area between the heat pipe and the PCM can be increased by changing the number of condenser pipes in the PCM. The addition of fins can be a consideration if the condenser pipes are smooth. Heat pipes are renowned for their quick response to changes in heat input and high thermal conductivity, meaning that the required time for melting/solidification of the PCM is significantly reduced.

Other applications of heat pipes in waste heat recovery have been identified in the ceramic industry. The characteristics of heat pipes such as high temperature working condition and low maintenance could aid waste heat recovery in the sector. The utilisation and implementation of heat pipes could reduce the process cost by reducing the overall energy consumption. The addition of heat pipes in such a high temperature environment could be problematic, as the shape of the heat pipe must be functional but not compromise the cooling of the product. Heat pipes can also be applied in the waste heat recovery industry in the form of thermosyphon Rankine cycle systems. The thermosyphon Rankine cycle shows some possibility of power generation using heat recovery and heat extraction. However, the efficiency of such a complex system is beneath expectations. The thermosyphon Rankine cycle has an efficiency of 2.85%–16.47%, but when a basic Rankine cycle system is used the efficiency in industrial power generation is 41.4% without superheat and reheat or supercritical pressure [206]. Consequently, the system is not able to produce enough power output to be viable for industrial use. Similarly, a thermo-electric module can be implemented in a waste heat recovery section. The proposed concepts have some benefits such as the potential to

convert heat to power with a small system, but the efficiency is relatively low compared to other heat recovery systems (Organic Rankine Cycle, Combined Heat and Power units). From a financial viewpoint, the thermoelectric module is expensive for output efficiency compared to other systems. When considering the implementation in large scale operations, the payback is too large to make the investment viable. There are many iterations and combinations of waste heat recovery modules containing heat pipes, but commonly the basic principle of complex geometry heat pipes proves to be the most effective.

The most recent development of heat pipes has been the application within the nuclear sector. Hybrid heat pipes are used to cool down nuclear reactors and increase the control of the system. One of the main advantages is that there is no cross-contamination between the radioactive fluid and the cooling fluid, which can only occur if the heat pipe is broken or there is a gap within the closed system. The utilisation of heat pipes in a nuclear application improves the heat transfer coefficient, which is higher than in conventional heat exchanger systems. The major limitation factors are the financial consideration to manufacture such a system in a large scale. The heat pipe manufacturing technology has been improved in the last five years. A new manufacturing technology has been developed to reduce the production cost and allow the development of the heat pipe technology in many industrial sectors [207]. Moreover, the heat pipe technology could be adopted in many different applications for the nuclear application where the need to prevent contamination is required.

Although the industrial applications of heat pipes are ever growing, the validation of the systems remains an issue. The CFD modelling of heat pipes is riddled with compromises and inaccuracies, with the majority of simulations needing the implementation of UDFs to accurately simulate the system. Both interior multiphase modelling and exterior modelling contain issues which can affect the accuracy of the system. Many commercial models contain multiphase models but do not account for the condensation-evaporative process; therefore, UDFs need to be implemented to account for such a system. The main issue with modelling with UDFs is the skills needed to develop such a function, as typically the function requires knowledge of C++. Alongside the skills needed to develop the UDFs, the functions require complex codes which are sensitive to errors. An alternative to commercial codes such as Fluent are open source codes such as OpenFOAM. The utilisation of open source codes holds the advantage of creating bespoke software, but needs a substantial amount of coding to set up the program. Research into multiphase modelling using open source software is not widespread at the moment, and this can be due to the strenuous task of coding with the consideration of the multiphase model. As there is no fundamental model in popular commercial CFD packages such as Fluent to cope with evaporation and condensation, there is a question mark on the future of CFD modelling for heat pipes. The turbulence models available are highly functional and can mimic the flow profile within the heat pipe, but the lack of advancements with multiphase modelling could push research into open source software. Although the implementation and creation of open source software is difficult and cumbersome, this will allow the user to create bespoke software just for multiphase modelling. If certain advancements such as evaporation and condensation were integrated with minimal need for UDFs the modelling advancements within heat pipes would be greater, and will allow an increase number of research into the applicability of heat pipes within different industries.

Although it is commonly said that the future of heat pipes resides within the application of nanofluids, commercial modelling tools around nanofluids are very rare. The majority of nanofluid modelling has been conducted using a Eulerian-Eulerian granular

model, in conjunction with UDFs. In other applications, the modelling of nanofluids has been commonly dealt with as a single phase approach, but the same considerations cannot be used within heat pipes. The evaporation and condensation processes can pose some issues with the modelling of nanofluids in heat pipes. The basic principle of nanofluids during operation is the suspension of metallic particles. When applied to a condensation-evaporation application, nanofluids can adhere to the heat pipe walls due to the lack of suspension fluid. The adhesion of particles on a heat pipe wall will effectively increase the thermal resistance within the heat pipe and compromise the system performance. Alongside the issue of adhesion, a large number of considerations need to be taken into account such as the effect of Brownian forces, particle geometry, conductivity, thermophoretic forces. All these considerations increase the complexity of the model. Commonly in particle modelling, the effects of Brownian forces, particle geometry and thermophoretic forces are generally neglected, but they play a key role in the performance of heat pipes. These considerations would need to be defined in a UDF, with the coupling method requiring increased complexity. Typically with particle modelling, it is ideal to use a one-way coupling defining the interaction between the fluid and the particles. With the modelling of nanofluids, the fluid itself requires a heavy amount of coupling such as a 4-way coupling to define the interaction between the fluid-particle, particle-particle and all viscous forces. The issues regarding the modelling of such a system are evident in the lack of literature in comparison to experimental data. The experimental data shows that the implementations of nanofluids have a promising future, but the modelling difficulties of using CFD as a validation tool could be a main contributor in the lack of progress.

Modelling issues are also evident throughout many industries with issues in hybrid cars, in particular applications to lithium battery cooling. The addition of PCM modules appears to be a good idea but there is an obvious lack of implementation to complex geometries and wick structures that can have the same heat sink properties as PCM modules. The technology behind heat pipes in other applications such as renewable and geothermal energy seems are also attached with their own issues. Geothermal collectors require a significant amount of computing power to define the heat transfer properties and variations throughout the seasons; although time modulation is available within the Fluent software, the simulation itself is still very computationally demanding. Whilst remaining in the power sector, the addition of heat pipes for nuclear applications is possible in the condenser section. The basic operation of a heat pipe requires two working fluids, one in the condenser section and one in the evaporator section. The issue with nuclear modelling is the properties of the radioactive by-product in the evaporation section. Radioactive waste is linked to many hazardous properties, and data on such a material is minimal. The fluid properties will not be available within a commercial fluid database, and therefore a UDF will be needed to define the properties of the fluid. There is a general limitation and current issues with CFD modelling in certain applications. The amount of published work regarding heat pipes in certain applications is vast but the validation of the proposed systems in full-scale applications is still lacking.

### 5.1. Future directions

The use of heat pipe technology in heat exchange and thermal management of challenging scenarios is expanding fast due to their advantageous characteristics compared with conventional heat exchangers and temperature control systems. Advances in the design and capabilities of heat pipes have led to the development of cost-effective manufacturing techniques for both wicked and

wickless heat pipes and this, in turn, is creating new areas of implementation for heat pipe based systems. The developments of heat pipe based systems in new waste heat recovery, temperature control and thermal management applications are demonstrating relatively short Return on Investment (RoI) timescales. An economic assessment by Jouhara [197] regarding the implementation of heat pipes into ventilation processes showed a total annual energy saving of 134 MWh, with an operation payback period of one month. In addition, with advances in automation and development in material sciences, new heat pipe materials can be investigated to deal with challenging areas that have so far been out of reach for conventional solutions, particularly in dealing with high temperature and strongly contaminated flows. The addition of heat pipes in a range of temperature scales and applications are a clear indication of the potential for such a technology, but there are significant modelling issues which are hindering the performance. The lack of advancements within commercial models will result in the increase of bespoke codes created in open source software. The use of nanofluids can be considered important for the future of heat pipes, but the validity of such claims is questionable with the lack of validation. Extensive research still needs to be conducted on Newtonian fluids before progression onto other fluids.

## 6. Conclusion

The implementation of heat pipes is beneficial for multiple industries, and they can be applied to a range of operation temperatures from cryogenics to kilns. Although the range of applications is large, this also means that there is a significant amount of work to be conducted to make the system viable in every combination of temperature and application. There are obvious gaps in research for different temperatures and applications. Within the low temperature application field, many applications of low temperature heat pipes have been studied to improve their thermal capacity. The technology has migrated into other applications and although this is positive, the reality of researching all these new formats and technologies is causing a backlog of research to conduct, with obvious research gaps. Low temperature heat pipes are commonly being implemented in cryogenic applications, but could be applied in permafrost regions. The scaling of technologies is one of the main issues. The research into primarily low temperature applications should be fully validated before being transferred to other industries, and needs to be fully tested and validated through numerical simulations. The same statement applies for high temperature applications, where the most common fields are in waste heat recovery and solar power. Both industries are manipulating the heat pipe technology to create complex geometries and hybrid PV/T modules. From the gathered observations from this review paper, the addition of heat pipes has expanded into the power industry in the bid to create more efficient systems alongside the lowering of emissions to meet set pollution limits. The addition of heat pipes within the power industry is proving to be beneficial to companies but they adopt the most basic heat pipe technology. In effect, both solar and waste heat recovery technologies are highly noted in such applications and face minimal modelling issues, but the addition of nanofluids poses a large issue in high temperature applications. Although the addition of nanofluids improves the thermal capacity of the system, the particles may adhere to the wall and increase the thermal resistance over a prolonged period of time. The validation and modelling of nanofluids in high temperature applications has many complexities that need to be addressed before modelling multiphase phenomena and the associated studies such as fill ratio, inclination and geyser boiling. Potentially, nanofluids could be important but there are still issues to be understood with Newtonian fluids that need to be

validated before moving on to the experimentation and validation of heat pipes containing nanofluids.

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