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REVIEW ARTICLE

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Major applications of heat pipe and its advances coupled with sorption system: a review

Abstract Heat pipe utilizes continuous phase change process within a small temperature drop to achieve high thermal conductivity. For decades, heat pipes coupled with novel emerging technologies and methods (using nanofluids and self-rewetting fluids) have been highly appreciated, along with which a number of advances have taken place. In addition to some typical applications of thermal control and heat recovery, the heat pipe technology combined with the sorption technology could efficiently improve the heat and mass transfer performance of sorption systems for heating, cooling and cogeneration. However, almost all existing studies on this combination or integration have not concentrated on the principle of the sorption technology with acting as the heat pipe technology for continuous heat transfer. This paper presents an overview of the emerging working fluids, the major applications of heat pipe, and the advances in heat pipe type sorption system. Besides, the ongoing and perspectives of the solid sorption heat pipe are presented, expecting to serve as useful guides for further investigations and new research potentials.

Keywords heat pipe, sorption system, heat transfer, solid sorption heat pipe

1 Introduction

Since the first patent was applied in 1944 by Gaugler [1] and the independent invention by Grover in the early 1960s [2], heat pipe (HP) has received widespread attention and achieved remarkable developments. Besides simple structure, reliability, and flexibility, the HP technology is well-known as a passive heat transfer method which could achieve a high thermal conductivity performance through continuous evaporation and condensation cycle.

The conventional wick HP consists of three parts in longitudinal direction, the evaporator section, the adiabatic section, and the condenser section. For the radial direction, HP is composed of container wall, wick structure and fluid chamber. Depending on the required operating condition, different working media such as water or ammonia are charged into HP with a certain filling ratio [3,4]. Heat source or thermal energy is applied to the evaporator part and conducted through the pipe wall, the wick structure, and then to the fluid, which evaporates into the vapor. The pressure difference drives the vapor via the adiabatic part to the condenser part, and then the vapor condenses and releases its latent heat to the heat sink or ambience. Afterwards, the condensed fluid returns to the evaporator part driven by capillary pressure and completes one mass cycle continuously with consequent heat transportation [4,5]. Various parameters influence the steady and transient operations of HP, and furthermore constrain its heat transfer capacity. There are a number of operating limits for the conventional HP, including capillary, entrainment, viscous, sonic, condenser, and boiling limits.

Different from the conventional wick HP, the wickless pipe in which the evaporator part should be located below the condenser part is called two-phase closed thermosyphon (TPCT). The condensate liquid flows back to the evaporator section by gravity, rather than the capillary forces in the conventional wick HP [6–8]. When the vapor flow reaches the highest rate caused by high power input, the liquid-vapor interface near the exit of the evaporator becomes wavy and agitated, which restricts the rate of the liquid flowing back and simultaneously increases the thickness of the liquid film. The discrepancy between the liquid return and the heat input in the evaporator causes a dry-out condition of the liquid film, which is referred as counter-current flow limit of thermosyphon [7–9].

Recently, the sorption technology has attracted a lot of attention due to its large reaction heat and broad range of operating temperatures [10]. Sorption systems could

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employ environmental friendly refrigerants and utilize low-grade heat such as solar energy and industry waste heat [11,12]. A conventional solid-gas sorption system contains one sorption bed, one evaporator, and one condenser [13]. The basic particularity of a one-stage solid sorption system is the intermittent and periodical cooling and heating phases.

Interesting connections of engineering applications combined with the HPs technology have been evidenced recently. Sorption machines with HPs as heat exchangers have the merits of compactness, short time cycle, increased COP and so on [14,15]. The adsorption refrigeration systems integrated with HPs are efficient to enhance the overall heat transfer performance for cooling, heating, and cogeneration [16–19]. A number of new commercial hybrid systems successfully highlight the HP's key characteristic of high effective thermal conductivity and, in turn, contribute to its widespread interest and developments.

As mentioned before, the typical solid sorption/desorption processes are not suitable for continuous heat transportation owing to its intermittent characteristics. In addition, all relevant studies on the HPs combined with sorption systems have neither concentrated on the principle of sorption with acting as the HP technology for transferring heat continuously nor considered to substitute the wick structure and working media for the conventional HP or thermosyphon. The solid sorption heat pipe (SSHP) has previously been introduced in which composite solid sorbents with the sorbates act as working pairs instead of wick and pure working fluid to transfer the heat continuously [20,21].

In this paper, following the fundamentals of the HP technology and the sorption technology, the latest developments in the working fluid of HP and its various applications are introduced. Furthermore, the advances in combination of HP and the sorption technology are reviewed. Finally, the progress and prospect of SSHP are presented to verify its feasibility for heat transfer and the potential for engineering applications.

2 Latest developments in working fluid of HP

Theoretically, HP can be used for a specific heat flux with the operation temperature in the range of the triple and critical points of a certain working fluid. Most applications of HP fall within the scope of 200 K to 550 K and the corresponding fluids commonly used are water, ammonia, and acetone. To fulfill the optimum thermal performance, the selection of working fluid is based on the desired temperature range and thermodynamic conditions. The enhancements of heat transport capacity related to the working fluid mean a very interesting alternative to meeting the growing thermal requirements [22]. In this section, two emerging technical fluids (nanofluids and self-rewetting fluids) are introduced and presented for heat transfer enhancement in almost all types of HPs.

2.1 Nanofluids used in HPs

Nanofluids are basically made of base fluid and dispersed nanoparticles with a certain volume fraction. The base fluid, like water, oil, and ethylene glycol, is known typical heat transfer fluid. The nanoparticles used include pure metals, metal oxides, and various forms of carbon [3,23]. The first investigation on nanofluid applied into HPs was published in 2003 by Chien et al. [24]. Due to the higher thermal conductivity, different nanoparticles like Al_2O_3 [25–34], CuO [35–39], and Cu [40–46] are used to form the nanofluids into various HPs to improve their heat transfer performance.

Putra et al. [25] investigated the influences of types and concentration of nanofluids on improving the thermal performance of HP. Al_2O_3-water and Al_2O_3-EG nanofluids with a concentration of 1% to 5% were used as working fluid. When the volume concentration of Al_2O_3-water nanofluid was set to 5%, the maximum thermal performance was obtained. Putra et al. [26] also examined the influence of Al_2O_3/water nanofluids on the thermal performance of loop heat pipes with biomaterial wick (Collaria). For any concentration, the application of nanofluids enhanced the thermal performance of HP as compared to distilled water. Mashaei et al. [27–29] presented a numerical study on the hydro-thermal performance of cylindrical HP using Al_2O_3/water nanofluid. It is noticed that the best thermal-hydraulic performance is obtained at a middle particle concentration level of 5% with a highest heat load of 112 W. The smaller size of nanoparticles improves the thermal-hydraulic performance of HP more effectively. Ramachandran et al. [30] investigated the thermal performance of the conventional cylindrical screen mesh HP with hybrid nanofluid of Al_2O_3 and CuO. The combination of 25% of Al_2O_3 and 75% of CuO with a volume concentration of 0.1% showed that a 44.25% reduction of thermal resistance and a maximum heat load of 250 W are reached. Sözen et al. [31] studied the alumina nanofluid which used as working fluid in a two-phase closed thermosiphon. At a heating power of 400 W and a coolant flow rate of 5 g/s, the thermal resistance was decreased by 5.2%. Ghanbarpour et al. [32] employed a modified analytical method combined with experimental studies to predict the thermal performance of cylindrical HP with Al_2O_3 nanofluid. It reveals that using nanofluid is an efficient way to reduce the entropy generation in HP due to the lower thermal resistance. Poplaski et al. [33] presented a 2-D numerical model to explore the effects of nanofluid property on the thermal conductivity and thermal resistance of HP. An optimal volume concentration of 25% vol for Al_2O_3 is obtained corresponding to the capillary limit. Senthil et al.

[34] experimentally investigated the overall heat transfer performance of HP with a volume concentration of 1% of Al_2O_3. The thermal efficiency by using Al_2O_3 nanofluid is found to be higher than that by using DI water, and with the condition of 75% charging and 30° inclination, it has a maximum thermal performance.

Various input powers, concentrations, and inclination angles of sintered wick HP with the CuO-water nanofluid were examined by Kumaresan et al. [35,36] and venkatachalapathy et al. [37]. For 1.0 wt% of CuO-DI water nanofluid at an inclination angle of 45°, a 66.1% reduction of thermal resistance and a 29.4% promotion for heat transfer coefficient were obtained compared with horizontal HP. Alizad et al. [38] utilized a comprehensive analytical model to characterize the transient response of flat-shaped HP with CuO nanofluid. It was found that a higher concentration of nanoparticles could increase the thermal performance of HP. Brahim and Jemni [39] numerically simulated the thermal performance of cylindrical-packed sphere wick HP with CuO nanofluid. The positive influence of using nanofluid was reflected on a reduction of 68% in thermal resistance with a 9% concentration as well as no significant shear stress effect with a 20% concentration level.

Kole and Dey [40] studied the improvement of thermal performance for HP in which Cu-DI water nanofluids were used. The results of thermal conductivity showed a 15% of enhancement with a 0.5 wt% of copper nanoparticles at indoor temperature. Under the condition of a heat input of 100 W with vertical location, the reduction of average wall temperature was 14°C for the evaporator. At the same ratio of nanoparticles, the thermal resistance was also decreased by 27%. Senthilkumar et al. [41] studied the thermal efficiency enhancement of HP using copper nanofluid as working fluid. The maximum thermal efficiency was obtained at a 45° inclination and a 70 W heat input, which demonstrated its performance metrics under variable conditions when compared with DI-water. Klinbun and Terdtoon [42] performed experimental study of the thermal performance of loop thermosiphon with Cu nanofluid. The results indicated that the thermal resistance decreased with the increase of concentration and a 50 ppm of copper nanofluid could improve the thermal performance effectively compared with the case of water. Riehl and Santos [43] tested an open loop pulsating heat pipe (PHP) with water-copper nanofluid. It was found that Cu nanoparticles could improve the film evaporation and the nucleation boiling at low heat loads and higher heat loads respectively. Karthikeyan et al. [44] carried out an experimental and visual study to investigate the thermal performance of the CLPHPs with Cu nanofluids. The main conclusions were that the presence of nanoparticles could enhance the heat transfer area in the evaporator section and lead to stronger temperature oscillations. A 33.3% of higher heat transfer limit was obtained as compared with DI-water. Solomon et al. [45] numerically studied the heat transfer performance of HP with Cu-water nanofluids. In addition to the enhancement in heat transfer capabilities, it was also noted that the liquid and vapor velocities in HP were 20% higher when compared that with DI-water under the same condition. Wan et al. [46] experimentally investigated the influence of Cu nanofluid on the thermal characteristics of mLHP. The results demonstrated that the evaporation heat transfer coefficient increased by 19.5% when using this nanofluid and 1.5 wt% was an optimal mass concentration which corresponded to the maximum heat transfer enhancement.

Related studies on nanofluids used in HPs are listed in Table 1.

2.2 Self-rewetting fluids applied in HPs

The concept of self-rewetting fluids was first proposed in 2004 [47]. Since then, a number of interesting and important phenomena related to self-rewetting fluids have been put forward and a number of experiments on the applications of HPs with these functional fluids have been conducted to verify influences on heat transfer improvement [48–55].

The heat transfer performance of loop heat pipe (LHP) by applying self-rewetting fluid (pentanol, butanol, and hexanol aqueous solutions) was studied by Wu [49]. It was founded that the critical heat load of LHP was 650 W with a 6% of butanol aqueous solution, prior to that of 250 W when using water as working fluid. The lowest thermal resistance with the same solution of butanol aqueous decreased by about 60% in LHP.

Senthilkumar et al. [50] also focused on thermal characteristics of water/alcohol (n-hexanol and n-heptanol) fluids charged in a HP. It was observed that the thermal resistance of the aqueous solution was nearly 70%–80% less than pure water with various heat source and inclinations.

A circular HP within pure water, 4 wt% of water/butanol and 7 wt% of water/butanol as working fluid was considered by Peyghambarzadeh et al. [51]. At maximum heat flux, a 25% of heat transfer improvement was obtained for a 7 wt% of butanol solution.

The thermal characteristics of self-rewetting fluids for gravity HPs at various inclination angles (0, 1°, 3°, 5°, 7°, and 10°) were investigated experimentally by Xin et al. [52]. It was discovered that self-rewetting fluids could significantly decrease the thermal resistance and dry-out limit at small inclination angles.

Su et al. [53] studied the self-rewetting nanofluids applied in the oscillating heat pipe (OHP) with an inner diameter of 2 mm and a length of 600 mm. It was revealed that the largest heat transfer performance occurred at the optimum constituent concentration (0.07 wt% of grapheme oxide as well as 0.7 wt% of n-butanol).

Heat transfer characteristics of microfin gravity HP using self-rewetting fluids (butyl alcohol solution with a

Table 1 Summary of different studies on nanofluids used in HPs

Ref.	Types of nanoparticles	Concentration	Base fluid	Types of heat pipes
[25]	Al_2O_3	1% to 5%	Water/EG	Cylindrical-screen mesh
[26]	Al_2O_3	1%, 3%, 5%	Water	LHP-biomaterial wick (Collaria)
[27–29]	Al_2O_3	2.5%, 5%, 7.5%	Water	Cylindrical-wick
[30]	Al_2O_3 and CuO	0.1%	Water	cylindrical-screen mesh
[31]	Al_2O_3	2%	Water	two-phase closed thermosyphon
[32]	Al_2O_3	1.3%	Water	Cylindrical-screen mesh
[33]	Al_2O_3	1% to 4%	Water	Cylindrical-wick
[34]	Al_2O_3	1%	Water	Cylindrical-wick
[35–37]	CuO	1.0%	Water	Cylindrical-screen mesh
[38]	CuO, Al_2O_3	2%, 4%, 6%, 8%	Water	Flat-shaped and disk-shaped
[39]	CuO, Al_2O_3	2%, 4%, 8%, 10%, 20%	Water	Cylindrical-packed sphere wick
[40]	Cu	0.5 wt%	Water	Cylindrical-stainless steel mesh wick
[41]	Cu	100 mg/L	Water	Cylindrical-stainless steel wrapped screen
[42]	Cu	10 ppm, 30 ppm, 50 ppm	Water	Loop thermosyphon
[43]	Cu	5%	Water	Open loop PHP
[44]	Cu	0.5 wt%	Water	Closed loop PHP
[45]	Cu	0.1 wt%	Water	Cylindrical-copper wire screen wick
[46]	Cu	1.0 wt%, 1.5 wt%, 2.0 wt%	Water	mLHP

5% of mass fraction) in both horizontal and vertical positions were investigated by Tian et al. [54]. It was demonstrated that for the horizontal location, self-rewetting fluids could significantly increase the limit of drying and decrease the thermal resistance.

Zhao et al. [55] presented experiments on thermal performances of self-rewetting fluids in OHP at filling ratios between 30% and 80%. When the heating load was 700 W, the best filling ratio was obtained (40%) with an effective thermal conductivity of 5676 $W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$. It was also indicated that large OHP with self-rewetting fluids could be utilized in large applications with longer heat transfer distances due to its larger heat density and lower thermal resistance.

Related studies on self-rewetting fluids used in HPs are listed in Table 2.

Table 2 Summary of different studies on self-rewetting fluids used in HPs

Ref.	Types of self-rewetting fluids	Types of heat pipes	Effect/remarks
[49]	Butanol/pentanol/hexanol/water	LHP with PTFE wick	A 160% increase of critical heat load and lowest thermal resistance with 6 wt% butanol aqueous solution
[50]	n-butanol, n-pentanol, n-hexanol and n-heptanol	Cylindrical-wrapped screen wick	Higher thermal efficiency and lower thermal resistance, increased capillary limit and boiling limit
[51]	Water/butanol 4 wt% and water/butanol 7 wt%	Cylindrical-screen mesh wick	Vapor departing and liquid arrival mechanism caused the heat transfer enhancement and 25% improvement was obtained when 7 wt% butanol solution
[52]	1-Butanol aqueous solution with 5% mass fraction	Gravity HP	At small inclination angle, self-rewetting fluid significantly increases the dry-out limit
[53]	Graphene oxide dispersion solution and n-butanol alcohol aqueous solution	OHP	The optimum constituent concentration of 0.07 wt% graphene oxide and 0.7 wt% n-butanol
[54]	Butyl alcohol solution with 5% mass fraction	Cross internal helical microfin gravity HP	Significantly increase the drying limit in the horizontal position
[55]	SRWF	OHP	Good thermal performance under large heat load when the FR is 40% and effective thermal conductivity reaches 5676 $W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$

3 Major applications of HPs

The investigations of HPs devoted with multiple respects of theoretical analysis, experimental test, and numerical simulation could lead to a better understanding of this promising technology. Moreover, the addition of HPs within various systems allows the fully utilization of high heat transfer and temperature control, making the systems ideal for various engineering applications. New applications emerged with time are listed in Table 3 [4].

Table 3 Emerging of new applications with time [4]

Years	Applications
1970s	Aerospace and astronautics
1980s	Energy conservation
1990s	Industrial and energy utilization
2000s	Computers and electronics cooling
2010s	Global warming and environment

3.1 Electronic cooling and thermal control

HPs based cooling is one of the most viable approach to removing high heat flux from electronic devices [56]. Details about the working principle and applications of HP cooling systems can be found in Refs. [57–59]. LHPs are highly efficient heat transfer devices, especially for electronic cooling and thermal control. The typical structure of LHP is shown in Fig. 1 [60].

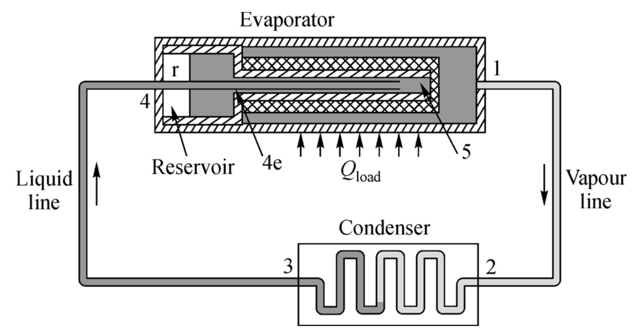


Fig. 1 Schematic of LHP system (adapted with permission from Ref. [60])

Becker et al. [61] and Maydanik & Vershinin [62] developed and investigated the operating characteristics and maximum thermal parameters of a copper-water LHP. The heat input varied between 5 and 900 W and the minimum thermal resistance of evaporator was only 0.014°C/W. The evaporator temperature was 100°C with a heat input of about 650 W, while at a heat load of 900 W with a 1 cm^2 surface, the evaporator temperature reached 275°C but the vapor temperature was only about 80°C.

A powerful cooler based on a copper-water LHP with a thickness of 4 mm was demonstrated in Ref. [63]. With a 20 mm × 20 mm heating surface, the heat load could reach up to 100 W and correspondingly, the temperature of the simulator in this condition was 87°C and the thermal resistance was 0.65°C/W [63].

Reference [64] also reviewed the latest aircraft applications within LHPs in detail. Moreover, vapor chamber (VC) and PHP or OHP are also effective methods of heat spreader for electronics. Both experimental studies and numerical analysis on a vertical vapor chamber (190 mm × 140 mm × 15 mm) were presented by Reyes et al. [65]. The maximum cooling power changed between 95 W and 145 W with the surface temperature in the range of 80°C–100°C. A theoretical model and an optimization process were also employed to verify the minimum weight of the heat spreader.

Yang et al. [66] demonstrated a FR4 vapor chamber with copper frame and copper meshes wick structure. At a filling ratio of 36%, it reduced the thermal resistance of flat HP by 20%–25%.

A silicon-based micro-PHP was tested by Qu et al. [67]. At a power load of 6.3 W, the evaporator wall temperature reduced about 42.1°C for R113 micro-PHP at a 41% filling ratio. For the PHP with FC-72 working fluid, the largest power input is about 9.5 W at a moderate rise in the wall temperature of the evaporator.

E et al. [68] set up a dynamics model for oscillation looped heat pipe to analyze the forces and heat transfer process inside it. The numerical simulation results indicated that the oscillation intensity and heat transfer performance could be improved significantly by increasing the temperature difference between the cooling and heating section. After that, a volume of fluid (VOF) model was developed to investigate the relationships between pressure distribution and vapor flow patterns in a closed oscillating heat pipe. A series of visualization experimental were also conducted to validate these simulation results. The flow shapes are mainly annular flow and semi-annular flow [69].

3.2 Free cooling for data centers

Nowadays, the increasing demands for data processing and storage systems have resulted in a rapid growth for data center industry where the increasing energy consumption in 2010 was almost three times of that in 2000 [70–73]. In this regard, implementing efficient cooling methods and systems are imperative for data centers. Some recent studies [74–79] adopted the HP heat exchanger such as thermosyphon for thermal management of data centers in order to minimize the thermal load as well as greenhouse gas emission.

As a method for free cooling and energy-saving, the integrated system of vapor compression and thermosyphon (ISVT) could operate flexibly both in vapor compression mode and thermosyphon mode based on the difference between indoor and outdoor temperature [80]. Zhang et al.

[81] proposed an ISVT with a tube-fin three-fluid heat exchanger (Fig. 2). The energy efficiency ratio for the thermosyphon mode reached 10.7 and 20.8 when the difference between indoor and outdoor temperature were 10°C and 20°C, respectively. The performance of ISVT was experimentally investigated in China with an annual energy-saving up to 47.3% while the room temperature was 27°C [81,82].

3.3 Solar collectors and hybrid system

Almost all types of HPs are considered to be available in the applications for heat recovery and renewable energy [83]. Cylindrical HPs and thermosyphons are commonly used and easily embedded in solar collectors to reduce the thermal resistance and enhance the efficiency of solar collectors [84]. The temperature distribution in Ref. [85] was well uniform in the carbon steel/naphthalene thermosyphon. The isothermal performance and heat transfer performance of the solar power system were investigated at different power inputs and inclined angles. It is shown that the device with an inclined angle of 4° and 8° could work stably and have a good heat transfer performance and axial isothermal performance.

Rittidech and Wannapakne [86] carried out an experimental study of the solar water heater with PHP (Fig. 3), which had an efficiency of approximately 62%. Kargarsharifabad et al. [87] also built a system where the solar energy was transferred to the PHPs. It was indicated that the optimal filling ratio and inclination angle were 0.3 and 20°, respectively.

He et al. [88] proposed a solar photovoltaic/HP/thermoelectric hybrid system (Fig. 4) for room cooling in summer and heating in winter. In summer, the simulation results based on a 0.5 m^2 solar panel showed that the minimum temperature of room condition is 17°C, and 18.5 L of hot water could be heated with the temperature rise of about 9°C. As the TE modules are relatively expensive, the hybrid system seems to be not attractive for commercialization although solar energy is freely and widely available throughout the year and worldwide [89].

3.4 Heat recovery in HVAC system

Heating, ventilation, and air-conditioning, often termed as HVAC, usually accounts for 40%–60% of the energy demand in a domestic building [90]. The heat recovery method is increasingly adopted to decrease the heating and cooling demands by means of pre-heating or pre-cooling [91]. Another wide utilization of TPCT is to make it act as gas-gas heat exchanger for heat recovery in the HVAC system (Fig. 5) [92].

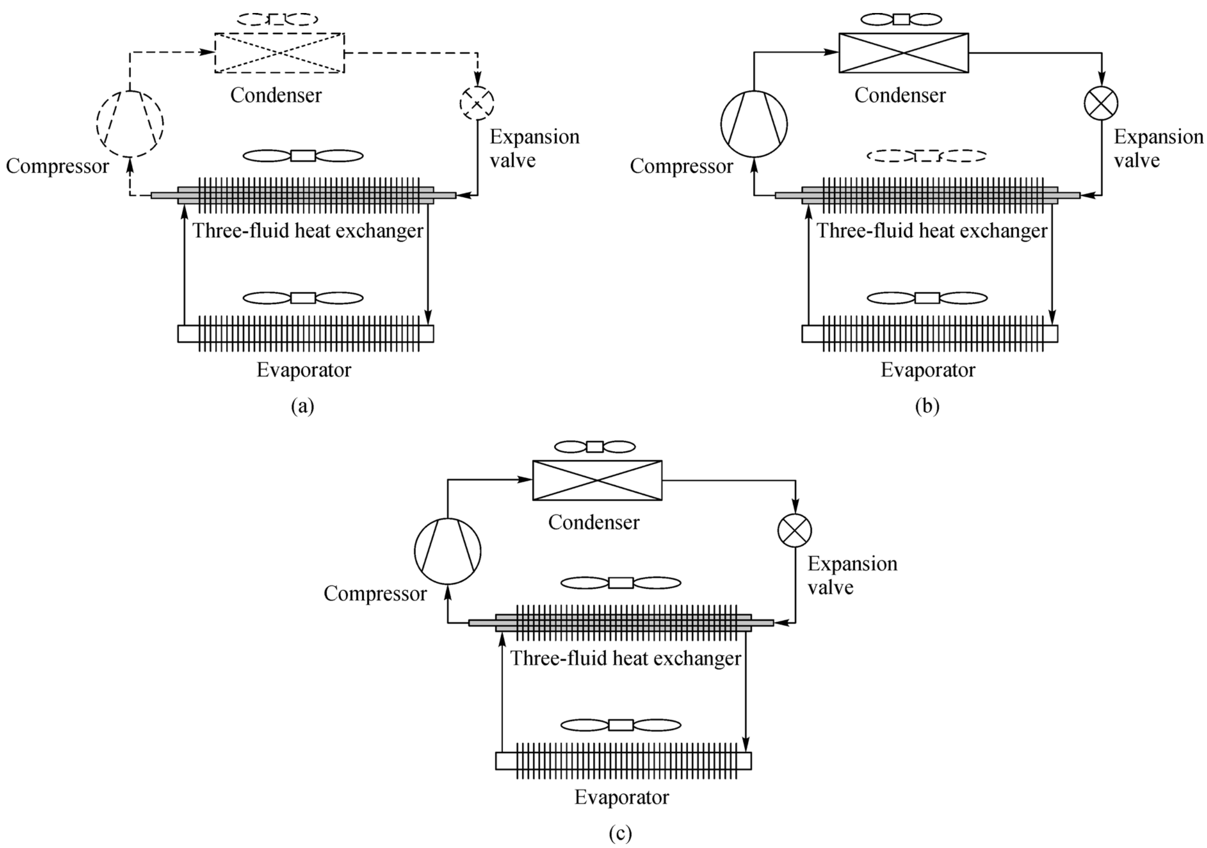


Fig. 2 ISVT system with three-fluid heat exchanger (adapted with permission from Ref. [81])
(a) Thermosyphon mode; (b) refrigeration mode; (c) dual mode

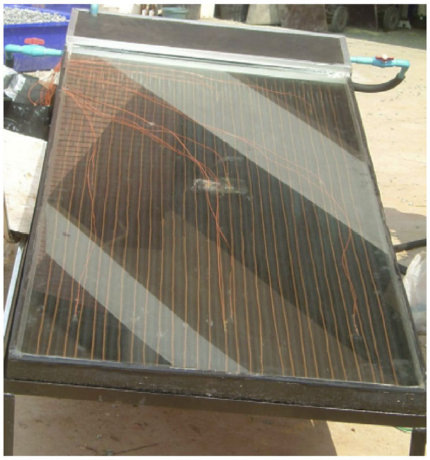


Fig. 3 Designs of solar water heater with PHPs (adapted with permission from Ref. [86])

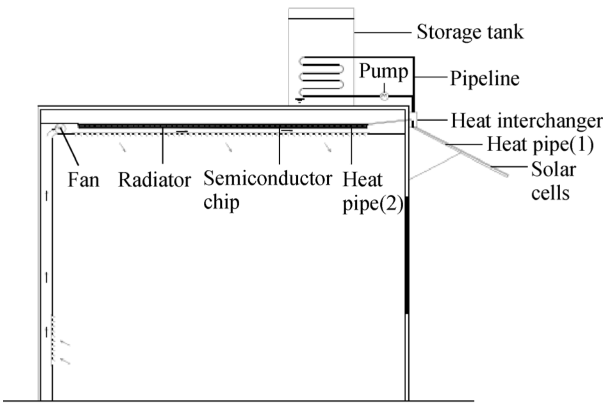


Fig. 4 Solar PV/HP/TE hybrid system (adapted with permission from Ref. [88])

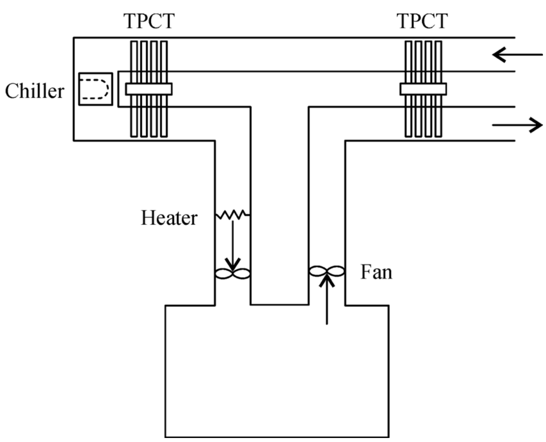


Fig. 5 TPCT applied in HVAC system (adapted with permission from Ref. [92])

Firouzfar et al. [93] experimentally studied a TPCT heat exchanger with methanol-silver nanofluid in an air conditioning system. It was found out that the TPCT heat exchanger could save about 8.8%–31.5% energy for cooling, and up to 100% by reheating the supply air.

A TPCT (d_i = 10 mm, L = 750 mm) within R407C for cogeneration of residential buildings was tested by Byrne et al. [94]. The results showed that the average performance increased by 16.6% compared with that for the standard reversible heat pump.

Jouhara and Merchant [95] examined a nine finned TPCT heat exchanger (d_i = 16 mm, L = 900 mm) and predicted the effectiveness of the heat exchanger. It was observed that the heat exchanger could provide a higher performance in vertical direction at various heat inputs (750–1500 W).

The performance of an air-to-air TPCT heat exchanger was predicted experimentally and analytically by Danielewicz et al. [96]. A good correlation between theoretical predictions and experimental data was obtained. The heat recovery rate and the effectiveness increased as the ratio of the condenser inlet mass flow rate to evaporator inlet mass flow rate increased.

Meena et al. [97] experimentally studied a TPCT heat exchanger (d_i = 17.5 mm and L = 500 mm) using Cu-DI nanofluid (filling ratio of 50%) for the temperature range of 60°C–80°C. It was observed that the maximum efficiency of the system using nanofluid occurred at 80°C and the heat transfer performance, as well as the thermal effectiveness performance increased compared with DI-water.

4 Progress of heat pipe technology combined with sorption technology

Known as environmental friendly, low control and cost-effective, the sorption technology powered by low-grade heat is an ideal alternative to electrical vapor compression. Except the promising advantages, the sorption systems for the practical applications commonly face the issue of enhancing heat and mass transfer effectively which is an ongoing interesting research field.

Vasiliev and Vasiliev Jr [98,99] earlier proposed a sorption system coupled with heat pipe, combining the conventional HP with solid sorbents. The sorption system (Fig. 6) was the combination of a LHP and a solid sorption cooler. The advantages of both the conventional HPs and sorption machines were included in one system [100,101].

Vasiliev also implemented HPs into adsorption refrigerators and heat pumps [5–7]. Several sorption machines which were integrated in various types of HP devices, includes loop heat pipe-solid sorption cooler, solar sorption heat pump with vapor-dynamic thermosyphon, and LHPs and so on [101–105].

It can be concluded that significant benefits from this integration or combination are realized through the process of heat and mass transfer with HP type heating and

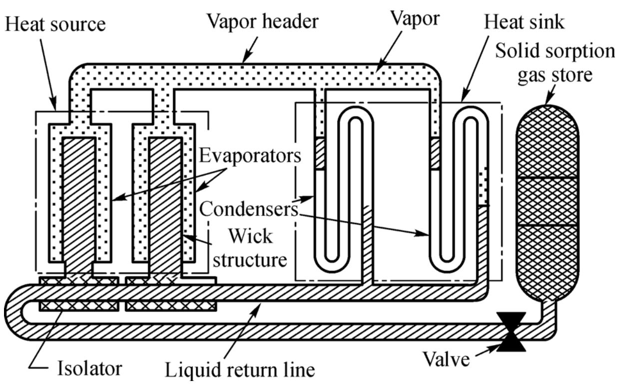


Fig. 6 Schematic of sorption system coupled with heat pipe (adapted with permission from Ref. [98])

cooling. Researchers in Shanghai Jiao Tong University have integrated the adsorption refrigeration systems (adsorption air conditioner, adsorption water chiller and adsorption ice maker) with the HP technology for cooling and heating [15–19].

Wang et al. [106] adopted the thermosyphon to heat and cool the adsorber of an adsorption ice maker on fishing boats (Fig. 7) using activated carbon and $CaCl_2$ compound adsorbent with ammonia as working pair. With the mass recovery between two beds, the average heating/cooling power of one HP for desorption/adsorption processes were 571/643 W and the cooling power of a two-bed adsorption ice maker was about 17.8 kW at an evaporating temperature of –15°C and a cycle time of 10 min.

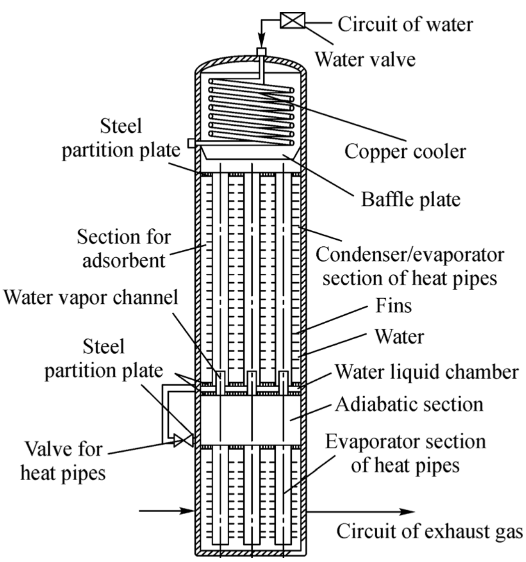


Fig. 7 Thermosyphon type adsorber for adsorption ice maker on fishing boats (adapted with permission from Ref. [106])

Wang et al. [18] coupled the split heat pipe with the adsorber for heating and cooling and set up a chemical adsorption refrigeration test system. Compared with the thermosyphon type adsorber, it was shown that when the evaporating temperature was around –15°C, the average cooling power was 1.37 kW, with a COP and a SCP of 0.41 and 731 $W \cdot kg^{-1}$, respectively. The average heat transfer coefficient was 155.8 $W \cdot m^{-2} \cdot °C^{-1}$ for a whole cycle.

An adsorption chiller combined with double heat pipe type for heating and cooling the adsorption bed was studied by Wang et al. [107]. One kind of HPs was split type heat pipe to heat the adsorber in the desorption phase, the other one was TPCT for cooling the adsorber in the adsorption phase. The performance of the chiller was predicted with a lumped parameter model and the simulation results demonstrated that the cooling power and COP were 5.1 kW and 0.38, respectively. Figure 8 displayed the double heat pipe type adsorption chiller.

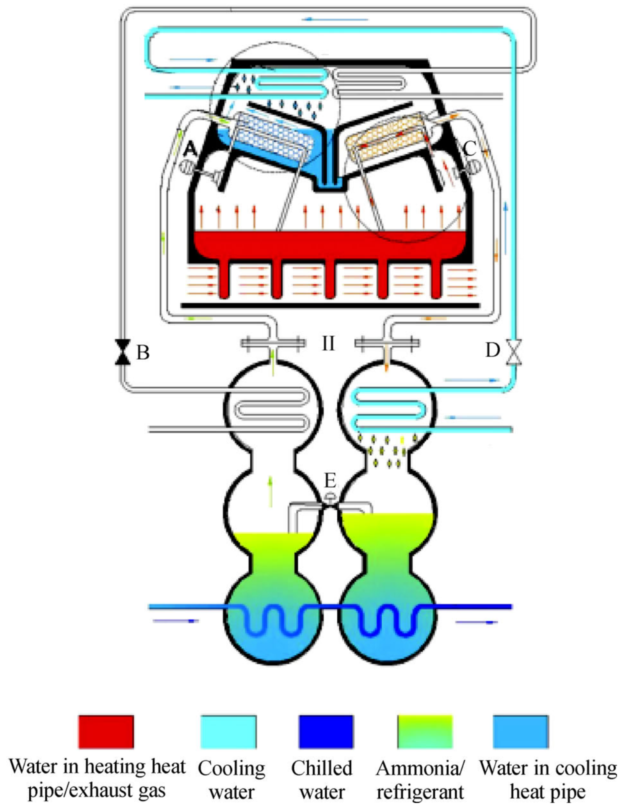


Fig. 8 Double heat pipe type adsorption chiller (adapted with permission from Ref. [107])

For a silica gel-water adsorption chiller, Wang et al. [16] combined the adsorption and the desorption units with a heat pipe heat exchanger for outputting continuous refrigerating capacities. The test results indicated that the refrigerating capacity and COP were 7.15 kW and 0.38, respectively, while the temperature of hot water, cooling water, and chilled water outlet were 84.8°C, 30.6°C and 11.7°C, respectively.

Lu et al. [108] investigated a dual-mode chemisorption refrigeration system in which the multifunction heat pipe for heating, cooling, as well heat recovery was proposed. It was observed that the first operation mode cycle could increase COP by 69% compared with the basic cycle. In the second operation mode cycle, the performance was improved by at least 23% contrasted to that of the conventional two-stage cycle under the same conditions of generation temperature of 103°C and cooling water temperature of 30°C.

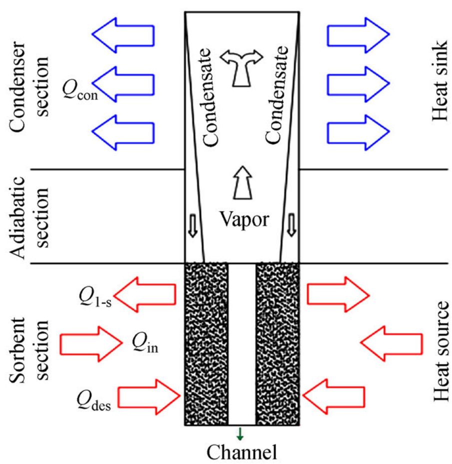
To take the advantage of sorption technology and alleviate heat transfer limits of the conventional HP, the research and development of SSHP has been conducted in our previous work [20,21], including preliminary analysis of the heat transfer process and experimental investigations under various operation conditions (heat source and heat sink temperatures, filling sorbates and inclination angles).

The schematic of SSHP and its setup are illustrated in Fig. 9.

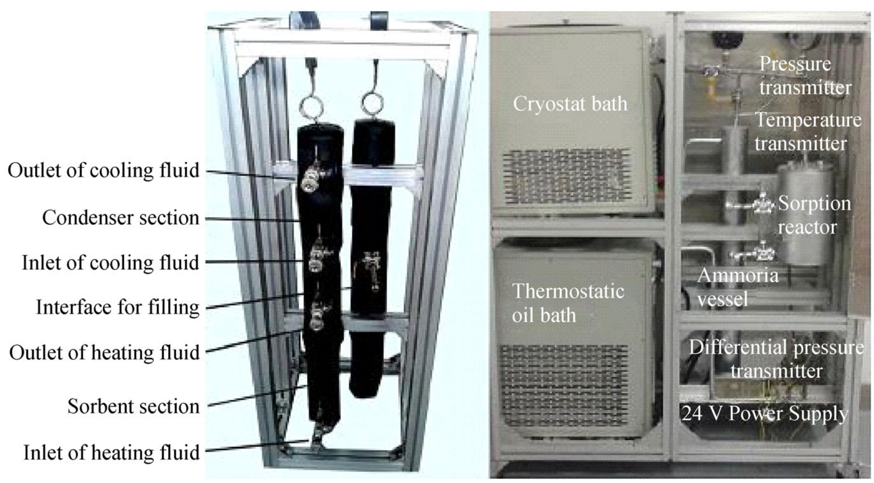
The results of the overall heat transfer performance of SSHP (for example in Fig. 10) verify the feasibility of SSHP at different operation temperatures for continuous heat transfer.

SSHP employs the composite solid sorbents (such as NaBr with ENG-TSA) with the sorbates (NH_3) to substitute the wick and working fluid in conventional HP or thermosyphon. The composite solid sorbents are filled with the sorbent section which is expected to alleviate the operation pressure and the phenomena of limitations. The combination of solid-gas, liquid-gas reaction and condensation process could transfer the low-grade heat continuously.

Moreover, featured with a certain extent of temperature difference between sorbent section and condenser section, SSHP could be used for non-isothermal heat transfer and/or heat recovery process in particular. Development in the new type of solid sorption materials which accomplish small temperature difference heat transfer could improve the adaptability of SSHP in the future.



(a)



(b)

Fig. 9 Schematic of SSHP and its test system
(a) Schematic of SSHP; (b) test system of SSHP

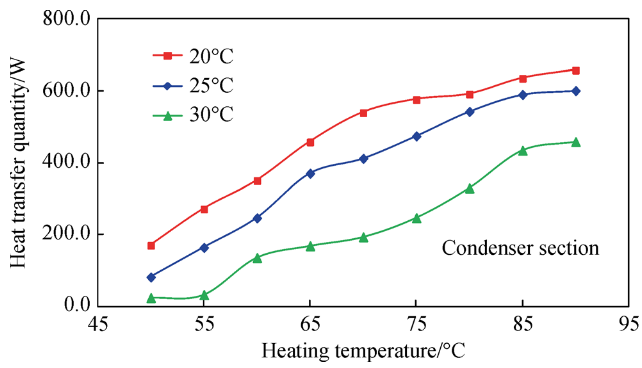


Fig. 10 Heat transfer performance of SSHP under different cooling temperature

5 Perspectives

The sustainable developments of HP based systems are promising in practical applications. However, it is also accompanied with emerging challenges, such as the applicability and economy for a certain system, and the accurate numerical model for analysis and simulation.

Sorption systems coupled with HPs have the benefits of compactness, short time cycle, and improved heat and mass transfer which are efficient for cooling, heating, and cogeneration.

To fulfill continuous low-grade heat transfer and long-distance energy transportation, it is proposed that SSHP be successfully coupled with each other to reduce the complexity of the sorption system and expand the fields of the application of HP, respectively.

For future endeavors, more intensive studies should be devoted to SSHP in the areas as follows:

(1) Combine the solid sorption reaction kinetic with the heat and mass transfer in porous media to push forward the operation mechanism of SSHP.

(2) Apply the advanced visualization technology with the addition of the CFD method and the field synergy principle [109] to analyze the reaction process quantitatively and in turn, to verify experiment results.

(3) More efforts should be made in in-depth investigations and experiments to promote the conditions of SSHP coupled with commercial applications (such as advanced sorption system, data centers cooling and low-grade heat transportation).

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References

1. Gaugler R S. Heat transfer device. US Patent, 2350348, 1944
2. Grover G M, Cotter T P, Ericson G F. Structures of very high thermal conductance. Journal of Applied Physics, 1964, 35: 1190–1191
3. Reay D A, Kew P A, McGlen R J. Heat Pipes: Theory, Design and Applications. 6th ed. Whitley Bay: Elsevier, 2013
4. Vasiliev L L, Kakac S. Heat Pipes and Solid Sorption Transformations: Fundamentals and Practical Applications. Florida: Taylor & Francis Group, 2013
5. Faghri A. Heat pipes: review, opportunities and challenges. Frontiers in Heat Pipes, 2014, 5(1): 1–48
6. Faghri A, Chen M M, Morgan M. Heat transfer characteristics in two-phase closed conventional and concentric annular thermosyphons. Journal of Heat Transfer, 1989, 111(3): 611–618
7. El-Genk M S, Saber H H. Flooding limit in closed, two-phase flow thermosyphons. International Journal of Heat and Mass Transfer, 1997, 40(9): 2147–2164
8. Nguyen-Chi H, Groll M. Entrainment or flooding limit in a closed two-phase thermosyphon. Journal of Heat Recovery Systems, 1981, 1(4): 275–286
9. Shatto D P, Besly J A, Peterson G P. Visualization study of flooding and entrainment in a closed two-phase thermosyphon. Journal of Thermophysics and Heat Transfer, 1997, 11(4): 579–581
10. Meunier F. Solid sorption heat powered cycles for cooling and heat pumping applications. Applied Thermal Engineering, 1998, 18(9–10): 715–729
11. Wang L W, Wang R Z, Oliveira R G. A review on adsorption working pairs for refrigeration. Renewable & Sustainable Energy Reviews, 2009, 13(3): 518–534
12. Yan T, Wang R Z, Li T X, Wang L W, Fred I T. A review of promising candidate reactions for chemical heat storage. Renewable & Sustainable Energy Reviews, 2015, 43: 13–31
13. Wang R Z, Wang L W, Wu J Y. Adsorption Refrigeration Theory and Applications. Beijing: Science Press, 2007
14. Critoph R E. The use of thermosyphon heat pipes to improve the performance of a carbon-ammonia adsorption refrigerator. In: IV Minsk International Seminar "Heat Pipes, Heat Pumps, Refrigerators", Minsk, Belarus, 2000
15. Wang R Z. Efficient adsorption refrigerators integrated with heat pipes. Applied Thermal Engineering, 2008, 28(4): 317–326
16. Wang D C, Xia Z Z, Wu J Y, Wang R Z, Zhai H, Dou W D. Study of a novel silica gel–water adsorption chiller. Part I. Design and performance prediction. International Journal of Refrigeration, 2005, 28(7): 1073–1083
17. Yang G Z, Xia Z Z, Wang R Z, Keletigui D, Wang D C, Dong Z H, Yang X. Research on a compact adsorption room air conditioner. Energy Conversion and Management, 2006, 47(15–16): 2167–2177
18. Wang L W, Wang R Z, Lu Z S, Xu Y X, Wu J Y. Split heat pipe type compound adsorption ice making test unit for fishing boats. International Journal of Refrigeration, 2006, 29(3): 456–468
19. Li T X, Wang R Z, Wang L W, Lu Z S, Chen C J. Performance study of a high efficient multifunction heat pipe type adsorption ice making system with novel mass and heat recovery processes. International Journal of Thermal Sciences, 2007, 46(12): 1267–1274
20. Yu Y, Wang L W, Jiang L, Gao P, Wang R Z. The feasibility of solid sorption heat pipe for heat transfer. Energy Conversion and

Management, 2017, 138: 148–155
21. Yu Y, Wang L W, An G L. Experimental study on sorption and heat transfer performance of NaBr-NH_3 for solid sorption heat pipe. International Journal of Heat and Mass Transfer, 2018, 117: 125–131
22. Jouhara H, Chauhan A, Nannou T, Almahmoud S, Delpech B, Wrobel L C. Heat pipe based systems—advances and applications. Energy, 2017, 128: 729–754
23. Gupta N K, Tiwari A K, Ghosh S K. Heat transfer mechanisms in heat pipes using nanofluids—a review. Experimental Thermal and Fluid Science, 2018, 90: 84–100
24. Chien H T, Tsai C I, Chen P H, Chen P Y. Improvement on thermal performance of a disk-shaped miniature heat pipe with nanofluid. In: Proceedings of 5th International Conference on Electronic Packaging Technology, Shanghai, China, 2003
25. Putra N, Septiadi W N, Rahman H, Irwansyah R. Thermal performance of screen mesh wick heat pipes with nanofluids. Experimental Thermal and Fluid Science, 2012, 40: 10–17
26. Putra N, Saleh R, Septiadi W N, Okta A, Hamid Z. Thermal performance of biomaterial wick loop heat pipes with water-base Al_2O_3 nanofluids. International Journal of Thermal Sciences, 2014, 76: 128–136
27. Mashaei P R, Shahryari M, Fazeli H, Hosseinalipour S M. Numerical simulation of nanofluid application in a horizontal mesh heat pipe with multiple heat sources: a smart fluid for high efficiency thermal system. Applied Thermal Engineering, 2016, 100: 1016–1030
28. Mashaei P R, Shahryari M, Madani S. Numerical hydrothermal analysis of water-Al_2O_3 nanofluid forced convection in a narrow annulus filled by porous medium considering variable properties. Journal of Thermal Analysis and Calorimetry, 2016, 126(2): 891–904
29. Mashaei P R, Shahryari M, Madani S. Analytical study of multiple evaporator heat pipe with nanofluid: a smart material for satellite equipment cooling application. Aerospace Science and Technology, 2016, 59: 112–121
30. Ramachandran R, Ganesan K, Rajkumar M R, Asirvatham L G, Wongwises S. Comparative study of the effect of hybrid nanoparticle on the thermal performance of cylindrical screen mesh heat pipe. International Communications in Heat and Mass Transfer, 2016, 76: 294–300
31. Sözen A, Menlik T, Gürü M, Boran K, Kılıç F, Aktaş M, Çakır M T. A comparative investigation on the effect of fly-ash and alumina nanofluids on the thermal performance of two-phase closed thermosyphon heat pipes. Applied Thermal Engineering, 2016, 96: 330–337
32. Ghanbarpour M, Khodabandeh R, Vafai K. An investigation of thermal performance improvement of a cylindrical heat pipe using Al_2O_3 nanofluid. Heat and Mass Transfer, 2017, 53(3): 973–983
33. Poplaski L M, Benn S P, Faghri A. Thermal performance of heat pipes using nanofluids. International Journal of Heat and Mass Transfer, 2017, 107: 358–371
34. Senthil R, Ratchagaraja D, Silambarasan R, Manikandan R. Contemplation of thermal characteristics by filling ratio of Al_2O_3 nanofluid in wire mesh heat pipe. Alexandria Engineering Journal, 2016, 55(2): 1063–1068
35. Kumaresan G, Venkatachalapathy S, Asirvatham L G, Wongwises S. Comparative study on heat transfer characteristics of sintered and mesh wick heat pipes using CuO nanofluids. International Communications in Heat and Mass Transfer, 2014, 57: 208–215
36. Venkatachalapathy S, Kumaresan G, Suresh S. Performance analysis of cylindrical heat pipe using nanofluids—an experimental study. International Journal of Multiphase Flow, 2015, 72: 188–197
37. Kumaresan G, Venkatachalapathy S, Asirvatham L G. Experimental investigation on enhancement in thermal characteristics of sintered wick heat pipe using CuO nanofluids. International Journal of Heat and Mass Transfer, 2014, 72: 507–516
38. Alizad K, Vafai K, Shafahi M. Thermal performance and operational attributes of the startup characteristics of flat-shaped heat pipes using nanofluids. International Journal of Heat and Mass Transfer, 2012, 55(1–3): 140–155
39. Brahim T, Jemni A. Numerical case study of packed sphere wicked heat pipe using Al_2O_3 and CuO based water nanofluid. Case Studies in Thermal Engineering, 2016, 8: 311–321
40. Kole M, Dey T K. Thermal performance of screen mesh wick heat pipes using water-based copper nanofluids. Applied Thermal Engineering, 2013, 50(1): 763–770
41. Senthilkumar R, Vaidyanathan S, Sivaraman B. Effect of inclination angle in heat pipe performance using copper nanofluid. Procedia Engineering, 2012, 38: 3715–3721
42. Klinbun J, Terdtoon P. Experimental study of copper nano-fluid on thermosyphons thermal performance. Engineering Journal (New York), 2017, 21(1): 255–264
43. Riehl R R, Santos N. Water-copper nanofluid application in an open loop pulsating heat pipe. Applied Thermal Engineering, 2012, 42: 6–10
44. Karthikeyan V K, Ramachandran K, Pillai B C, Brusly Solomon A. Effect of nanofluids on thermal performance of closed loop pulsating heat pipe. Experimental Thermal and Fluid Science, 2014, 54: 171–178
45. Solomon A B, Ramachandran K, Asirvatham L G, Pillai B C. Numerical analysis of a screen mesh wick heat pipe with Cu/water nanofluid. International Journal of Heat and Mass Transfer, 2014, 75: 523–533
46. Wan Z, Deng J, Li B, Xu Y, Wang X, Tang Y. Thermal performance of a miniature loop heat pipe using water-copper nanofluid. Applied Thermal Engineering, 2015, 78: 712–719
47. Abe Y, Iwasaki A, Tanaka K. Microgravity experiments on phase change of self-rewetting fluids. Annals of the New York Academy of Sciences, 2004, 1027(1): 269–285
48. Hu Y, Huang K, Huang J. A review of boiling heat transfer and heat pipes behaviour with self-rewetting fluids. International Journal of Heat and Mass Transfer, 2018, 121: 107–118
49. Wu S C. Study of self-rewetting fluid applied to loop heat pipe. International Journal of Thermal Sciences, 2015, 98: 374–380
50. Senthilkumar R, Vaidyanathan S, Sivaraman B. Comparative study on heat pipe performance using aqueous solutions of alcohols. Heat and Mass Transfer, 2012, 48(12): 2033–2040
51. Peyghambarzadeh S M, Hallaji H, Bohloul M R, Aslanzadeh N. Heat transfer and Marangoni flow in a circular heat pipe using self-rewetting fluids. Experimental Heat Transfer, 2017, 30(3): 218–

234
52. Xin G M, Qin Q Y, Zhang L S, Ji W X. Thermal characteristics of gravity heat pipes with self-rewetting fluid at small inclination angles. Journal of Engineering Thermophysics, 2013, 36(6): 1282–1285
53. Su X J, Zhang M, Han W, Guo X. Experimental study on the heat transfer performance of an oscillating heat pipe with self-rewetting nanofluid. International Journal of Heat and Mass Transfer, 2016, 100: 378–385
54. Tian F Z, Xin G M, Hai Q, Cheng L. An investigation of heat transfer characteristic of cross internal helical microfin gravity heat pipe with self-rewetting fluid. Advanced Materials Research, 2013, 765– 767: 189–192
55. Zhao J, Qu J, Rao Z. Experiment investigation on thermal performance of a large-scale oscillating heat pipe with self-rewetting fluid used for thermal energy storage. International Journal of Heat and Mass Transfer, 2017, 108: 760–769
56. Sohel Murshed S M, Nieto De Castro C A. A critical review of traditional and emerging techniques and fluids for electronics cooling. Renewable & Sustainable Energy Reviews, 2017, 78: 821–833
57. Faghri A. Review and advances in heat pipe science and technology. Journal of Heat Transfer, 2012, 134(12): 123001
58. Chen X, Ye H, Fan X, Ren T, Zhang G. A review of small heat pipes for electronics. Applied Thermal Engineering, 2016, 96: 1–17
59. Maydanik Y F, Chernysheva M A, Pastukhov V G. Review: loop heat pipes with flat evaporators. Applied Thermal Engineering, 2014, 67(1–2): 294–307
60. Siedel B, Sartre V, Lefèvre F. Literature review: steady-state modelling of loop heat pipes. Applied Thermal Engineering, 2015, 75: 709–723
61. Becker S, Vershinin S, Sartre V, Laurien E, Bonjour J, Maydanik Y F. Steady state operation of a copper-water LHP with a flat-oval evaporator. Applied Thermal Engineering, 2011, 31(5): 686–695
62. Maydanik Y F, Vershinin S. Development and investigation of copper-water loop heat pipes with high operating characteristics. Heat Pipe Science and Technology, An International Journal, 2010, 1(2): 151–162
63. Pastukhov V G, Maydanik Y F. Low-noise cooling system for PC on the base of loop heat pipe. Applied Thermal Engineering, 2007, 27: 894–901
64. Su Q, Chang S, Zhao Y, Zheng H, Dang C. A review of loop heat pipes for aircraft anti-icing applications. Applied Thermal Engineering, 2018, 130: 528–540
65. Reyes M, Alonso D, Arias J, Velazquez A. Experimental and theoretical study of a vapour chamber based heat spreader for avionics applications. Applied Thermal Engineering, 2012, 37: 51–59
66. Yang K S, Yang T Y, Tu C W, Yeh C T, Lee M T. A novel flat polymer heat pipe with thermal via for cooling electronic devices. Energy Conversion and Management, 2015, 100: 37–44
67. Qu J, Wu H Y, Wang Q. Experimental investigation of silicon-based micro-pulsating heat pipe for cooling electronics. Nanoscale and Microscale Thermophysical Engineering, 2012, 16(1): 37–49
68. E J, Zhu R, Chen J, Long Y, Hu X. Oscillation heat transfer dynamic model for the new type oscillation looped heat pipe with double liquid slugs. Journal of Central South University, 2012, 19 (11): 3194–3201
69. E J, Zhao X, Deng Y, Zhu H. Pressure distribution and flow characteristics of closed oscillating heat pipe during starting process at different vacuum degrees. Applied Thermal Engineering, 2016, 93: 166–173
70. Ebrahimi K, Jones G F, Fleischer A S. A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renewable & Sustainable Energy Reviews, 2014, 31: 622–638
71. Sevencan S, Lindbergh G, Lagergren C, Alvfors P. Economic feasibility study of a fuel cell-based combined cooling, heating and power system for a data centre. Energy and Building, 2016, 111: 218–223
72. Whitney J, Delforge P. Data Center Efficiency Assessment. New York: Natural Resources Defense Council, 2014
73. Daraghmeh H M, Wang C. A review of current status of free cooling in datacenters. Applied Thermal Engineering, 2017, 114: 1224–1239
74. Zhou F, Ma G, Wang S. Entropy generation rate analysis of a thermosyphon heat exchanger for cooling a telecommunication base station. International Journal of Exergy, 2017, 22(2): 139–157
75. Zhou F, Li C, Zhu W, Zhou J, Ma G, Liu Z. Energy-saving analysis of a case data center with a pump-driven loop heat pipe system in different climate regions in China. Energy and Building, 2018, 169: 295–304
76. Zhang L Y, Liu Y Y, Guo X, Meng X Z, Jin L W, Zhang Q L, Hu W J. Experimental investigation and economic analysis of gravity heat pipe exchanger applied in communication base station. Applied Energy, 2017, 194: 499–507
77. Zhang L Y, Liu Y Y, Jin L W, Liu X, Meng X, Zhang Q. Economic analysis of gravity heat pipe exchanger applied in communication base station. Energy Procedia, 2016, 88: 518–525
78. Tong Z, Ding T, Li Z, Liu X H. An experimental investigation of an R744 two-phase thermosyphon loop used to cool a data center. Applied Thermal Engineering, 2015, 90: 362–365
79. Zhang H, Shi Z, Liu K, Shao S, Jin T, Tian C. Experimental and numerical investigation on a CO_2 loop thermosyphon for free cooling of data centers. Applied Thermal Engineering, 2017, 111: 1083–1090
80. Zhang H, Shao S, Tian C, Zhang K. A review on thermosyphon and its integrated system with vapor compression for free cooling of data centers. Renewable & Sustainable Energy Reviews, 2018, 81(1): 789–798
81. Zhang H, Shao S, Xu H, Zou H, Tian C. Integrated system of mechanical refrigeration and thermosyphon for free cooling of data centers. Applied Thermal Engineering, 2015, 75: 185–192
82. Zhang H, Shao S, Xu H, Zou H, Tang M, Tian C. Numerical investigation on fin tube three-fluid heat exchanger for hybrid source HVAC & R systems. Applied Thermal Engineering, 2016, 95: 157–164
83. Blet N, Lips S, Sartre V. Heat pipes for temperature homogenization: a literature review. Applied Thermal Engineering, 2017, 118: 490–509
84. Chaudhry H N, Hughes B R, Ghani S A. A review of heat pipe

systems for heat recovery and renewable energy applications. Renewable & Sustainable Energy Reviews, 2012, 16(4): 2249–2259

85. Liu Y, Zhang H. Experimental studies on the isothermal and heat transfer performance of trough solar power collectors. Advanced Materials Research, 2014, 1044–1045: 320–326
86. Rittidech S, Wannapakne S. Experimental study of the performance of a solar collector by closed-end oscillating heat pipe (CEOHP). Applied Thermal Engineering, 2007, 27(11–12): 1978–1985
87. Kargarsharifabad H, Mamouri S J, Shafii M B, Rahni M T. Experimental investigation of the effect of using closed-loop pulsating heat pipe on the performance of a flat plate solar collector. Journal of Renewable and Sustainable Energy, 2013, 5 (1): 013106
88. He W, Zhou J, Hou J, Chen C, Ji J. Theoretical and experimental investigation of a thermoelectric cooling and heating system driven by solar. Applied Energy, 2013, 107: 89–97
89. Ong K S. Review of solar, heat pipe and thermoelectric hybrid systems for power generation and heating. International Journal of Low Carbon Technologies, 2016, 11(4): 460–465
90. WBCSD. Energy Efficiency in Buildings Facts & Trends. World Business Council for Sustainable Development's Report. Switzerland: Atar Roto Presse SA, 2008
91. O'Connor D, Calautit J K S, Hughes B R. A review of heat recovery technology for passive ventilation applications. Renewable & Sustainable Energy Reviews, 2016, 54: 1481–1493
92. Jafari D, Franco A, Filippeschi S, Di Marco P. Two-phase closed thermosyphons: a review of studies and solar applications. Renewable & Sustainable Energy Reviews, 2016, 53: 575–593
93. Firouzfar E, Soltanieh M, Noie S H, Saidi S H. Energy saving in HVAC systems using nanofluid. Applied Thermal Engineering, 2011, 31(8–9): 1543–1545
94. Byrne P, Miriel J, Lénat Y. Experimental study of an air-source heat pump for simultaneous heating and cooling–part 2: dynamic behavior and two-phase thermosiphon defrosting technique. Applied Thermal Engineering, 2011, 88: 3072–3078
95. Jouhara H, Merchant H. Experimental investigation of a thermosyphon based heat exchanger used in energy efficient air handling units. Energy, 2012, 39(1): 82–89
96. Danielewicz J, Sayegh M A, Sniechowska B, Szulgowska-Zgrzywa M, Jouhara H. Experimental and analytical performance investigation of air to air two phase closed thermosyphon based heat exchangers. Energy, 2014, 77: 82–87
97. Meena P, Tammasaeng P, Kanphirom J, Ponkho A, Setwong S. Enhancement of the performance heat transfer of a thermosyphon with fin and without fin heat exchangers using Cu-nanofluid as working fluids. Journal of Engineering Thermophysics, 2014, 23 (4): 331–340
98. Vasiliev L L, Vasiliev L Jr. Sorption heat pipe—a new thermal control device for space and ground application. International Journal of Heat and Mass Transfer, 2005, 48(12): 2464–2472
99. Vasiliev L L, Vasiliev L Jr. The sorption heat pipe—a new device for thermal control and active cooling. Superlattices and Microstructures, 2004, 35(3–6): 485–495
100. Vasiliev L L. Sorption refrigerators with heat pipe thermal control. In: Cryogenics and Refrigeration–Proceedings of ICCR. Beijing: Science Press, 2003, 405–415
101. Vasiliev L L. Solar sorption refrigerator. In: Proceeding of 5th Minsk International Seminar "Heat Pipes, Heat Pumps, Refrigerators", Minsk, Belarus, 2003
102. Vasiliev L L, Mishkinis D A, Antukh A A, Vasiliev L L Jr. Solar–gas solid sorption heat pump. Applied Thermal Engineering, 2001, 21(5): 573–583
103. Vasiliev L L, Kanonchik L E, Antuh A A, Kulakov A G, Kulikovsky V K. Waste heat driven solid sorption coolers containing heat pipes for thermo control. Adsorption, 1995, 1(4): 303–312
104. Vasiliev L L. Electronic cooling system with a loop heat pipe and solid sorption cooler. In: 11th International Heat Pipe Conference, Musachinoshi, Tokyo, Japan, 1999
105. Vasiliev L L. Heat pipes and solid sorption machines. Heat Transfer Research, 2004, 35(5–6): 393–405
106. Wang L W, Wang R Z, Wu J Y, Xia Z Z, Wang K. A new type adsorber for adsorption ice maker on fishing boats. Energy Conversion and Management, 2005, 46(13–14): 2301–2316
107. Wang K, Wu J Y, Xia Z Z, Li S L, Wang R Z. Design and performance prediction of a novel double heat pipes type adsorption chiller for fishing boats. Renewable Energy, 2008, 33 (4): 780–790
108. Lu Z S, Wang R Z, Li T X, Wang L W, Chen C J. Experimental investigation of a novel multifunction heat pipe solid sorption icemaker for fishing boats using $CaCl_2$/activated carbon compound–ammonia. International Journal of Refrigeration, 2007, 30(1): 76–85
109. E J, Zhao X, Liu H, Chen J, Zuo W, Peng Q. Field synergy analysis for enhancing heat transfer capability of a novel narrow-tube closed oscillating heat pipe. Applied Energy, 2016, 175: 218–228