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Phase change cooling in data centers: A review

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ABSTRACT

With the advent of big data era, data centers (DCs) related energy use accounts for approximately 3% of the global electric power consumption. As the augmentation of data-processing performance and thermal density in DCs, its energy use will undoubtedly continuously burst. Meanwhile, the potential safety hazards, caused by IT equipment local overheating, threaten the safe operation and restrict the further development of DCs. Thus, efficient cooling approaches should be applied in DCs to ensure its safe operation and optimize its thermal environment and cooling efficiency. Phase change cooling (PCC) technology is regarded as one of the effective and widely-used cooling methods, which have been applied in DCs for several years. In this paper, the up-to-date PCC technologies are reviewed and summarized, as well as the latest progress in DC cooling field. Four main PCC technologies are discussed in this paper, namely independent heat pipe cooling, integrated heat pipe cooling, two-phase immersion cooling, and cold storage systems. Finally, the shortcomings of the current researches on the PCC methods are summarized, while some suggestions for future researches are provided to promote the application of PCC technologies and achieve safe operations and energy savings in data centers.

Contents

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Nomenclature

c_v	Specific heat at constant volume
E_n	Energy stored in an object
M	Mass
Q	Heat
Q_{vh}	Heat stored in an object (thermal charge)
Ts	Air intake temperature of the rack
T_h	Outlet temperature of the rack
T_{chip}	Chip temperature
T	Temperature
Tc	Outlet air temperature of the CRAC
Tr	Inlet air temperature of the CRAC

Abbreviations

AC	Air conditioner/Air conditioning
CFD	Computational fluid dynamics
COP	Coefficient of performance
CPU	Central processing unit
CRAC	Traditional computer room air conditioning
DC	Data center
dB	Decibel
EER	Energy efficiency ratio
HFCs	Hydrofluorocarbons
HTC	Heat transfer coefficient
ISVT	Integrated vapor compression and thermosyphon
IT	Information technology
PCM	Phase change material
PUE	Power usage effectiveness
SSHP	Solid sorption heat pipe
TGHS	Three Gorges Hydropower Station
TS	Thermosyphon
T-loop	Thermosyphon loop
VOF	Volume of fluid
VC	Vapor compression

1. Introduction

Data centers (DCs) server as the main infrastructure in IT industry, which are centralized repositories housing IT equipment (e.g., servers) and corresponding systems for data storage, acceleration, display, data processing and transmission [1]. A typical DC is mainly comprised of IT equipment, supporting equipment, redundant data communication connections, and various security devices [2,3], while Fig. 1 shows the layout of a typical DC and its major equipment [4]. During the past several years, 5G and artificial intelligence have ushered in an explosive development [5]. Under this circumstance, the global DC market reached 45.19 billion US dollars with a growth rate of 17.5% in 2016, while this figure increased up to 53.47 billion US dollars in 2017 [6].

The highly-integrated central processing unit (CPU) chips cause better processing performance and smaller size of computing servers, but higher heat flux and thermal density [7]. The increase tend of chips' integration density and usage will undoubtedly go on, which threatens the safe operation of servers and reduces its operaion efficiency [8]. Recently, the continuous optimization of data processing performance has increased the server rated power from 1 kW to around 20 kW per single rack [9], while the heat flux of servers has also risen by approximately 20 times compared with the level 20 years ago [10]. Relevant data indicates that the energy intensity of DCs is at least 100 times bigger than that of ordinary office buildings [10–12]. Thus, the achievement of high-performance and high-energy-efficient DCs is of the significance [13], which greatly affects global energy market and carbon emissions caused environmental problems [14,15].

The energy use in DCs during operating and maintenance stages accounts for about 70% of the total energy consumption [16]. In China, the famous Three Gorges Hydropower Station (TGHS) has an average energy output of around 84.7 billion kWh per year, while the annual electricity demand within DCs in worldwide is equivalent to about eight times that of annual total electricity output of TGHS [17]. According to Anwar et al. [18], IT industry is responsible for about 2% of global CO_2 emissions, while DCs are the fastest-growing CO_2 emitters whose carbon emission is equivalent to that of the aviation industry [19]. In 2010, DCs are responsible for around 1.3% of global electricity use, whose energy use was almost three times than that in 2000 [20], while the proportion of DC energy use has reached 3% of global electricity use by 2019 [21].

CPU operation consumes a large amount of electricity power, while part of them is ultimately converted into heat and dissipated into the DC [22,23]. The generated heat needs to be removed immediately and effectively; Otherwise, it may cause heat accumulation and overheating servers, and threaten its safe operation [24]. Thus, air-conditioning (AC) systems are required to remove the server overheating, promise the efficient and safe operation of IT equipment, and prolong its lifespan. The highly integrated electronic chips result in more serious thermal threats to servers and the increasing cooling demand [25]. Fig. 2 shows the energy spilt of a typical DC, while the energy use for cooling system (40%) is only second to that for IT equipment operation (44%) [26]. According to the research of Global Market Insights [27], the DC AC market will reach USD 20 billion in 2024. The overall energy use and CO_2 emissions in DCs can be significantly reduced by improving the cooling efficiency [28]. Besides, the cooling characteristics of AC systems directly affect the overall efficiency and level of power usage effectiveness (PUE) in DCs [29].

At present, many cooling strategies are available and applicable in DCs, mainly including traditional computer room air conditioning units (CRACs), airflow and cooling management, free cooling, liquid cooling and thermosyphon [31], while they can be classified into air-side and liquid-side cooling. Air-side cooling system is generally preferred due to its high reliability of cooling and lower initial investment and maintenance costs. Among all the air-side

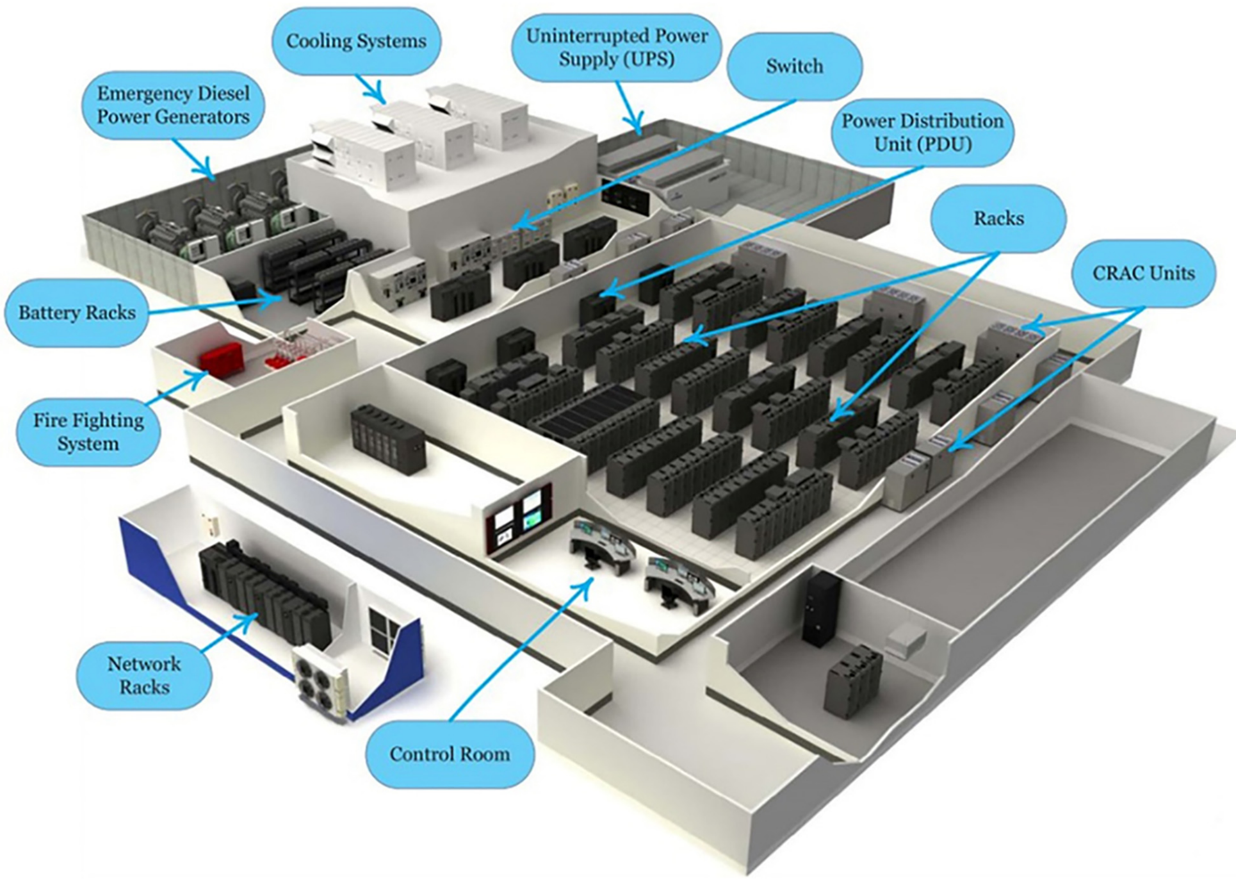

Fig. 1. The main components and layout of a typical DC [4].

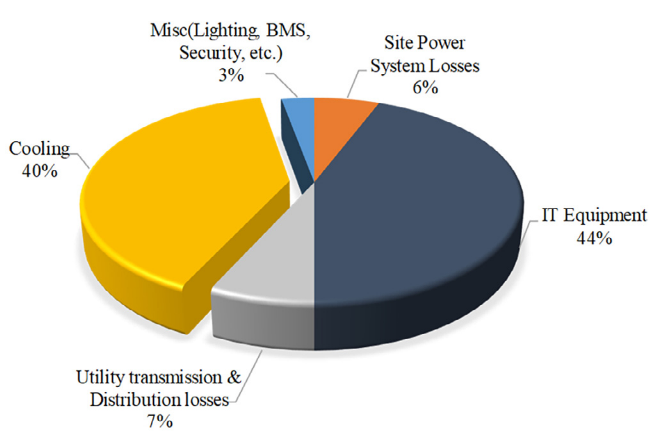

Fig. 2. Energy consumption of various parts of DCs [30].

cooling systems, CRACs are the most widely used cooling method applied in DCs, while this system is generally composed of chillers, water pumps, fans and cooling towers [32]. The vapor compression system has much high energy consumption due to the characteristics of working 24/24 h, 365 days/year. Also, the pipeline system consumes much energy, and the long-distance transportation causes some cooling capacity loss [25]. In a traditional l CRACs system, the mixing of hot and cold airflow is difficult to be avoided due to the lack of airflow control devices. To sum up, although the traditional CRACs have the benefits of high applicability and reliable cooling conditions, it has high energy consumption and low energy efficiency.

With the increased power and heat density of racks, traditional CRACs are unable to fulfill the explosive cooling demand in high-density DCs. Thus, many emerging cooling technologies have been introduced. Fig. 3 summarizes the available high-performance and effective cooling technologies applied in DCs. Not only can these new cooling systems improve the cooling efficiency, but also can they reduce energy and investment costs. The widely used energy-efficient cooling methods are as follows: liquid cooling [33,34], free cooling (e.g. air-side economizer, waterside economizer) [35–37], airflow management (e.g. hot and cold aisle forms, diversion baffles, server placement form) [38–43], SAT of CRACs [44] and cooling management (e.g. thermal contact water cooling system, indices parameters) [45,46].

Recently, phase change cooling (PCC) has become an innovative and promising cooling technology [47–49]. PCC can make up for the cooling lack of CRACs and achieve better thermal environment and energy saving of CRACs at the cost of only little energy use [50]. PCC can realize the forward state change of a thermally conductive medium from liquid to gas and corresponding reverse state change from gas to liquid [51]. When the operating powers and temperatures of computer parts are too high, the evaporating process of PCC can take away the heat and prevent them from overheating and damage [52]. PCC essentially utilize renewable energy and free cooling sources, which has the following advantages:

(1) The latent heat used is hundreds of times higher than sensible heat [53]. Compared with other cooling methods, PCC can achieve the decrease of the heated surface temperature variation and improvement of the heat transfer rate and heat dissipation of racks;

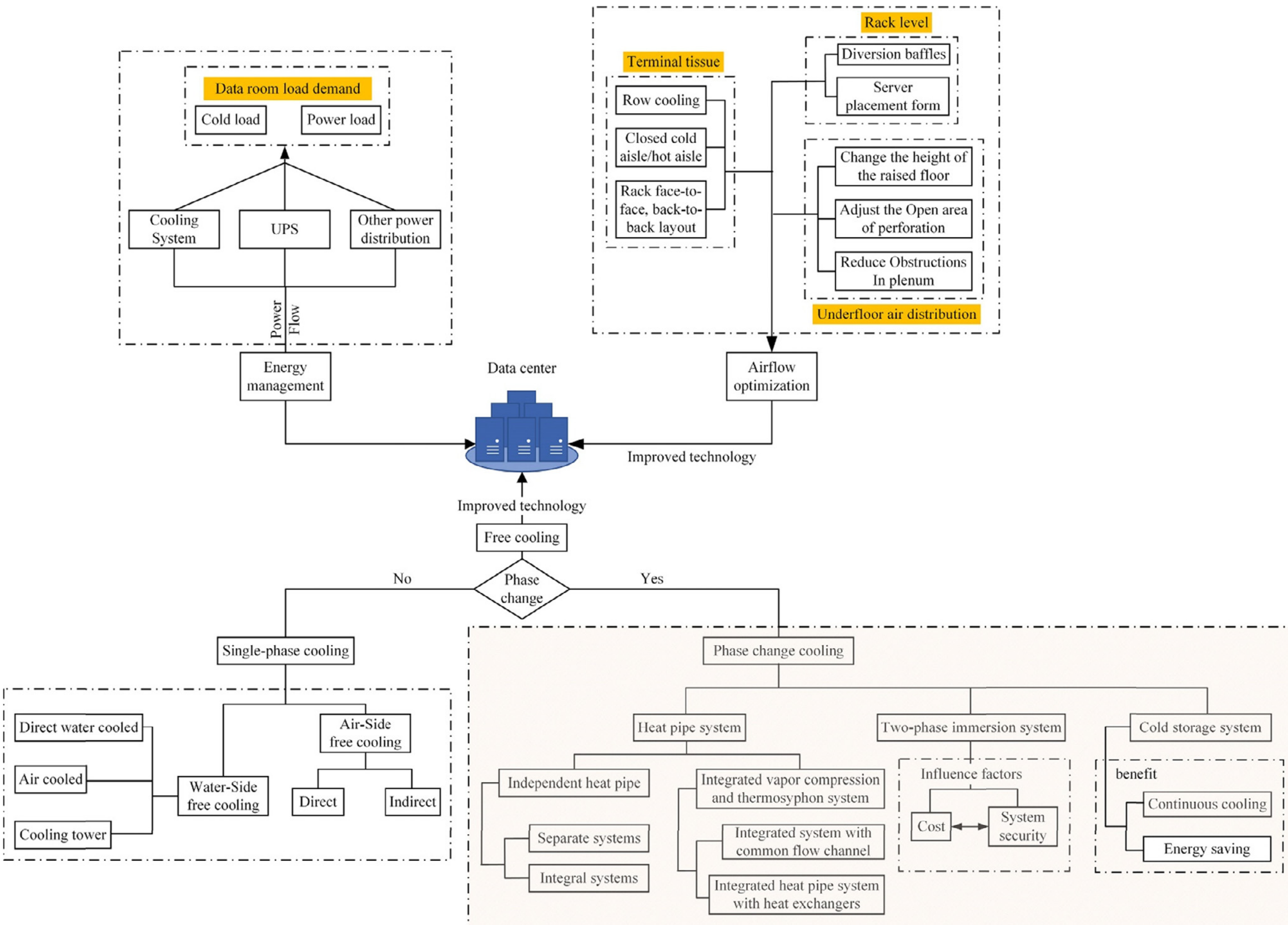

Fig. 3. Summary of current available high-performance and effective cooling technologies applied in data centers.

(2) It reduces the risk of airflow leakage inside the servers and achieves a more reliable and flexible cooling form in DCs [54];
(3) The reduction in the use frequency of the fan reduces the noise, and the noise level can be controlled below 45 dB [55].

The evaporating and condensing processes are achieved by phase change materials (PCMs), absorbing and releasing much heat, while the evaporating process will improve the thermal environment and reduce the ambient temperature by 3–10 °C [56,57]. The cooling capacity of PCC is more than 1000 times higher than that of the air-side cooling technologies [58]. Compared with other cooling technologies, PCC always undergoes an evaporation process, while various low-boiling electrolyte fluids and refrigerants can be used as coolants [50]. Reasonable selection of refrigerant will greatly affect the cooling performance of PCC [59]. PCC technologies have been widely investigated and applied in DCs, which has been proved to be high thermal performance and energy-saving.

The innovation of this paper is to comprehensively introduce and summary the recent progress of PCC applied in DCs, and divide them into four categories, including independent heat pipe cooling, integrated heat pipe cooling, two-phase immersion cooling, and cold storage systems. Besides, their separate characteristics, benefits and shortcomings are analyzed and summarized. This paper can give comprehensive and objective suggestions to scientific audiences in the field of PCC application and energy saving potential in DCs. Also, this paper gives some recommendation of potential research topics or research questions for future studies.

2. Independent heat pipe system

2.1. Characteristics of the heat pipe

Fakhri [60] defines the heat pipe as "a heat-transfer device that combines the principles of both thermal conductivity and phase transition to effectively transfer heat between two solid interfaces". The heat pipe can achieve long-distance heat transfer using the two-phase circulation within the pipe without any additional power. It has the characteristics of excellent thermal conductivity, reversibility, sustainability, variability and environmental adaptability [61], which ensures its wide applications in the field of spacecraft, computer systems, solar thermal, etc. The basic working principle of heat pipe is illustrated in Fig. 4. The temperature difference of working fluid is the only cause to the phase change circu-

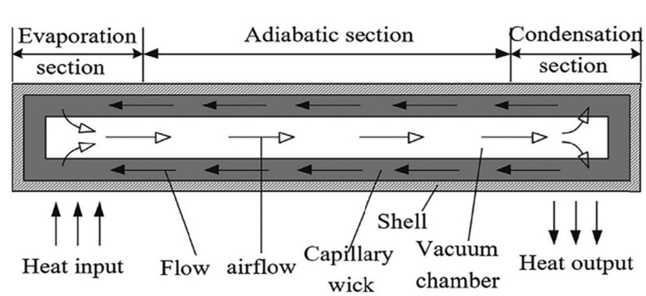

Fig. 4. The fundamental operating principle of the heat pipe [71].

lation [25], while the used cooling source is natural and sustainable [62]. Recently, many scholars have applied the heat pipes to DCs and investigated its energy saving potentials due to its simple but safe operation principle [63–70].

Heat pipe technology belongs to free cooling area, which is divided into two parts, independent heat pipe and integrated heat pipe system [25]. The difference between them is that independent heat pipe can improve the thermal environment without any additional mechanical cooling, while extra cooling device is required in the integrated system [72]. Under the circumstance of low outdoor temperature, heat pipe units can make use of the temperature difference between indoor and outdoor air to trigger the phase change process without operating the compressors and other refrigeration components, and then achieve the refrigerant circulation and cooling effects [73,74]. Heat pipe technologies applied in DCs can effectively use the natural cooling sources, but has higher requirements of outdoor environments [75].

2.2. Separate systems

In the separate heat pipe system, the only energy consumer is the fans of indoor and outdoor units; thus, its operating energy use is approximately three quarter less than that of the vapor compression (VC) system with the same cooling capacity [76]. In the DC application scenario, the phenomenon of air mixing and recirculation can be obviously alleviated by the separate heat pipe system.

2.2.1. Typical separate heat pipe

Ding et al. [77] studied the influencing factors of the separated heat pipe system. The relationship between filling rate and heat transfer capacity was explored, and the heat transfer capacity of each coolant was compared. As the filling ratio increases, the heat transfer capacity first increased and then remained almost constant. Finally, when the filling rate was high enough, the heat transfer capacity decreased. Qian et al. [78] presented the relationships between entransy-dissipation-based thermal resistance and supply air temperature in data center cooling system. The study found that the smaller the thermal resistance based on heat transfer, the better the heat transfer performance of the separate heat pipe. Based on the principle of minimum thermal resistance, the optimal area distribution relationship between the evaporator and the condenser was derived.

In addition, Ding et al. [54] applied entransy as an evaluation index to analyze the heat transfer characteristics of both traditional CRAC system and separate heat-pipe system. In addition, Guo et al. [79,80] also used entransy to describe the physical properties of stored heat and the internal energy (see Eq. (1)), while the irreversible loss in the thermal transmission process is calculated by the entransy dissipation in Eq. (2). The operation of the separation heat pipe cooling system will be more energy-saving than that of a traditional system with the same heat transmission loss of cooling air.

$$E_n = \int_0^T Mc_v T dT = \frac{1}{2}Mc_v T^2 = \frac{1}{2}Q_{vh}T \tag{1}$$

$$\Delta E_n = Q\Delta\overline{T} \tag{2}$$

where E_n is the energy stored in an object, M is the mass, Q_{vh} is the heat stored in an object, c_v is the specific heat at constant volume and T represents the thermal potential.

Samba et al. [81] conducted experiments on the French Telecom outside the rack with a thermosyphon loop (T-loop) and investigated its impacts on heat dissipation efficiency of servers. Fig. 5 shows the schematic map of the system. The results show that the system has the lowest working temperature and minimum thermal resistance in the case of optimum charging ratio of approximately 9.2%. In addition, the maximum load limit for T-loop cooling system is 600 W, which is 2.4 times that for conventional cooling system.

2.2.2. Micro-channel separate heat pipe

Micro-channel heat pipe exchangers have been used in the DC due to its advantages such as compact structure, low wind resistance and strong heat exchange capacity. Ling et al. [82] proposed an innovative concept of micro-channel heat pipe and investigated the effect of its environmental conditions and geometrical parameters on the thermal performance, while Fig. 6 shows the schematic diagram of the proposed micro-channel heat exchanger. They concluded that this system can greatly reduce the cooling energy use, while the cooling capacity is greatly affected by the evaporator fin fitch. Under the circumstance that the temperature difference between the indoor and outdoor air increased from 6 to 8 °C, the cooling capacity is improved the most, reaching 135%. Then, Yue et al. [66] established a complete volume of fluid (VOF) simulation model for a micro-channel structure of a heat pipe evaporator to study the airflow distribution and thermal environment in DC. They concluded that the optimum refrigerating charging ratio in heat pipe is between 68% and 100%, at which thermal environment can be effectively improved. In addition, Yue et al. [69] numerically studied the effects of liquid charging ratio on the heat transfer of heat pipe, and concluded that the larger the liquid charging ratio, the higher the liquid pool and larger the heat-transfer area of the two-phase refrigerant. The optimal liquid charging ratio is from 68% to 100%, while the flowrate distribution is largely affected by the liquid charging ratio and the position of import and export.

In summary, either typical separate heat pipe system or micro-channel separate heat pipe can achieve thermal environment improvement and energy saving in DCs and have further potentials. However, the application of these separate heat pipe system is relatively single and limited.

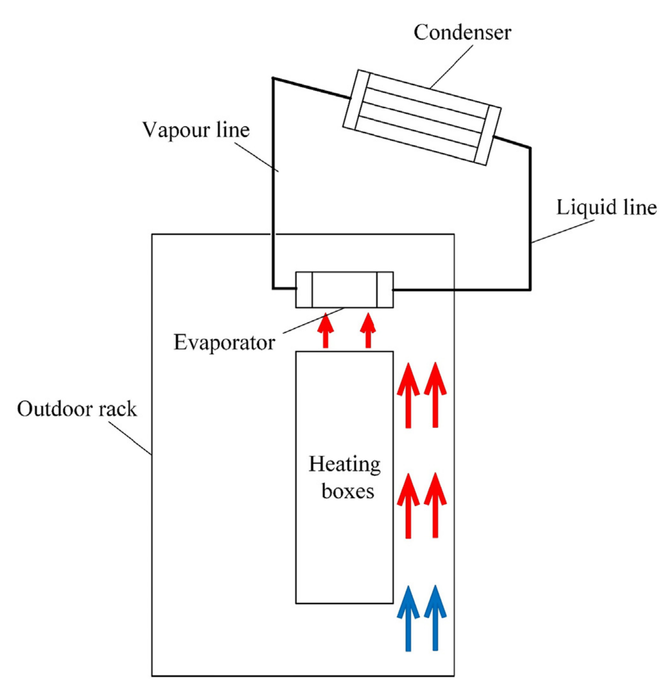

Fig. 5. Tiled T-loop for cooling telecommunications equipment in outdoor racks [81].

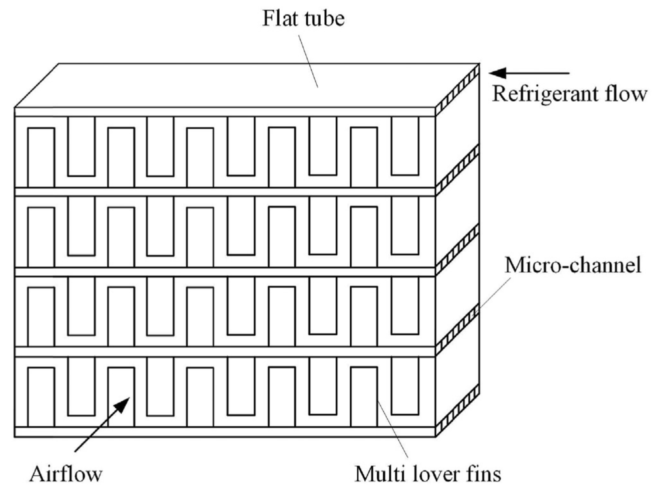

Fig. 6. Schematic diagram of the micro-channel heat exchanger proposed by Ling et al. [82].

2.3. Integral systems

As mentioned above that separate heat pipe system has limited application, so the integral heat pipe system has been considered and investigated further in existing literatures. The evaporating and condensing sections of the integral heat pipe are in the upper and lower spaces of the same whole [83]. The system has high heat transfer efficiency, and fins can be used to enhance heat transfer on the cold and hot sides of the heat pipe as required.

2.3.1. Pulsating integral heat pipe

A compact cooler for electronic devices based on a closed-loop pulsating heat pipe was put forward and studied by Maydanik et al. [84], while water, methanol, and R141b were used to be working fluids respectively to provide a well-distributed and centralized thermal load in different modes. They found that the most appropriate working fluid is methanol, guaranteeing that the cooler can be used in the widest thermal load range in both cooling mode and uniform cooling mode. Lu and Jia [85] designed a rack-level cooling system equipped with large-scale plate pulsating heat pipes, while Fig. 7 shows its schematic diagram. The results show that the working of the pulsating heat pipe will reduce the temperature in the rack and make the temperature distribution more uniform. Under the circumstance of most uniform temperature distribution, the optimum load has a relationship to the charging ratio of the pulsating heat pipe, while the increase of cold air speed causes the decrease of rack temperature.

2.3.2. Integral heat pipe systems with air duct

Li et al. [86] designed a novel heat pipe AC system with a specific air duct in DCs, while the outdoor natural cold source is used in the system. Fig. 8 shows the proposed integral heat pipe with air duct. The results showed that the new heat pipe AC system has the characteristics of high energy efficiency ratio (EER) and low energy consumption. When the temperature difference between indoor and outdoor air is between 5 °C and 24 °C, EER of the unit can reach 3.6 to 10.6, whose value is greater than the national standard EER (2.15-3.30).

2.3.3. Loop heat pipe

Loop integral heat pipe system can address the problems of high-power density of servers in DC and limited available cooling space in electronics. Zimbeck and Slavik [87] designed and analyzed an air-cooled loop heat pipe to cool dual processor servers, while the loop heat pipe is mainly made of copper alloy, and water is used as a working fluid. They found that design of the loop heat pipe can provide a 100 W processor with lower thermal resistance cooling for the server and maintain the chassis temperature lower than the stipulated 70 °C when the environment temperature reaches at least 50 °C.

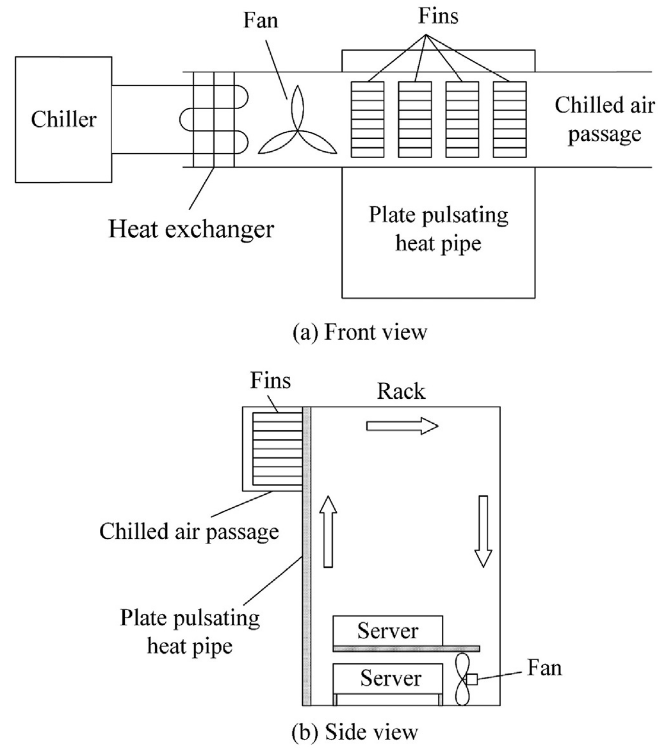

Fig. 7. Pulsating heat pipe refrigeration system put forward by Lu et al. [85].

In early 2001, Zhou et al. [88]built a mock-up based on an actual DC in Beijing to investigate the heat dissipation load and energy consumption characteristics of various pieces of equipment. The results showed that the heat dissipation of the envelope structure cannot meet the needs of the DC in winter, and additional cooling equipment must be installed. Its energy consumption can be saved by 41% compared with traditional system when the temperature difference between indoor and outdoor air is below 20 °C. Based on their previous research, Zhou et al. [67] put forward a pump-driven circulating heat pipe system and systematically investigated its cooling efficiency and thermal optimization effects on the DC. Fig. 9 shows the schematic map of the system combined free cooling and circulating heat pipe system. They found the correlation between EER and outdoor air temperature. They also found that the indoor ambient temperature can be maintained between 18 °C and 25 °C with this cooling system. This technology can be applied to approximately 74.2% of China's areas, while the average period for profitable investment is about 3.9 years, with an annual energy saving rate of more than 30%. Zhou et al. [89] also found that the AC energy consumption will be greatly affected by outdoor air temperature. When the outside air temperature has gone up 1 °C, the energy usage of AC system increases by 5.5% in average.

Table 1 compares and summarizes the characteristics and benefits of different independent heat pipe systems, which can be or have been used in DCs.

3. Integrated vapor compression and thermosyphon system

The application scope of independent heat pipe system described above is limited, and requires additional and separate

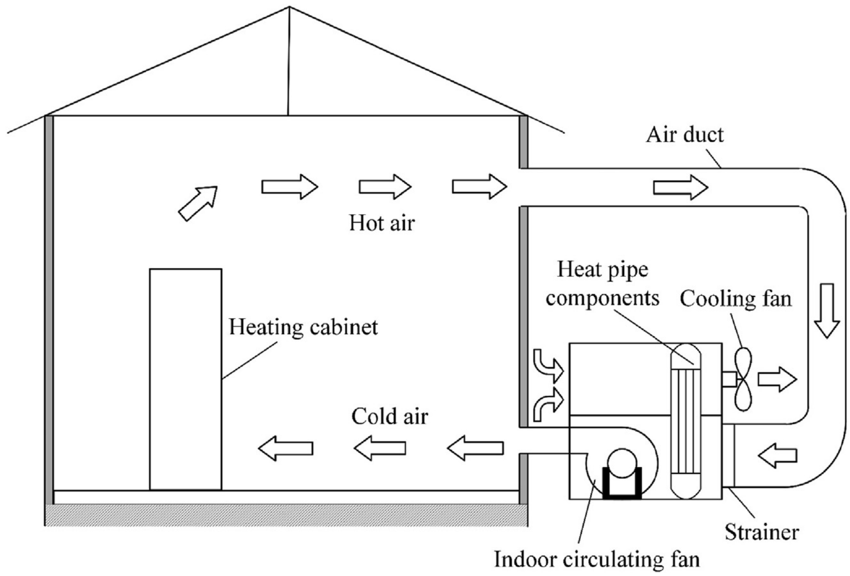

Fig. 8. An AC system of heat pipe desined by Li et al. [86].

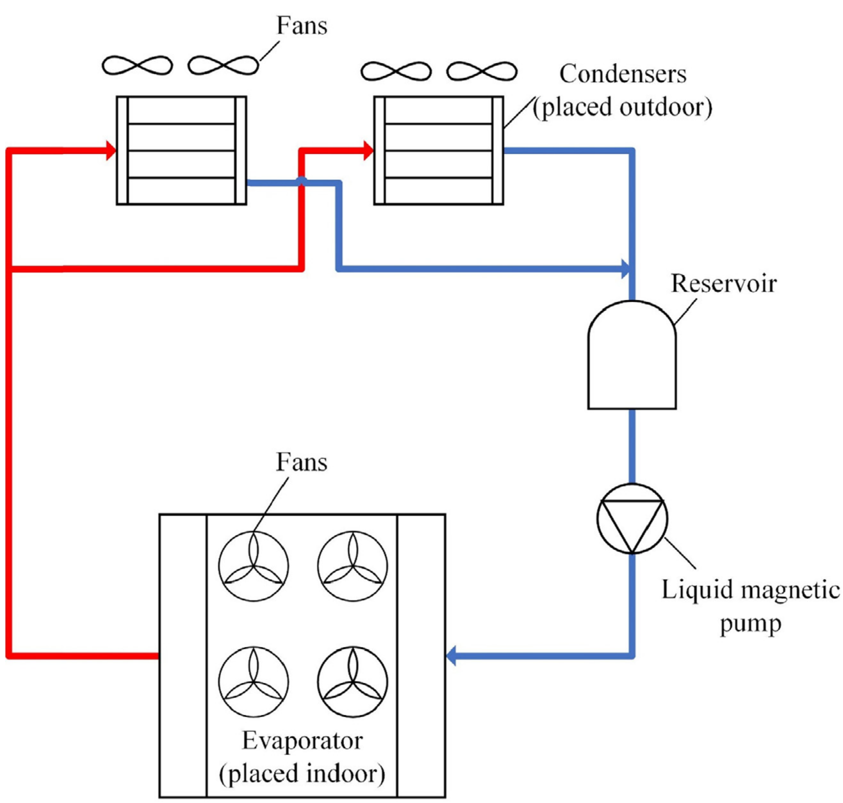

Fig. 9. Schematic map of a pump-driven circulating heat pipe system for the natural cooling [67,88,89].

AC system to meet cooling demand during hot season, increasing the installation and maintenance space requirements in DC as well as investment cost [84]. Apart from the independent heat pipe system, heat pipe system can also be integrated with vapor compression and thermosyphon system to further enhance its application scope and energy saving potentials, but auxiliary mechanical cooling is required in the integrated heat pipe system [72].

3.1. Integrated system with common flow channel

Integrated system with common flow channel is one of widely used cooling solutions, which integrates the vapor compression circuit and T-loop into the same entity. Based on the reform of vapor compression AC, Okazaki et al. [90] first proposed a cooling system in which the refrigerant utilizes a natural circulation loop.

Table 1
Characteristics of independent heat pipe systems in DCs.

Reference	Working fluid	Research method	Technologies description	Advantages	Major contributions and conclusions
Ding et al. [77]	Freon coolant	Experiment	(1) Separated heat pipe	- The filling ratio increases, the heat transfer capacity first increased and then remained almost constant. Finally, when the filling rate was high enough, the heat transfer capacity decreased.	The separate heat pipe system has a best filling rate, which depends on the relationship between the *K* of the evaporator and the condenser.
Qian et al. [78]	R22, R134a	Experiment	(1) Separate heat pipe	- The smaller the thermal resistance based on heat transfer, the better the heat transfer performance of the separate heat pipe.	The optimal area distribution relationship between the evaporator and the condenser is derived.
Ding et al. [54]	Chilled water	Experiment	(1) Separated heat pipe (2) T-Q diagram	- Much better airflow organization. - Uses cold air as a radiator in winter. - Almost no local hotspot in the rack.	The entransy dissipation of the CRAC system is 25.4% higher than that of separated heat pipe system.
Samba et al. [81]	N-pentane	Experiment	(1) Circulating loop(2) Separate heat pipe	- The maximum heat load obtained by the T-loop cooling system is twice that of the traditional one.	Double the maximum heat load and the best fill rate is about 9.2%.
Ling et al. [82]	R22	Experiment and simulation	(1) Micro-channel separate heat pipe (2) Enthalpy difference laboratory (3) Steady-state mathematical model	- Reduces energy consumption. - Ensures the indoor air cleanness of telecommunication stations.	The best refrigerant fill rate ranges from 88 to 100%.
Yue et al. [66,69]	R22	Experiment and simulation	(1) Micro-channel separate heat pipe	- Reduce computation cost. - Improve Thermal distribution.	The charging ratio is a critical parameter that affects the effective heat transfer area of two-phase refrigerant and the optimum ratio is 68–100%.
Maydanik et al. [84]	Water, methanol, R141b	Experiment	(1) Closed-loop pulsating heat pipe	- The cooler has a simple and compact structure and can operate efficiently in different heating modes.	The most suitable working fluid is methanol.
Lu and Jia [85]	R600a	Experiment	(1) Flat plate pulsating heat pipe	- The use of a pulsating heat pipe causes lower rack temperature and more uniform temperature distribution.	- Temperature decrease of the local hotspot by 3.8 °C and much uniform temperature distribution. - The optimal load is related to the filling ratio of the pulsating heat pipe.
Li et al. [86]	N/A	Experiment	(1) Heat pipe type AC unit	- The unit can be run to carry total or partial cooling loads of the DC with high EER.	Achievable COP of 3.63–10.64.
Zhou et al. [67]	R32	Experiment and simulation	(1) Pump-driven loop heat pipe system	- High EER compared to ACs.	The average payback period of the system in most regions of China is about 3.9 years, with an annual energy saving rate of more than 30%.
Zhou et al. [89]	R32	Experiment	(1) Heat pipe exchanger	- The system makes full use of outdoor cold air as a natural cold source.	The energy consumption of the heat pipe exchanger system is 41% of that of the AC under winter conditions in Beijing.
Li et al. [86]	N/A	Experiment	(1) Heat pipe type AC unit	- The unit can be run to carry total or partial cooling loads of the DC with high EER.	Achievable COP of 3.63–10.64.

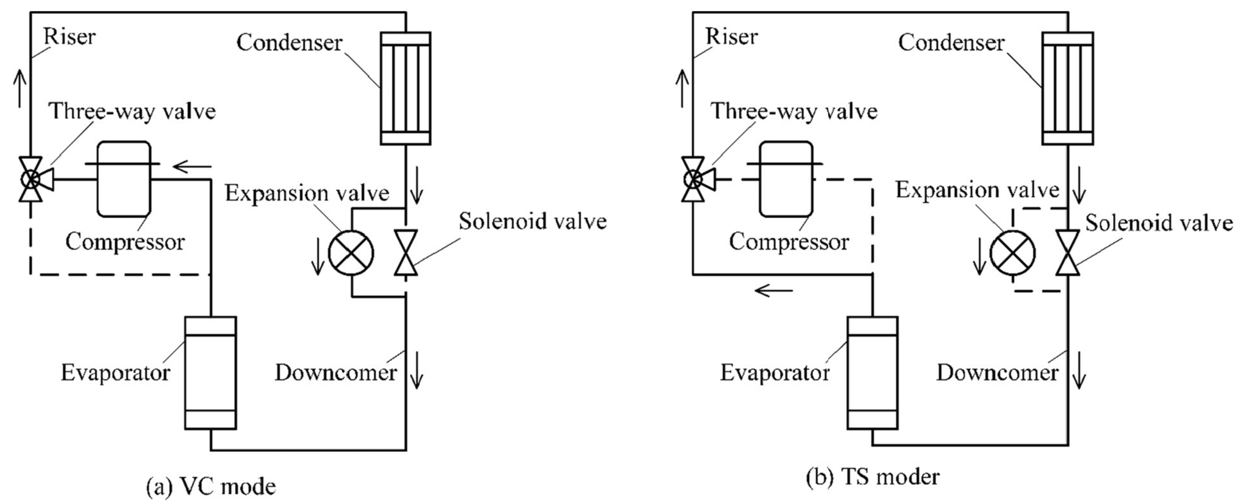

Fig. 10. Integrated AC with the T-loop improved by Han et al. [95].

In the thermosyphon mode, the cooling capacity increases linearly as a function of the indoor and outdoor temperature difference. The operating ratio of the natural circulation circuit compressor could be about 70% smaller than that of the traditional AC, while the energy consumption could be reduced by about 50%. In addition, Okazaki et al. [91] found that under two-phase conditions, the cooling capacity of R410A at a 20 °C temperature difference is about 30% greater than that of R407C, while the refrigerating capacity of CO_2 is about 4–13% greater than that of R410A. Lee et al. [92] designed a hybrid rack cooler specifically for the cooling device of outdoor communication systems and found that the refrigerating capacity of the hybrid chiller in the natural circulation mode is 95% of that in the vapor compression mode when the temperature difference inside and outside the rack is about 30 °C. Later, Lee et al. [93] also attempted to solve the difference of the best refrigerant charging ratio between the two operation modes by setting the liquid receiver. However, the capacity of these early integrated systems in the T-loop operating mode is often small, bringing some limitations in applications [94].

To simultaneously improve the performance of both vapor compression and T-loop modes, the combined systems require to be specifically designed in terms of their respective characteristics. Han et al. [95] proposed an improved integrated vapor compression and thermosyphon (ISVT) system (as shown in Fig. 10). In VC mode, the compressor runs with closing the solenoid valve. Under this circumstance, the compressor and condenser are connected by the three-way valve. However, in the thermosyphon (TS) mode, the condenser and evaporator are directly connected by the three-way valve. The system developed a self-operated three-way valve and designed a special inlet distributor of the evaporator and connecting tube to achieve low flow resistance. It works in the TS mode when the outdoor temperature is low or the cooling load is small, otherwise, it operates in the VC mode. A model that simulates the annual energy consumption of ISVT was established [96]. They found that the ISVT system saves 19–28% energy compared to a conventional AC system. It saves more energy in hotter districts, but the energy-saving rate is smaller. In addition, compared with the traditional design, the refrigerating capacity of this ISVT system is significantly improved.

Daraghmeh et al. [97] proposed a two-phase T-loop system as auxiliary cooling for a DC with AC as the main cooling system. The AC was connected from the top through ducts, passing the cold air to the diffuser located between the tops. The finned tube thermosyphon heat exchanger was installed on the back of the rack. The results showed that the higher the filling rate, the bigger the energy saving to a certain extent. However, the highest energy saving (38.7%) was achieved at a filling rate of 70%, and further increasing the filling rate will increase energy use. Yu and Wang [98] designed a novel dual-mode thermal control system, coupled solid sorption heat pipe (SSHP) with direct air convection system in DC. When the outdoor temperature is low, the cooling of the condenser section is free. At the same time, the forced convection of a fan attached to single server was used to enhance heat transfer, which will help to achieve effective heat management of the rack. After adopting this system, the PUE of DC is decreased approximately from 2.0 to 1.7.

3.2. Integrated heat pipe system with heat exchangers

Wang et al. [99] proposed a composite AC system combining vapor compression with a heat pipe (as shown in Fig. 11) and its control scheme for zone operation. In the system, the plate heat exchanger is connected in series with the air-cooled heat exchanger in the thermosyphon circuit. According to the outdoor ambient temperature and the thermal load condition of the regulated object, the integrated refrigeration system can adopt three different operation modes (vapor compression refrigeration mode, composite refrigeration with heat pipe mode, and heat pipe mode) [109]. Compared with conventional cooling system, the energy saving ratio of the integrated system is as high as 40%, which can achieve significant emission reduction [25,94]. It is particularly suitable for the ambient temperature control of high heat density electronic integrated systems [101]. The energy saving of the integrated refrigeration system is based on the low energy consumption heat exchange of the heat pipe system in the low-temperature season. Under this circumstance, the COP reaches as high as 10–13, and the energy consumption and running cost of the system have been severely depleted [100]. The introduction of composite run mode has widened the application temperature zone of heat pipes and increased the annual operation hours of typical heat pipe applications.

Besides, Wang et al. [102] put forward another integrated refrigeration technology. As shown in Fig. 12, the heat pipe loop and the vapor compression loop are connected by a plate heat exchanger and they run in parallel. Refrigerant R22 can dissipate the heat to the surroundings through two ways: parallel heat pipe and compressor condensers. This study measured the capacity and EER of the system and simulated the energy saving effect. The

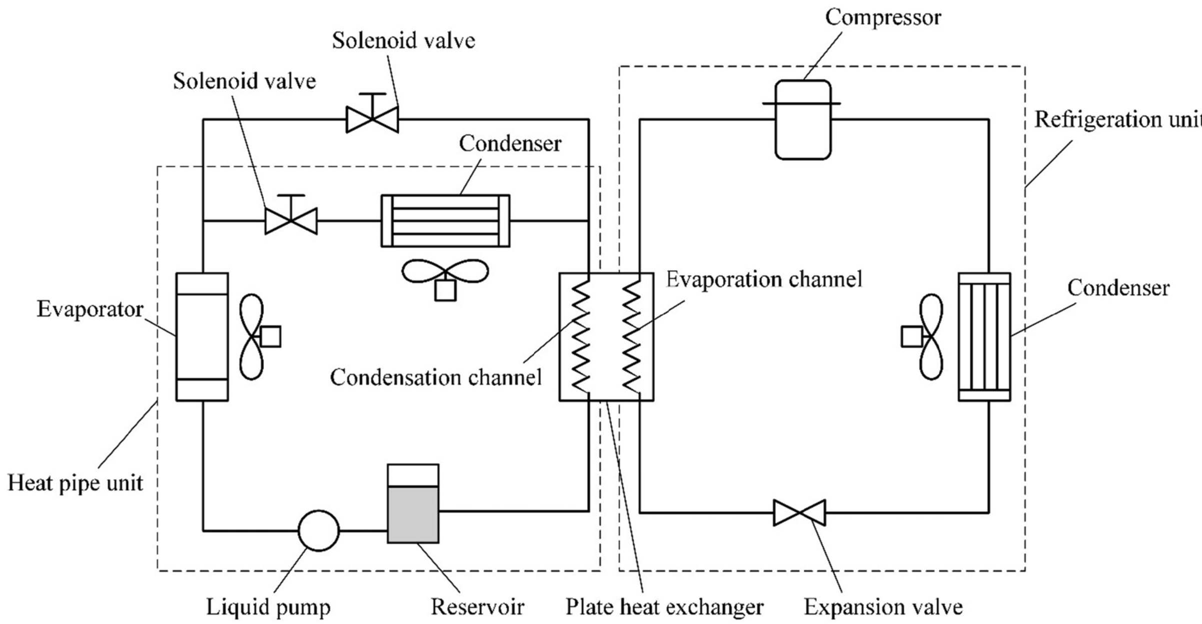

Fig. 11. A composite AC put forward by Wang et al. [99].

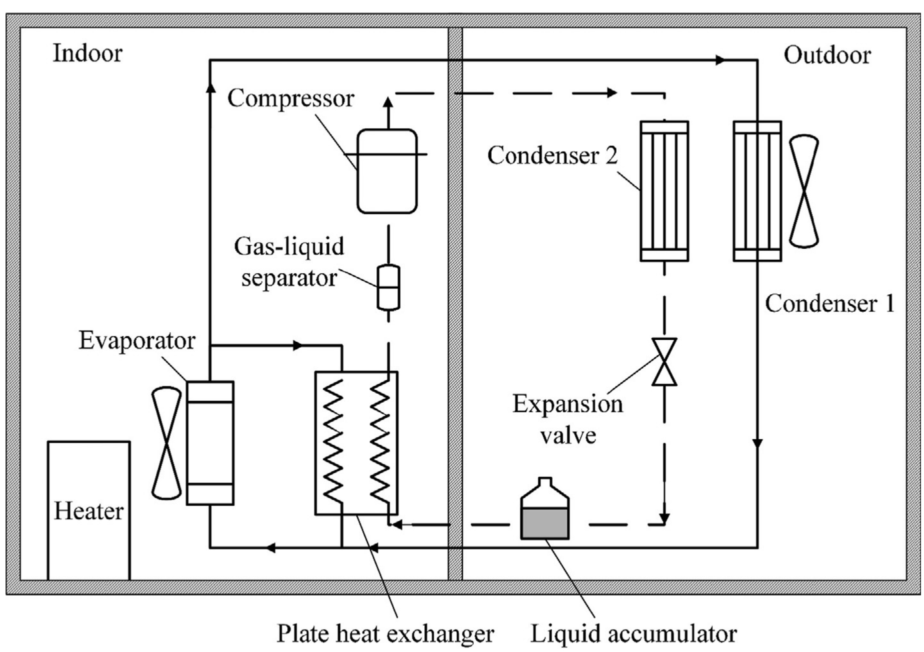

Fig. 12. An Integrated cooling technology put forward by Wang et al. [102].

energy conservation potential of this system varies with the change of season and regional climate. The thermodynamic analysis indicates that the PUE of DCs applying integrated heat pipe loop systems is 0.3 lower than that of applying traditional AC refrigeration systems in cold regions. Compared with other integrated systems [93,95], this system does not share any operating components and the problem of various heat exchange area and refrigerant dosage existing in the other dual-mode systems will not occur. In addition, no refrigerant flows into the compressor, thus avoiding refrigerant and lubricant mixing [94]. The system will be more durable by the fact that the pipeline is not fitted with valves.

To solve the difficulty of fluid distribution and flow control, Zhang et al. [36] put forward an integrated refrigeration technology with a three-fluid heat exchanger (as shown in Fig. 13). It combines two independent circuits of the VC refrigeration circuit and the T-loop through a three-fluid heat exchanger and avoids the reliability risk caused by mode switching [91,95]. The system is equipped with three different flow channels, which are used for the fluid of the refrigeration circuit, the fluid of the T-loop, and the outdoor air, while it can work under three modes in terms of the ambient temperature changing [94]. The results show that the three modes have enough cooling capacity, while the cooling capacity increases with the increase in the indoor-outdoor temperature difference. By calculating the annual energy consumption of four cities located in various climatic regions of China, and comparing it with the traditional AC system. They found that the annual energy saving ratio of the system is 5–47% when the room temperature at 27 °C. In addition, compared with other existing integrated systems [91,96,99], this system is more reliable and convenient to use and shows a huge potential utility in the natural cooling of DCs.

The heat pipe system integrated with heat exchangers can exchange heat under a small temperature difference without additional energy consumption [103], which can be combined with the traditional compressed AC technology. These two sets of equipment operate alternately and back up each other, which can reduce the energy consumption and guarantee system operation safety in DC at the same time. In addition, the heat pipe system does not have high energy-consuming components, and the moving and wearing parts are less used. Both ends of the heat exchanger are isolated, which effectively ensures the cleanliness and humidity of the air in DCs.

Table 2 summarizes the research on the integrated system. It is found that most integrated systems have three cooling modes:

(1) When the ambient air temperature is sufficiently low, the thermosyphon circuit system can separately undertake the cooling work of the DC;
(2) When the ambient air temperature is moderate, the thermosyphon circuit and the vapor compression loop operate simultaneously to ensure the ambient temperature of the DC is stable;
(3) When the outdoor temperature is high, the thermosyphon circuit system stops working and the vapor compression system operates separately to offer the required refrigerating capacity of the DC.

4. Two-phase immersion system

4.1. Characteristics of two-phase immersion cooling

Two-phase immersion cooling is an effective method to eliminate the thermal generated by the electronic equipment, and is also known as pool boiling [104,105]. It immerses the electronic equipment of the system in a tank with boiling volatile dielectric coolant [106,107]. The heat generated by the electronic device is effectively absorbed in the form of saturated vapor, and can be efficiently transferred by condensation to an external cooling medium. Fig. 14 shows the simplified operation principle of immersion cooling system [108]. The vapor generated in the boiling pool flows to the condenser and falls back to the container as a droplet. In addition, this system controls the temperature of the component according to the coolant temperature, while the immersed coolant is selected based on the chemical compatibility with the component [109]. This system can reduce the floor area of refrigeration equipment, eliminate the need for air cooling infrastructure, and simplify the construction of facilities. However, it is not easy to repair, and may suffer from the risk of leakage.

Almaneea et al. [110] combined the experience curve fitting and flow analysis with a CFD simulation of the liquid immersion server in parallel structure in the DC rack. Fig. 15 shows its schematical diagram, it is made up of a dry air cooler and a buffered heat exchanger. They found that the PUE of the cooling system can be reduced to 1.08, which is far lower than the current average PUE of 1.5 of the traditional system. In addition, the value of PUE is affected by the occupancy rate of the rack. When the occupancy rate decreased by 80%, the value of PUE can increase by 26%. Therefore, the higher the occupancy rate of the server rack, the better the PUE value. Kuncoro et al. [111] applied a computer aided molecular design method and combined it with a quality factor analysis and determined novel heat transfer working fluids for the direct immersion cooling of electronic equipment. Their thermophysical properties are generally in a similar range.

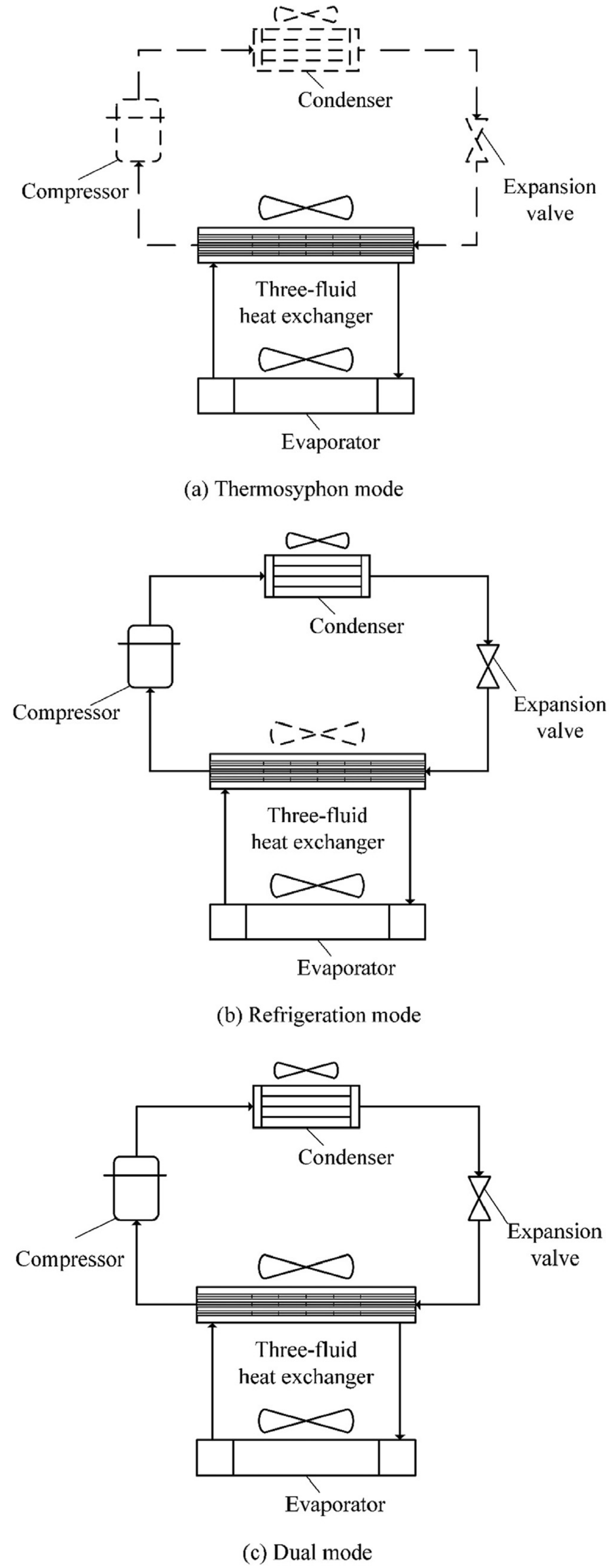

Fig. 13. The ISVT system of the three-fluid heat exchanger put forward by Zhang et al.[36].

Table 2
Summary of research on integrated systems.

Type	Researcher	Working fluid	System description	Benefits	Drawbacks	Major contributions and conclusions
Integrated heat pipe system with common flow channel	Okazaki et al. [90]	HFCs	- VC refrigeration cycle - Natural-circulation loop	Save energy for AC in electronics shelters.	For TS mode, the connection pipes between the evaporator and condenser result in pressure drop and reduced system performance.	The operating rate of VC refrigeration cycle is about 70% lower than that of traditional ACs. It consumes about 50% less energy than traditional ACs.
	Okazaki et al. [91]	HFCs and CO_2	- VC refrigeration mode - TS mode, - Solenoid valve - Check valve	The system can cut down the energy consumption of the communication base station.	The connection pipe will cause significant pressure drop when the system operates in TS mode.	The cooling capacity is related to the refrigerant charge. It increases linearly with the increase of indoor-outdoor temperature difference.
	Lee et al. [92]	R134a	- VC - Natural circulation	The hybrid cooler could conserve energy and improve the cooling failure of the compressor when the ambient temperature is low.	In TS mode, the diameter pipe can cause considerable pressure drop and reduce performance.	When the indoor-outdoor temperature difference is large enough, the cooling capacity of the hybrid cooler under natural cycle mode is 95% of that in the VC mode and increases with the cooling charge increases.
	Lee et al. [93]	R134a	- VC refrigeration mode - TS mode - Liquid receiver	The design parameters and operating conditions are considered to optimize the performance of the hybrid cooler.	Compared with the VC cycle, the function of the natural circulation was influenced by the fin type, coil circuitry and vertical distance.	The optimum quantity of refrigerant for VC and natural circulation modes is 0.125 and 0.175, respectively and the optimum tube length and vertical distance for each path of the hybrid cooler are 2.0 m and 1.0 m, respectively.
	Han et al. [95]	R22	- VC refrigeration mode - TS mode	The integrated AC can save energy and space.	The improper use of mode switching valves and small connecting pipes will cause excessive pressure drop and reduce the refrigerating capacity in TS mode.	The integrated AC with thermosyphon saves about 34.3–36.9% more energy than the traditional one.
	Han et al. [96]	R22	- VC refrigeration mode - TS mode - Switching valves	This system can reduce energy consumption in different regions.	The operation time and energy consumption of this system are greatly influenced by the external environment	ISVT system saves 19.1–28.2% more energy than conventional AC systems. In hotter regions, it saves more energy, but the energy saving ratio is smaller.
	Daraghmeh et al. [97]	R-134a	- VC refrigeration mode - TS mode	When the filling rate reached 70%, 38.7% of energy was saved.	At a lower filling rate, the air temperature distribution at the exit of rack is very uneven.	The higher the filling rate, the bigger the energy saving to a certain extent. The highest energy saving (38.7%) was achieved at a filling rate of 70%, and further increasing the filling rate will increase energy use.
	Yu and Wang [98]	Composite sorbents	- Solid sorption heat pipe - Direct air convection system	This system can reduce the PUE of DC.	The optimization effect of the system for DC in a dynamic workload environment has not been verified.	The PUE has decreased approximately from 2.0 to 1.7.
Integrated heat pipe system with heat exchangers	Wang et al. [99]	N/A	- VC refrigeration mode - TS mode - evaporative condenser	This technology can cut down the energy consumption of the cold source system and avoid cold start and oil retrieving lubrication.	The system cannot meet the application need of high power and variable working conditions, and it has poor environmental adaptability.	The energy saving ratio of the integrated system is as high as 40%.
	Wang et al. [102]	R22	- VC system - TS system - plate heat exchanger	The system can run in three different modes.	The energy conservation of this integrated system will be affected by seasonal and regional climate changes.	The PUE value of the integrated system is 0.3% lower than that of the conventional refrigeration system.
	Zhang et al. [36]	N/A	- VC system, - TS system, - Three-fluid heat exchanger	The new system is more reliable and more convenient to apply than the existing ISVT system.	The application of this system has regional restrictions.	The annual energy saving ratio of the system is 5.4–47.3%.

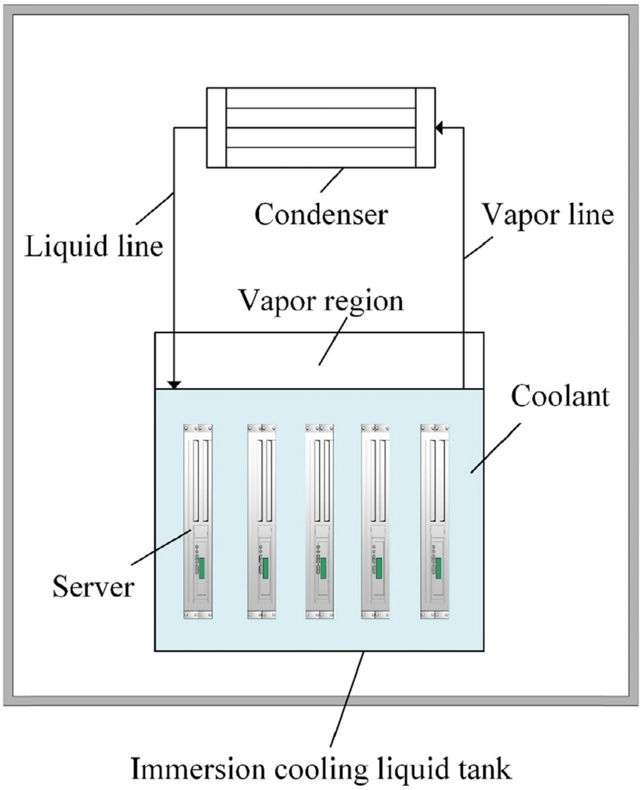

Fig. 14. The operation principle of immersion cooling [108].

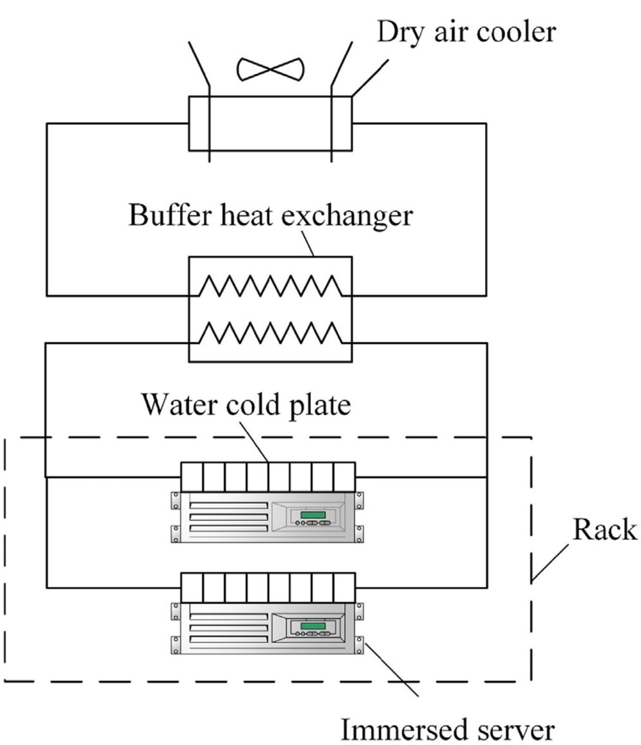

Fig. 15. The cooling system proposed by Almaneea et al. [110].

4.2. Advanced developments

Tuma et al. [112] studied the economic and environmental advantages of passive two-phase immersion with a dielectric liquid semi-open bath for cooling data communication devices. In this system, each server or node is inserted into the bottom plate of the storage tank that is partially filled with volatile working fluid. Compared with the traditional AC system, liquid cooling can greatly reduce the power required for refrigeration [113]. All the equipment is at the same temperature, and system costs and greenhouse gas emissions are lower than that of traditional AC systems [114]. The most significant advantage of this open pool boiling cooling system is that there is no server-level piping system, fluid connector and sealed shell, which makes the scheme applicable to more environments and the maintenance of its server components is less [115].

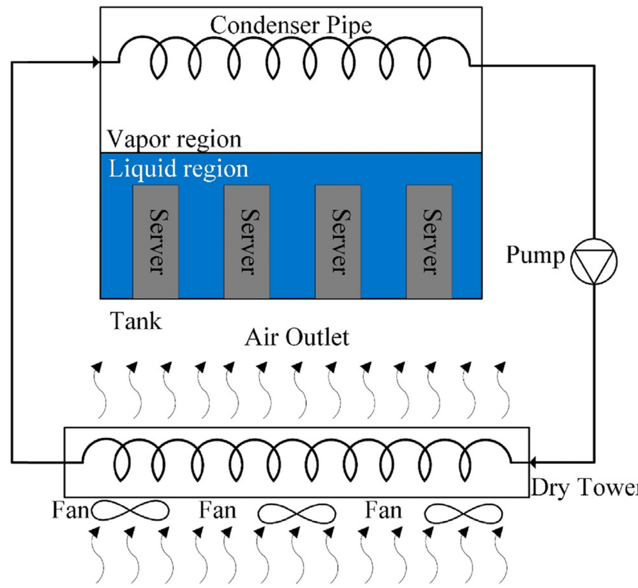

Fig. 16. Two-phase immersion cooling system constructed by Wu et al. [116].

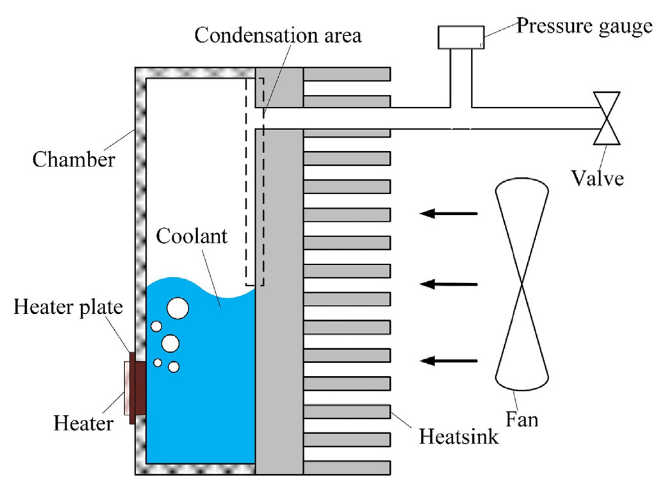

Fig. 17. The overall design of the immersion refrigeration device put forward by Wada et al. [118].

Wu et al. [116] used a highly wetted insulating liquid Novec 7100 as a coolant to construct a two-phase liquid immersion cooling system and investigated the heat distribution and equipment operation of the system. Fig. 16 shows the structure of the system. Even if the server is running at full power, the system can maintain the temperature of the server under proper working conditions. The energy evaluation inferred that COP reaches the highest value in the maximum power supply, and the system had the lowest

Table 3
Effects of different parameters on the heat flow function of the pool boiling method.

Influence parameter	Research object	Research results
Surface material [122]	Mild steel, copper, stainless steel	Compared with copper tube and stainless-steel tube, the heat transfer coefficients (HTCs) of the low carbon steel tube are less sensitive to the increase of heat flux. The copper tube has the highest HTC
Roughness and saturation [122]	Different roughness at 5 °C and 25 °C saturation temperatures	The increase of active nucleation sites increases roughness and HTC
Wettability [123]	Copper foam	The absorption capacity of the super hydrophilic sample is high, so the boiling heat transfer is enhanced
Uniform electric field [124]	Flat pool boiling	The electric field has an obvious heat transfer enhancement effect on boiling heat transfer

energy efficiency at full load and the highest energy efficiency at zero loads.

Sarangi et al. [117] used the wetted dielectric fluid FC-72 to study the strengthening effect of the copper particles on the pool surface boiling heat transfer. This technique places loose copper particles on the heated copper surface to form a nuclear location in the cavity. The results show that compared with the free particles of the same size and thickness, the heat transfer enhancement effect of fixed sintered particles on the polished surface has been increased significantly. Wada et al. [118] put forward a two-phase immersion cooling system to reduce thermal resistance and effectively dissipate heat, while Fig. 17 shows its cooling device. When the system has high heat density, heat transfer resistance is reduced. The convection caused by two-phase immersion boiling will enhance the internal thermal diffusion of the device and take away the heat emitted from the IT equipment. It is found that the increase in coolant filling rate will not cause a significant change of thermal resistance, but enhances the heat exchange and simplifies the thermal design of the system [119,120].

In conclusion, the heat flow characteristics of the two-phase immersion cooling make it a major contender for air cooling solutions. The whole-process energy consumption of heat dissipation is almost zero, and the overall energy efficiency is much high. This system is not affected by the natural environment, which greatly increases its application potential in DC. In addition, it not only ensures efficient heat exchange but also eliminates the potential threat of water. However, this cooling method requires a high demand for refrigerant [121]. Firstly, the refrigerant should have a low boiling point at low pressure and be close to normal temperature. At the same time, it must have no impact on electronic components. The performance and heat flow of the system are decided by different parameters, which have been thoroughly studied under different surface roughness and coolant conditions. Table 3 summarizes the influence of various parameters on the heat flow function of the pool boiling method.

5. Cold storage system

5.1. Characteristics of cold storage

Cooling demand must be met continuously in DC throughout the year due to its characteristic of 24/24 hrs, 365 days operation [125]. Cold storage system can make up for the cooling demand in case of emergency power failure, whose purpose is to overcome the mismatch in energy supply and demand in time [126]. When the energy price fluctuates greatly, it can reduce the peak load demand in a certain period, which brings benefits to the smart grid. Phase change materials (PCMs) are usually combined with cold storage technology. The application effect of PCMs in buildings is better than that of sensitive energy storage materials, and high energy storage density can be obtained [47].

6. Research progress

Sundaram et al. [49] developed a novel passive refrigeration system, which includes phase change material and a two-phase closed thermosyphon. It absorbed the heat emitted by the device at the hottest time of the day, stored it as latent heat, and released the heat into the environment through a thermosyphon in the evenings. The thermal energy storage unit stored enough cooling capacity and it could be used to absorb the heat emitted by the electronic device in daytime. Investigation results demonstrate that replacing a traditional AC system operated by a grid or diesel generator with this refrigeration system can save about 14 tons of CO_2 per year [125,127]. The system is not equipped with power supply, which is effective, environmentally-friendly and low-cost. It has good applicability in remote districts without power grid and system maintenance [25]. The air inside the DC is completely cut off from the outside air, thus ensuring the cleanliness of the working environment. Also, the temperature of each month is not the same, the capacity of the phase change material may not meet the needs, so the design needs to be optimized to maintain the stability of the system.

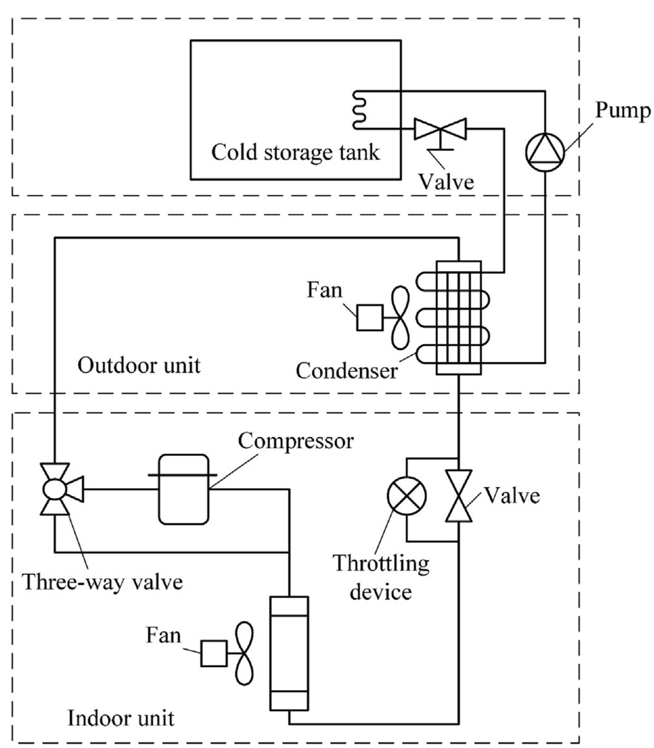

Fig. 18. Schematic diagram of a heat pipe cold storage system put forward by Wang et al. [132].

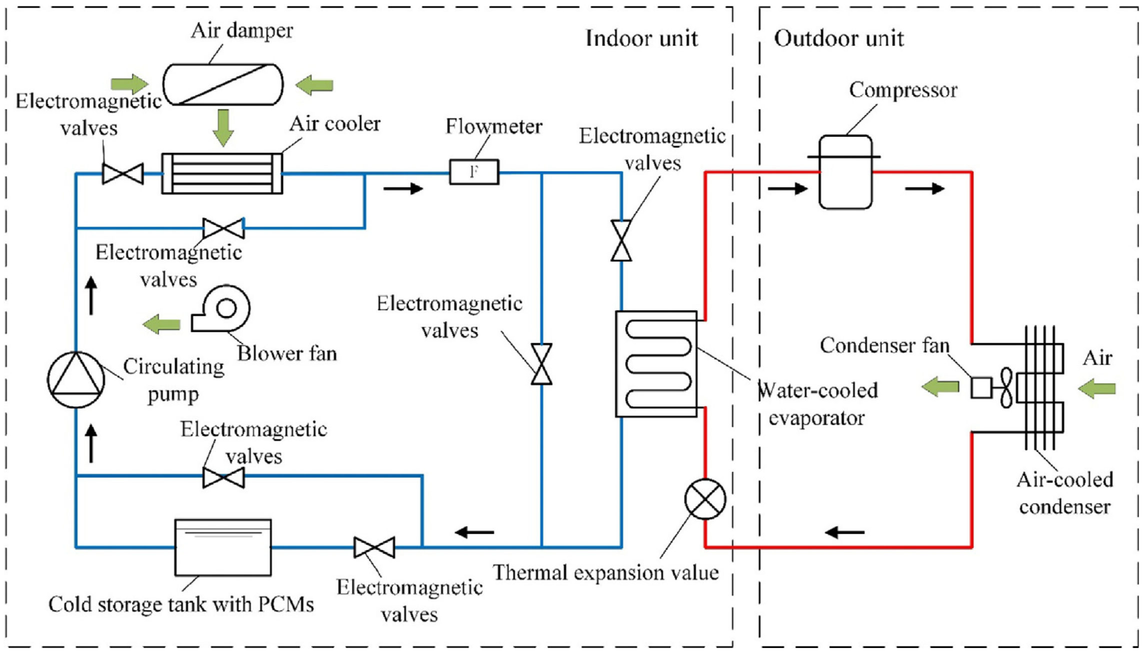

Fig. 19. The diagram of the refrigeration system put forward by Chen et al. [133].

Table 4
Phase change cold storage material for the AC system [134,135].

AC system type corresponding to phase change temperature	Phase change cold storage material	Type	Transformation latent heat	Phase change velocity
Low temperature cooling systems	-Dodecanol/ Caprylic acid	Organic	Big	Medium
	-Hexadecane-Tetradecane	Organic	Big	Fast
	-Caprylic acid–Lauric acid	Organic	Medium	Medium
Conventional AC systems	-Ice	Inorganic	Big	Fast
	-Caprylic acid–Palmitic acid	Organic	Small	Medium
	−40% Tetra–n–butylammonium -Bromide	Inorganic	Medium	Medium
	−76% Na2SO4·H2O	Inorganic	Small	Fast
	-Hexadecane–Tetradecane (2:1–2:3 by volume)	Organic	Medium	Fast
High temperature cooling systems	-Capric acid–Lauric acid	Organic	Small	Fast
	-Hexadecane–Tetradecane (6.5:1–2:1 by volume)	Organic	Big	Medium

To save energy consumption when the chiller equipment is shut down, Singh et al. [128] proposed a cooling system that uses heat pipes to store cold energy. The heat produced by the rack is taken away by the high-efficiency plate heat exchanger, and the cooling water is provided by the cold storage. The indirect contact high efficiency plate heat exchanger avoids contamination of the liquid cooled radiator [129]. Depending on the geographical location, the local annual climatic conditions, and the economics of the system, cold water storage or ice storage can be used [130]. Both storage methods can help minimize the heat load on the chiller unit, saving power and associated costs [131]. Wang et al. [132] proposed the construction of a hybrid AC system (as shown in Fig. 18) using unidirectional diode-type heat pipes. It adds a cold storage system by applying solidified dodecanol stearic acid. The results show that the PUE of the system is reduced from 2.1 to 1.51, the natural cooling time accounts for 75% of the whole year, the annual energy saving ratio is 28%, and the electricity cost is USD 9 591.

Chen et al. [133] introduced a refrigeration system using PCMs. According to climate conditions and cooling demand, the system can run in six modes. The cooling capacity generated by outdoor air or night steam compression refrigeration is stored by PCMs, and the stored energy is released in the daytime for indoor cooling supply. The illustration of this system is shown in Fig. 19. VC cooling can be used for real-time space cooling and cold charging at the same time. The feasibility and running effects of the system are evaluated by experiments. The results indicate that this system can cut down the amount of space required for refrigeration and greatly reduces the energy consumption of DCs.

The characteristics of typical phase change cold storage materials for AC systems is shown in Table 4. Wang's research indicates that the cold storage system is still in the exploration stage, but it has great application potential for the future [134]. The main differences between the latent heat storage system and the sensible heat storage system are shown in Table 5.

7. Discussion and further work

As cloud computing continues to heat up, high-density DCs will undoubtedly become the futural development trend in DC industry, which poses a huge challenge to thermal environment management and energy conservation. Based on the afore-mentioned researches, PCC could efficiently improve cooling performance and energy efficiency. In addition, this technology has low investment cost and energy-saving potential. Therefore, DCs with

Table 5
Comparison of latent heat storage system and sensible heat storage system [136].

Item	Latent heat storage system	Sensible heat storage system
Cold storage tank volume	Small	Big
Cooling temperature	1–3 °C	4–6 °C
Refrigerator power consumption	High	Low
Initial investment in cold storage system	High	Low
Cold storage source	Needs a stand-alone unit	System cold source can be used
Design and operation	High technical requirements and high operating costs	Low technical requirements and low operating costs
COP	Low	High

advanced PCC systems could have a notable competitive advantage over traditional systems.

This paper divides the DC phase change cooling technology into four categories, independent heat pipe cooling, integrated heat pipe cooling, two-phase immersion cooling and cold storage systems. Independent heat pipe system can meet the cooling demand only through the heat pipe without any other mechanical cooling. The only trigger of this system is the temperature difference; thus, no power transmission is needed for the cold source to take away the heat, causing low system energy consumption. It dramatically reduces the energy use of current general CRAC in DCs, and makes full use of outdoor natural cold sources to dissipate heat, achieving good indoor cooling effects. In addition, this system uses fewer moving parts and wearing parts, and has high stability.

However, when limited by the external environment temperature conditions, the independent heat pipe unit cannot undertake the cooling task in the DC and more. Under this circumstance, additional cooling system must be used to meet cooling demand in hot season. In order to avoid using two sets of cooling equipment, an integrated system, combined heat pipe and other cooling systems, was proposed. The system can reduce the initial investment to a certain extent, and flexibly switch the operating mode according to the ambient temperature. When the outdoor environment temperature is too high to satisfy natural heat dissipation, the system switches to VC mode (VC system working time is reduced). The system combined with vapor compression and thermosyphon system operate alternately and back up each other, which not only greatly saves energy consumption, but also effectively guarantees the safety and reliability of DC operation. It can be used as the first choice for environmental control of electronic equipment operating throughout the year such as DCs, especially in low temperature areas.

In addition, the two-phase immersion cooling technology doubles the heat transfer efficiency by boiling and condensing the coolant. This method hardly includes moving parts, but the control is relatively complicated. The pressure will change during the phase change, which places high requirements on the container, and the coolant is easily contaminated during use. The cold storage technology is suitable for newly built instead of in-use DCs, which using the phase change latent heat (much higher than sensible heat) to passively store and release energy. It is expected that the application market of cold storage system will develop rapidly in the future. Table 6 summarizes the characteristics, pros and cons of these PCC technologies, and make comments on future research.

In the future, PCC technology can be applied to different levels of DC cooling. Heat pipe cooling technology can be focused on overcoming material surface modification technology. The immersion liquid should be further investigated and optimized in the field of immersion phase change liquid cooling technology. The phase-change energy storage peak shaving technology can be further extended from room-level cooling to the rack-level, and even to the chip-level.

8. Summary and recommendation

PCC has stronger heat transfer capacity per unit area and is more suitable for cooling heating devices with higher heat load. The existing PCC technologies applied in DCs are reviewed and summarized in this paper. The broad conclusions and suggestions are as below:

1. Heat pipe system can be and has been applied as independent cooling or integrated/supplementary cooling modes at DCs with high heat density, while it has become a research hotspot in DC high-efficient cooling area. However, the application of this technology is limited by the outdoor ambient temperature.

Table 6
The characteristics, pros, and cons of these four PCC technologies.

Category	Independent heat pipe system	Integrated vapor compression and thermosyphon system	Two-phase immersion system	Cold storage system
Characteristics	-Cooling demand is met totally by the heat pipe; -DC can be cooled without other mechanical cooling.	Realize simultaneous operation of vapor compression and heat pipe cooling	Two-phase coolant can produce two states: liquid and gas.	The latent heat of phase change stores cold energy and releases cold energy when needed
Pros	-It does not affect the indoor air quality and humidity; -The heat transfer effect and the utilization rate of natural cold sources are relatively high.	-The heat transfer effect and the utilization rate of natural cold sources are higher; -Solve the problem that independent heat pipe system cannot meet the cooling requirements during hot seasons.	-The heat transfer efficiency is doubled; -System temperature is stable; -Operating environment is quiet.	The AC system can achieve the function of continuous cooling and has high economy
Cons	Limited by the ambient temperature conditions	-Most ISVT systems rely on solenoid valves for mode switching, which has high requirements for solenoid valves. -The reliability of the system for long-term operation cannot be guaranteed	Compared with single-phase coolant, the cost of two-phase coolant is too high.	The cold storage device takes up a certain amount of building space and increases the cost of cold storage equipment

2. Both the independent heat pipe system and integrated vapor compression and thermosyphon system can obtain a good natural cooling effect, while less moving parts and wearing parts are used, and the operation stability is high. However, independent heat pipe system application is limited by the outdoor ambient temperature, while integrated vapor compression and thermosyphon system can handle the problem of insufficient cooling capacity in case of high ambient temperature. Most existing performance studies on the integrated system use experimental models, and the internal flow performance parameters and geometric optimization of the system are still missing, and further simulation studies are needed.
3. The selection of working fluid for the heat pipe system lacks a unified and applicable standard. Due to factors such as price and performance, the DC heat pipe system uses R22 and other Freon refrigerants as the refrigerant, but it cannot meet the environmental requirements. Therefore, researchers should put more efforts on studying the green working fluid.
4. Two-phase immersion cooling can offer lower server operating temperatures, and reduce fan noise. However, the control of the evaporation of the cooling fluid is relatively complicated, and it is susceptible to contamination. This technology requires adjusting the design of DC around the working characteristics of the coolant, which increases DC construction cost greatly. Therefore, the system is more suitable for in-built DCs instead of existing ones.
5. The cold storage system can be used as an emergency backup cold source to achieve continuous cooling in DC. For areas with time-sharing peaks and valley electricity price differences, it can significantly reduce system operating costs and improve energy efficiency. In addition, the storage time for DCs is limited, and the cooling capacity provided by the system has certain limitations.

Currently, PCC systems lack an authoritative performance evaluation standard for the system design. When making standards, we should consider the cooling efficiency, interference with the indoor environment, carbon emission, investment cost, and expected working life. Besides, the lack of industry standards to regulate the use of PCC will lead to a waste of energy and environmental pollution.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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