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A review of thermal management and innovative cooling strategies for data center

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ABSTRACT

Within a data center, 52% of the electricity is used by the IT equipment, 38% by the cooling system, and 10% for the remaining equipment (electrical power distribution, UPS…). The cooling system is mandatory to maintain optimal air temperature and relative humidity and provide a safe environment for all the electronic equipment. This paper presents a review on thermal management in data centers and various potential cooling technologies developed respecting energy saving constraint. Numerous researchers have proposed different alternative cooling strategy and solutions to free air cooling. This article describes a state of the art cooling strategies of data centers. The open aisle configuration is the most often used technique to remove heat. It does not affect energy efficiency but increases the electricity consumption dedicated to air conditioning. The most promising cooling systems, capable of absorbing energy flux while decreasing electricity consumption and rising the energy efficiency, are identified and discussed. It includes free cooling, liquid cooling, two-phase technologies and building envelope.

1. Introduction

Data center is a large-capacity facility (up to 500 000 m^2) in which are gathered Information Technology (IT) equipment, such as servers or processors, and support systems designed to provide a safe and reliable environment for IT equipment. An example of data center is shown in Fig. 1. Electricity used by data centers worldwide doubled from 2000 to 2005, then increased by about 56% from 2005 to 2010. Recent energy statistics indicate that the data center industry is responsible for 1.3% of the world and 2% of the United States electricity consumption [1]. In fact, between 25% and 35% of the worldwide power consumption of data centers is consumed by US data centers [1].

Within a data center, roughly 52% of the electricity is used by the information technology (IT) equipment, 38% by the cooling system, and 10% for the remaining equipment (electrical power distribution, UPS…). Most of the energy supplied to the IT equipment is converted into heat. Thus, the cooling system is necessary to maintain optimal air temperature and relative humidity and provide a safe environment for all the electronic equipment.

In a data center, the temperature maintenance is often handled by a Computer Room Air Conditioning (CRAC) unit. With this unit, it is important to configure air flows well in order to avoid that temperature rises too high, which could imply property damages. The most regularly used configuration is the open aisle configuration where cold air from air conditioning and hot air from racks are separated [2]. This configuration does not affect the energy efficiency but increases the electricity consumption dedicated to air conditioning [3]. That is why it is relevant to design a less energy-intensive cooling system.

This review paper introduces the four most promising cooling systems capable of decreasing the electricity consumption and rising the energy efficiency. The free cooling technology consists of using the natural fluid to cool data centers. The liquid cooled technology is useful when the data centers have a high-power density. The two-phase flow technology consists of using a refrigerant capable of removing dissipated heat by racks and rejecting to the outside environment. The building envelopes technology consists of using a container or phase change materials (PCMs).

2. Energy and environment context

2.1. Energy consumption

The repartition of the electricity consumption in a data center is specified by Fig. 2. Demand-side systems, including processors, server power supplies, or storage and communication equipment, account for 52% of total consumption. Supply-side systems include the UPS, power

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Fig. 1. Data center in Nokia, Lannion.

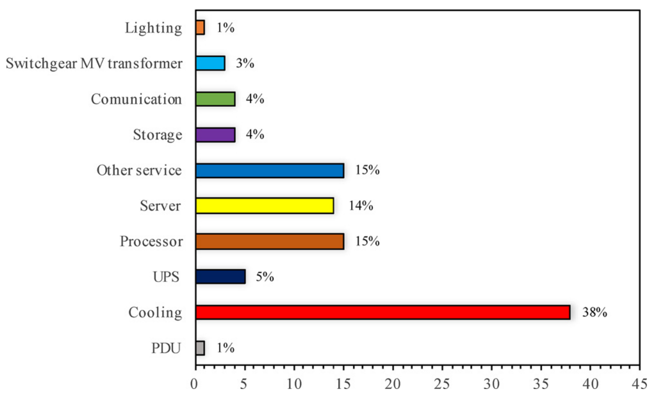


Fig. 2. Electricity distribution in data centers [4].

distribution, lighting and building switchgear represent 10% of total consumption. Energy consumption of data center traditional cooling is around 38% of data center total energy consumption [4].

The worldwide electricity usage in data centers has increased between 2000 and 2005 from 71 to 152 billion kWh per year, as shown in Fig. 3. This growth of the electricity consumption represents approximately 10% per year. In 2005, electricity consumed by data centers was about 1% of world electricity use. By 2010, world data center electricity use represents between 1.1 and 1.5% of the world electricity use. The lower bound figures represent 20 to 33% growth in data center electricity use compared to 2005. According to the Japanese Ministry of Economy, the electricity consumption will be five times greater in 2025 [6]. The strong electricity usage, particularly in cooling, has placed energy efficiency at the top of the agenda for both datacom businesses and policy makers [5].

2.2. Carbon footprint

The environmental impact has to take into account: in 2008, the Smart 2020 study highlights that in 2002, the global data center footprint, including equipment use and embodied carbon, was 76 $MtCO_2e$ and, by 2020, the value of 259 $MtCO_2e$ is expected – an increase of 7% per year until 2020 [7]. Fig. 4 shows the composition of data center footprint in 2002 and 2020.

2.3. Metrics for energy efficiency of data centers

The Power Usage Effectiveness (PUE) is proposed by the Green Grid initiative [8] as a fraction of total power of the data center to that used

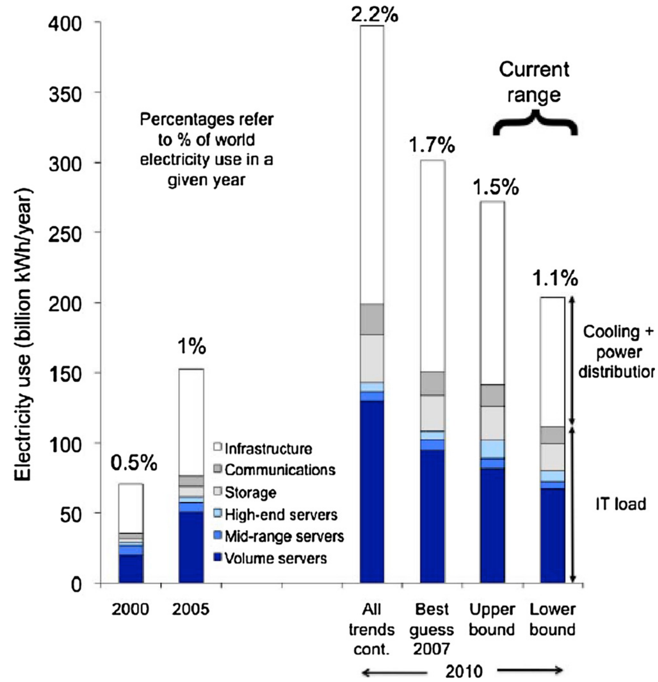


Fig. 3. Electricity consumption worldwide in data centers [6].

by the IT equipment. It is defined to assess the energy efficiency of data center over the year:

$$PUE = \frac{P_{DC}}{P_{IT}} \tag{1}$$

Where P_{DC} is the power of the data center, P_{IT} is the input power of the IT equipment

This can be expanded as [9]:

$$PUE = \frac{P_{cooling} + P_{power} + P_{lighting} + P_{IT}}{P_{IT}} \tag{2}$$

Where $P_{cooling}$ is the cooling equipment input power, P_{power} is the power lost in the energy distribution system through line-loss and other infrastructure (UPS or PDU) inefficiencies, $P_{lighting}$ is the power used to light the data center and support spaces, P_{IT} is the input power of the IT equipment.

A PUE of 1 would be an ideal value because it implies that all energy is used by the IT equipment. However this is possible if there is no cooling equipment or no power delivery components [10]. With proper design, a PUE value of 1.6 should be achievable but it could be equal to 1.2 [4]. The reduction in this value depends strongly on the cooling design and its effectiveness. PUE could be reduced by 50% using liquid cooling (passive or active) instead of a traditional raised floor. The reduction of PUE leads to increase the power per cabinet from 5 kW to 40 kW [5]. A study conducted by Lawrence Berkeley National Labs [11] where the authors benchmarking 22 data centers and showed a set of the best practice technologies for reducing the PUE value among which the authors included the use of evaporative liquid cooling and energy optimization of the cooling infrastructure.

The PUE itself does not take into account any reuse of energy, therefore the Green Grid defined the Energy Reuse Effectiveness (ERE) as [9]:

$$ERE = \frac{P_{cooling} + P_{power} + P_{lighting} + P_{IT} - P_{reuse}}{P_{IT}} \tag{3}$$

Where $P_{cooling}$ is the input power of the cooling equipment, P_{power} is the power energy lost in the power distribution system through line-loss and other infrastructure (UPS or PDU) inefficiencies, $P_{lighting}$ is the power used to light the data center and support spaces, P_{IT} is the input

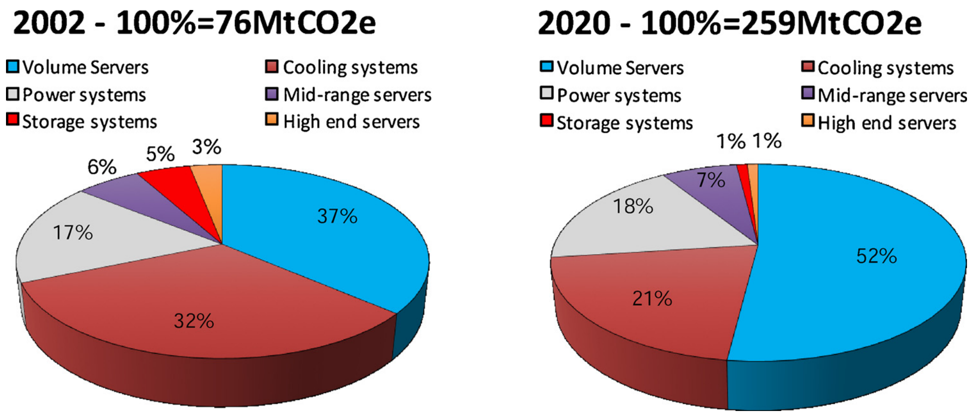


Fig. 4. Carbon footprint in data centers: (a) in 2002, (b) in 2020 [7].

power of the IT equipment, P_{reuse} is the heat reuse factor.

2.4. Temperature and heat load ranges

With the rise of data centers, dissipated energy flux, which was between 430 and 861 W/m^2, has been increased at least by 10 times (6 458 – 10 764 W/m^2). Design and manufacture of thermal management systems is one of the most challenging aspects of data center design : they must be capable of handling the increasing thermal loads while maintaining the temperature of electronic components at a safe operational level [1]. To design such a system, it is necessary to have accurate and reliable information about the maximum thermal loads and temperature limits in each component of a data center.

Rambo and Joshi [12] considered high power racks with heat dissipation of 57 kW in a model for data center airflow and heat transfer. Marcinichen et al. [13] stated that in designing cooling system for today's data centers, the assumed heat capacity for the racks is between 10 and 15 kW. However, if rack is filled with supercomputer servers, it can generate in excess of 60 kW of heat.

A server, which can be considered as the smallest data processing unit in a data center, contains microprocessors or additional memory (or DIMMs). Microprocessor chips are the major power dissipation components in servers: a typical server with two processors consumes almost 50% of the total server power through the microprocessors.

The majority of the electronics thermal management research considers 85 °C as the maximum allowable junction temperature for the safe and effective operation of microprocessors. However, microprocessors are not the only power dissipation components in a typical server : an individual hard disk can dissipate powers as high as 12 W, and up to 20–30 % of the total power supply can be consumed by mass storage devices [1].

3. Active cooling: air conditioning

In order to cool efficiently the IT equipment, a good layout of the data centers is necessary. It means to allow the good circulation of the air flow to cool the servers and to respect the climatic norms defined by the ETSI [14] and ASHRAE [15], introduces in Table 1.

The hot-aisle/cold-aisle configuration is the most widespread technique: the cold air is in a raised floor and goes in the data center through perforated tiles. Next the cold air is aspired by racks on the front side, gains the heat created by racks and is expelled at the rear of each rack. The hot air is then aspired by Computer Room Air Conditioning (CRAC) units and rejected to the exterior environment. The configuration is shown in Fig. 5 [16]. This layout provides the advantages of reducing equipment fan speeds, prolonging the life of the equipment and decreasing cooling costs by reducing mixing of hot and cold air. Indeed, the recirculation are harmful to the energy efficiency because this leads to an increase of the temperature on the front rack, which leads to set the output temperature of air conditioning to a lower level. The supply fan are then blower when the output temperature is low.

Table 1
Air temperature and humidity ranges.

Norm	Low air temperature	High air temperature	Low humidity	High humidity
ETSI (normal)	5 °C	40 °C	5% RH	85% RH
ETSI (exceptional)	−5 °C	45 °C	5% RH	90% RH
ASHRAE 2011 (recommended)	18 °C	27 °C	5.5 °C DP	60% RH and 15 °C DP

The issue with hot aisle/cold aisle design is the hot exhaust air and the cold air are likely to mix. Data center containment allows to reduce once again this mix. There are two containments, shown in Fig. 6: cold aisle containment and hot aisle containment. In the cold aisle containment approach, the cold aisle is enclosed by wall, enabling the data center to be full of large hot air. In the hot aisle containment principle, the hot aisle is enclosed and the hot exhaust air from IT equipment is collected through a raised floor and return to the CRAC units.

A CRAC unit is a device that monitors and maintains the temperature, air distribution and humidity in a data center. The CRAC unit uses the principle of compression refrigeration cooling, schematized in Fig. 7. It consists of extracting the heat from the room to cool and rejecting this heat to another place. Refrigerant flows through the compressor, which raises the pressure of the refrigerant. Next the refrigerant flows through the condenser, where it condenses from vapor form to liquid form, giving off heat during the process. Then, the refrigerant goes through the expansion valve, where it experiences a pressure drop. Finally, the refrigerant goes to the evaporator. The refrigerant draws heat from the evaporator which causes the refrigerant to vaporize. The evaporator draws heat from the region that is to be cooled. The vaporized refrigerant goes back to the compressor to restart the cycle.

The refrigeration compression cooling system is reflected in higher acoustic noise emission and an increase in fan power consumption. The acoustic noise emission is a general problem not only for telecommunication system but for electronics cooling. Besides noise emission, air blowers and fans are causing concerns in terms of reliability and energy consumption.

To reduce the 38% of electricity consumption brought by refrigeration cooling, pumps or fans, and to avoid recirculation caused by the hot-aisle/cold-aisle configuration, passive cooling techniques have been developed.

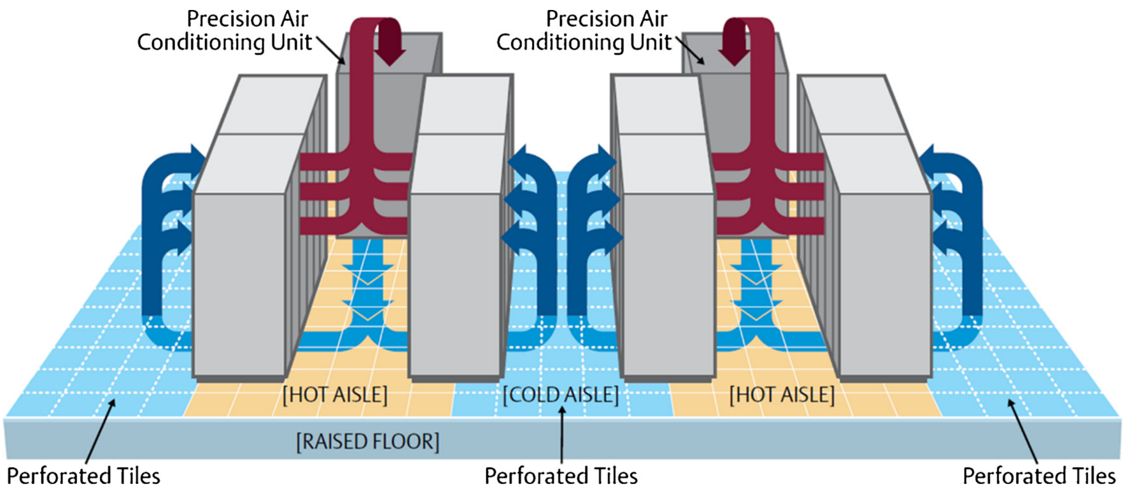


Fig. 5. Hot-aisle/cold-aisle configuration [16].

4. Passive cooling technologies

Four main passive cooling solutions have been created over the past few years: free cooling, liquid cooling, two-phase cooling and the influence of the building envelope. These technologies turn to be the more efficient passive cooling to improve heat transfer [18] and heat rejection to air ambient, to enhance the energy savings and to reduce instability especially for two-phase flow in micro-channels [19]. They also offer compactness, simplicity and less maintenance. The hot aisle and cold aisle containment could be considered as a passive solution [20] but the presence of CRACs and the PUE varying from 1.7 to 2.1 [5] turn to be an inefficient solution.

A particular attention will on introduction of passive evaporative cooling, due to its potential for improving the equipment sustainability, encoring the control and an efficient operating limit temperature under various constraints: temporal variation of heat dissipation, non-uniform repartition of heat and temperature, and fluctuation of the ambient temperature.

4.1. Passive cooling technologies

4.1.1. Free cooling

Free cooling technology consists of using natural fluid to cool data centers, by bypassing mechanical active component. This results in energy and cost savings, and improves energy efficiency. The airside economization and the waterside economization are distinguished. The airside economizers use natural cold air to cool data center, while waterside economization uses natural cold water. In the case of airside economization, the outside air needs to be at least 5 °C cooler than inside air. For both economization, the free cooling can be direct or indirect.

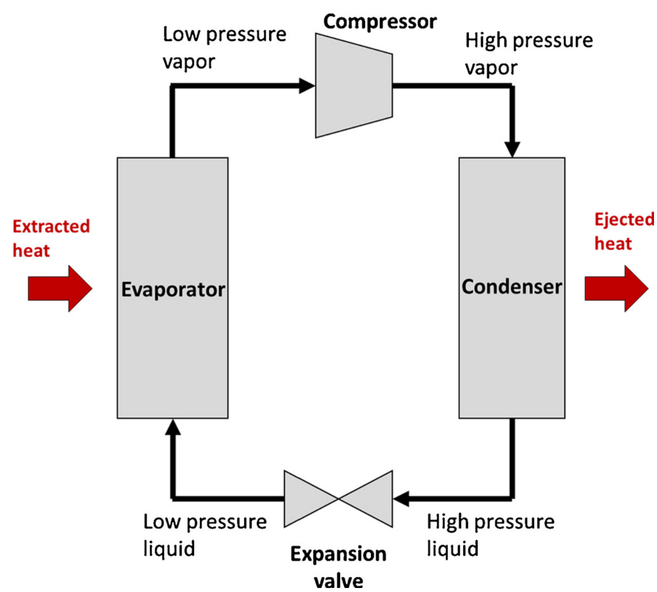


Fig. 7. Refrigeration compression cooling.

4.1.1.1. Direct airside economization. Direct airside economizer, shown in Fig. 8, uses fans to draw cold outside air into the data center. The indoor temperature and the humidity range are carried out by mixing exhaust hot air coming from the racks and cold outside air. This mixing

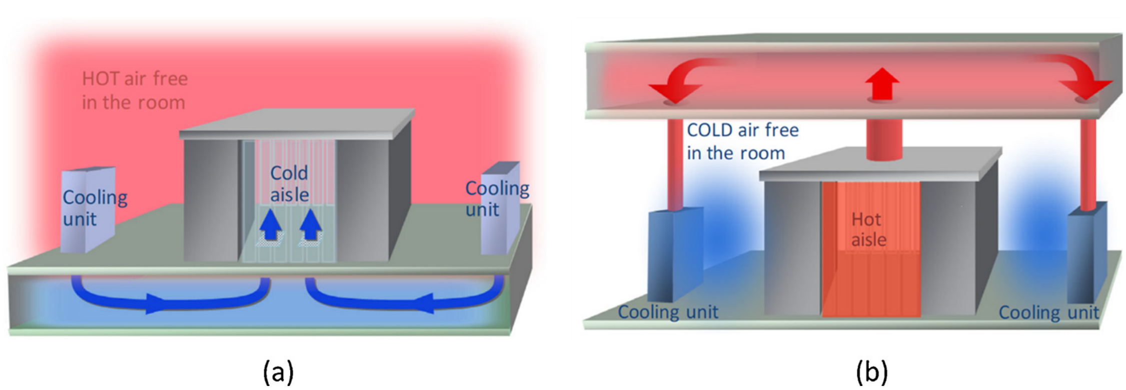


Fig. 6. Data center containment: (a) cold aisle containment; (b) hot aisle containment [17].

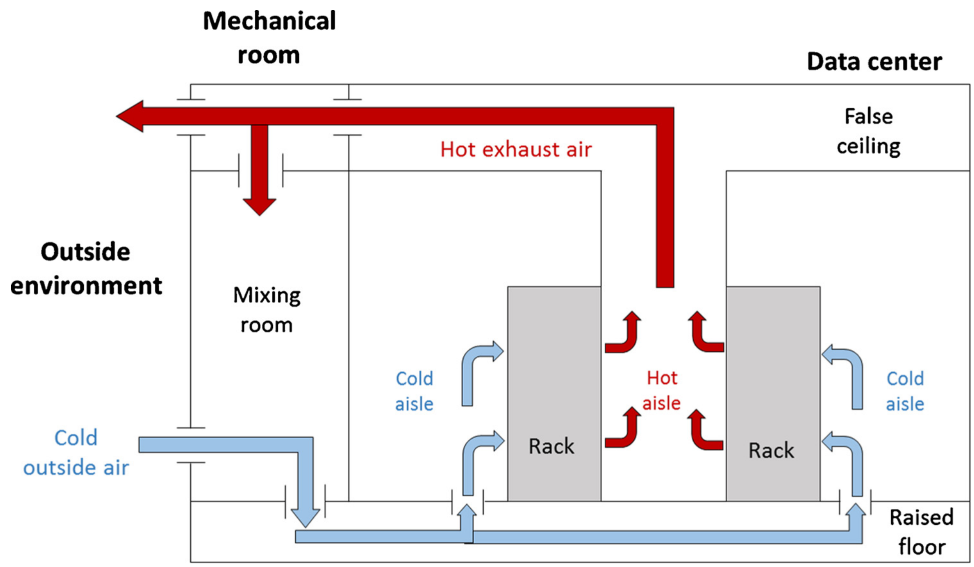


Fig. 8. Direct airside economizer.

air is injected into the telecom room by fans and louvers. Hot air is evacuated preferably by a false ceiling provided with perforated tiles. A part of this air is directly rejected outside while the other part is recycled in the mixing room [21].

The main advantage is the particularly low levels of energy consumption thanks to the lack of any supplementary cooling system such as CRAC. A system able to deliver 3 m^3/s can keep a cooling power value at 30 kW and consumes 1.5 kW. Therefore, the coefficient of performance (COP) is about 20 and the PUE is greatly decreased [22].

With the outside temperature, relative humidity in data center must take into consideration the allowable values between 20% and 80%. Too much humidity can increase conductive failures and corrosion. Conversely, too dry air is associated with electrostatic discharge and damaging equipment [16]. Air filtration is a real issue in data center because outdoor air contains impurities like dust or air contaminants. That is why air filtration has to be implemented to reduce any ingress which will cause damage or malfunction. Smoke can enter a data center through air inlets systems and cause false alarms on fire detection equipment [16].

Chen et al. [23] proposed a ventilation cooling strategy for a typical telecommunication base station in China. The air conditioners were substituted by fans for environmental control when the temperature and humidity of the outdoor air met the cooling requirements. The authors claimed energy conservation achieved was about 49% by the use of ventilation cooling technology.

4.1.1.2. Indirect airside economization. Indirect air economization uses the principle of heat transfer between the inside and the outside, materialized by the air-to-air heat exchanger [24] : outdoor air enters to the unit and flows through one side of the heat exchanger. Hot air from the data center hot aisles enters to the other side of the unit and flows through the opposite side of the exchanger, completely separated from the outdoor air by sealed heat exchanger plates. As the hot air flows through the heat exchanger, it transfers heat to the cooler outdoor air [25]. Fig. 9 schematizes the air-to-air heat exchanger technology.

Thus, outside air flow never enters into the telecommunication room. Therefore, there is a reduced risk of outdoor air impurities, and indoor humidity and pressure are not impacted, resulting in the potential to lower humidification costs and maintain. But a large quantity of these impurities going through the heat exchanger will accumulate over time, reducing its effectiveness and increasing maintenance frequency. Moreover, although these systems are very efficient, they need to be quite large, due to the sizeable surface area required to maintain an acceptable pressure drop and heat transfer.

Bao et al. [26] investigated a communication base station containing a plate exchanger to remove heat when the outdoor temperature was low enough. The results showed that the plate heat exchanger could cool the station instead of air conditioning for about 5014 h each year, and the corresponding electronic power saving rate reached up to 29%.

4.1.1.3. Waterside economization. When the data center is closed to a cold-water source, waterside free cooling is required to use water as a cooling source. A waterside economizer system is generally divided into indirect waterside and direct waterside economizers. Fig. 10 illustrated the chiller bypass via heat exchanger economizer mode. It uses the cold water to indirectly cool the data center chilled water when the outside air conditions are within specified set points.

4.1.2. Liquid cooling system

When data centers have a high-power density, different cooling technologies should be employed, such as liquid cooled systems. The main advantage is the higher heat transfer capacity per unit, which allows working with lower temperature difference between the Central Processing Unit (CPU) and the coolant. Higher inlet temperatures can potentially eliminate the need of active equipment for the heat rejection, and also open up the possibility of heat reuse [27].

4.1.2.1. Direct liquid cooling. The direct liquid cooling consists of attaching the CPU with a cold plate, while other components are cooled by chilled air flow. Direct liquid cooling improves the cooling efficiency by enhancing two heat transfer processes: the sink-to-air heat transfer process and air-to-chilled-water heat transfer process. Li et al. [28] pointed out that the total cost of the installation of the liquid cooling system for 1280 servers is approximately 396 000 $. Zimmermann et al. [29] studied the energy performance of Aquasar, the first hot water cooled supercomputer prototype. Fig. 11 shows that, on the server level, the liquid cooling was achieved with cold plate heat exchangers, placed on every component dissipating more than 3 W.

The prototype consists also of comparing the performance between this system and an air-cooled system. The cooling system has three cycles, with building heating grid as final loop, where the waste heat was reused. An intermediate loop was necessary to prevent overheating of the system. It was demonstrated that the temperature difference between the electronics and coolant was over 35 °C for the air cooling system while only 15 °C for liquid cooling. Moreover, the calculated

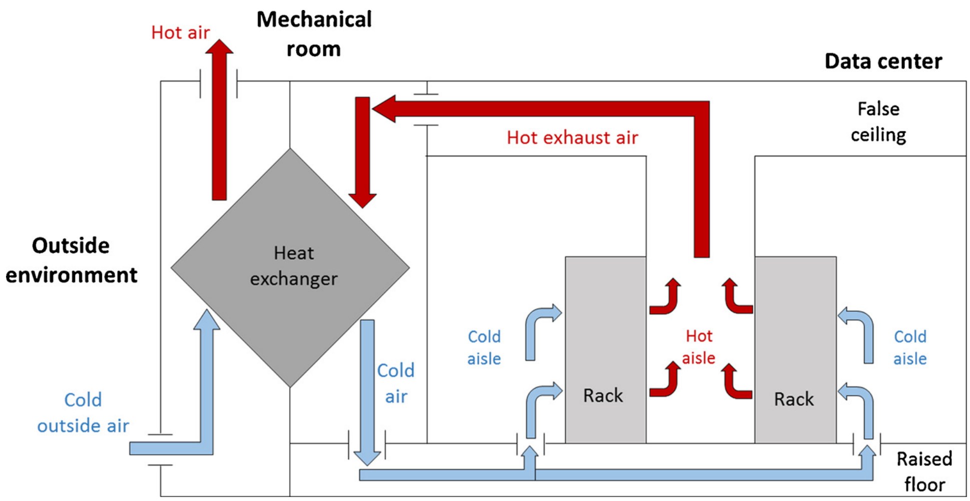


Fig. 9. Air-to-air heat exchanger for cooling data centers.

PUE was 1.15.

4.1.2.2. Rack-level liquid cooling. Unlike the direct liquid cooling, the rack-level liquid cooling consists of installing a liquid-cooled door, which is an air-to-liquid heat exchanger, on the back of the rack, as shown in Fig. 12. The hot exhaust air leaving the servers encounters the door and thus gets cooled down. This technique can avoid the need to separate the cold and hot air streams in traditional hot/cold aisle arrangements. Li et al. [28] assumed that, to replace 32 racks with liquid-cooled racks, a total cost of 987 968 $ is needed. Almoli et al. [30] developed a CFD code where a liquid loop heat exchanger is attached at back door. This study aims to compare liquid back door cooling versus traditional air cooling, and to prove the benefits of air-to-liquid heat exchanger in terms of energy savings. According to Garimella et al. [5], this method can reach a PUE of 1.3.

4.1.2.3. Submerge cooling. Another emergent liquid cooling technology is the fully immersed direct liquid-cooled system. It consists on submerging servers in liquid, usually mineral oil. The heat can be then directly transferred to an external loop and eventually released or reused. Its cooling enclosures can eliminate the need for CRAC units and chillers, allowing users to cool high-density servers. An example of submerge cooling solution is introduced in Fig. 13.

Haywood et al. [31] proved that 123 servers encapsulated in mineral oil can power a 10 ton chiller with a design point of 50.2 kW h. Compared with water-cooling experiments, the mineral oil experiment reduced the temperature drop between the heat source and discharge line by up to 81%. Due to this reduction, the heat quality in the oil discharge line was up to 12.3 °C higher than for water-cooled experiments. Furthermore, mineral oil cooling holds the potential to eliminate up to 50% cooling cost.

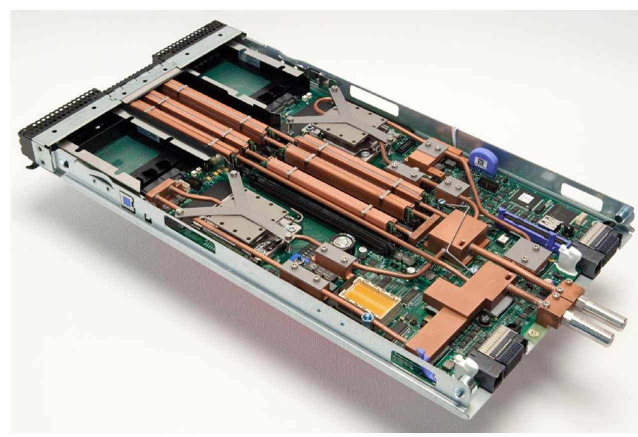


Fig. 11. Water cooled IBM blade center [29].

4.1.3. Two-phase cooling system

The need to find effective cooling solutions for devices which remove huge energy loads has been the driving motivation behind the use of two-phase cooled systems [1]. The particularity of this technology is to combine several cooling systems, which always includes the evaporative process. Passive evaporative liquid cooling can be considered in various applications [32–34]. Different coolants are available (water, air, refrigerants, nanofluids…) but the appropriate choice of coolant is specific to each application and packaging level.

4.1.3.1. Heat pipe system. Heat pipe heat exchanger has superior temperature control features and ability to transfer heat at small temperature difference without external energy, which is suitable for

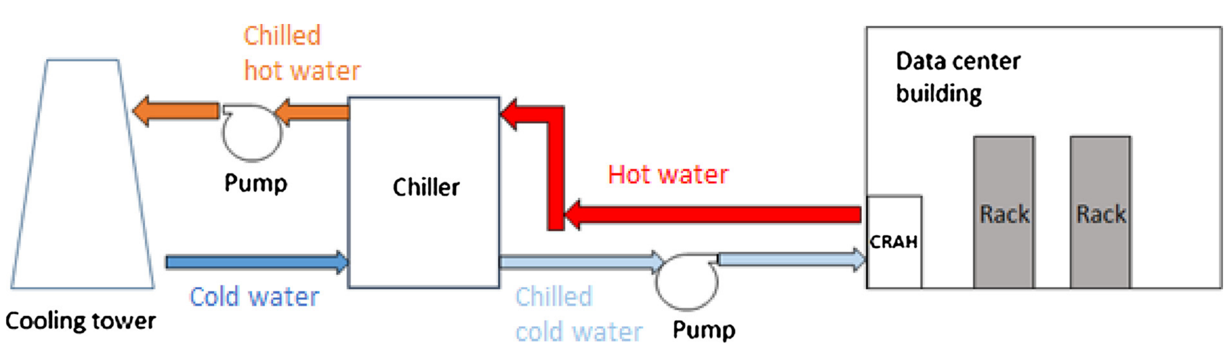


Fig. 10. Chiller bypass via heat exchanger economizer mode.

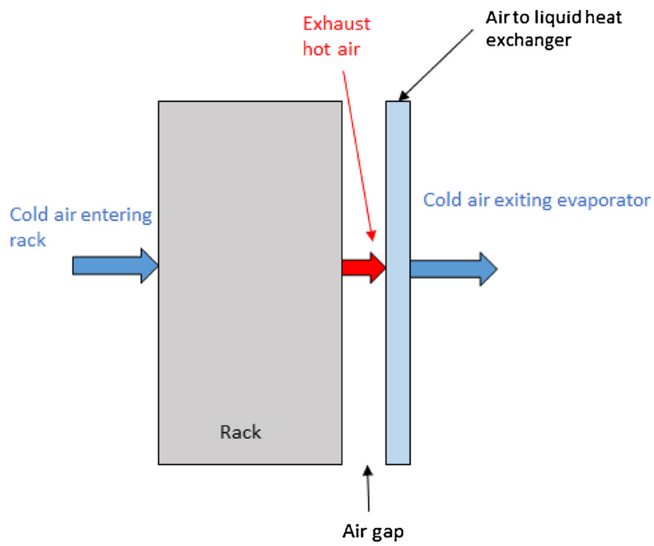


Fig. 12. Rack-level liquid cooling.

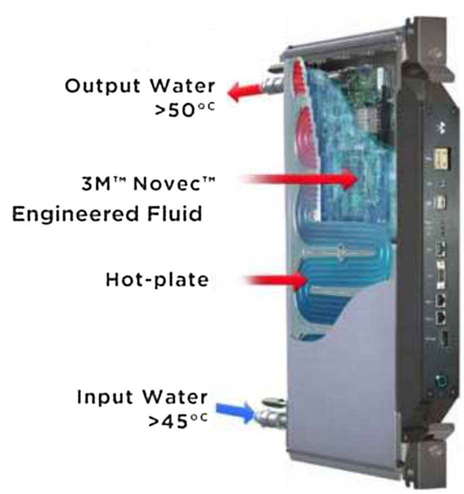


Fig. 13. Liquid-immersed module [27].

utilizing natural cold source [21]. Among the air-to-air heat exchangers, it is the most widespread. The heat pipe is a passive, hollow tube divided into three zones: the evaporation zone, the adiabatic zone, the condensation zone. Working fluid evaporates by absorbing the heat of the hot exhaust air. It travels through the hollow core and turns into liquid when it is in the condensation section. At the same time, it releases heat to the environment. In a horizontal configuration, as shown in Fig. 14 [35], the liquid travels back to the evaporator section via the wick by capillary action. Fig. 15 schematizes one possible schematic of an indirect free cooling unit incorporating a heat pipe [36].

In a vertical configuration, the heat pipe is called thermosyphon, as shown in Fig. 16. There is no wick and the working fluid, in liquid phase, travels back to the evaporator section by gravity. However, heat pipe has various limitations, particularly, capillary limitation that happens when the sum of all pressure losses inside the heat pipe exceed the maximum capillary pressure that the wick can sustain. Therefore, the driving capillary pressure is insufficient to provide adequate liquid flow from the condenser to the evaporator and dry-out in the evaporator zone will occur [37].

A chilled-cooling tower system is added to the heat pipe based cold storage system designed by Singh et al. [38] for data centers as shown in Fig. 17 in order to provide sufficient capacity. The cold storage provides the chilled water for extracting heat from the rack chipsets via highly effective plate type heat exchanger, which also helps to avoid contamination of the liquid cooled heat sink. The cold storage can be water storage or ice storage. The chiller-cooling tower system is connected to the cold storage and helps to provide extra cold energy to the storage water, when the capacity of the heat pipes is not enough. The downtime of the chiller equipment attributed to the cold energy storage system can save electricity cost. The above studies show that heat pipe system of data center has good energy saving effect compared to traditional CRACs for its excellent thermal control performance. Though it is still in the exploratory stage and has not been widely adopted due to unfamiliarity and reliability concerns, it has great application potential in the future.

4.1.3.2. Thermosyphon heat exchanger with interconnecting tubes. Thermosyphon heat exchanger is the combination of indirect airside free cooling and two-phase cooling technology. It is composed by an evaporator, a condenser and interconnecting tubes. The working fluid flows from the condenser to the evaporator by gravity, since the condenser is above the evaporator. The main advantage is the non-presence of mechanical components. But it needs a supportive vapor compression refrigeration system when the ambient temperature is relatively high. Fig. 18 shows an example of a two-phase thermosyphon loop in a data center. The evaporator absorbs heat from the racks to vaporize the working fluid. Vapor is flowed towards the condenser where it is transformed into liquid by air convection. Heat flux generated by condenser is then transferred to the outside.

. Ling et al. [39] designed a micro-channel separate heat pipe, where the effect of geometrical parameters and environment conditions are

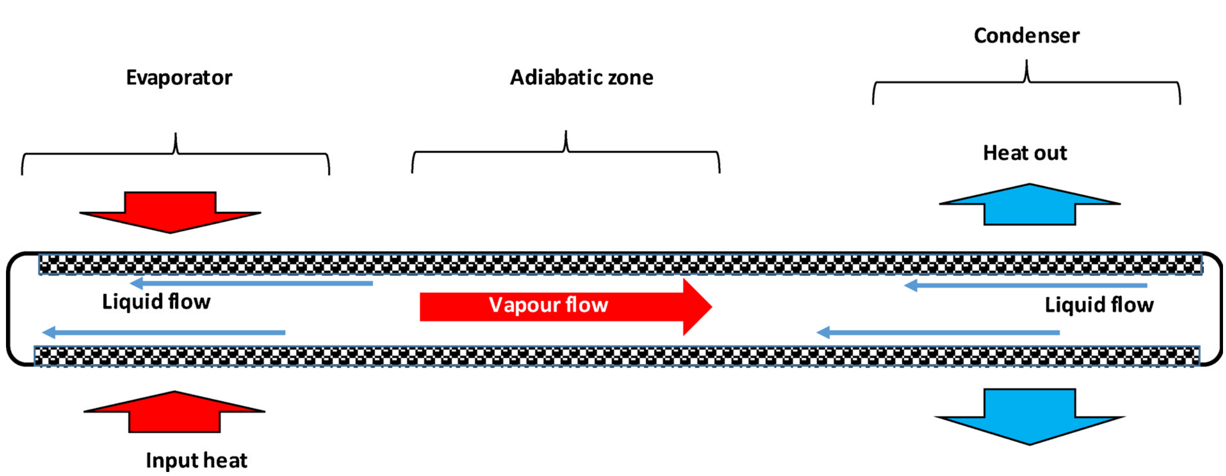


Fig. 14. Principle of the heat pipe.

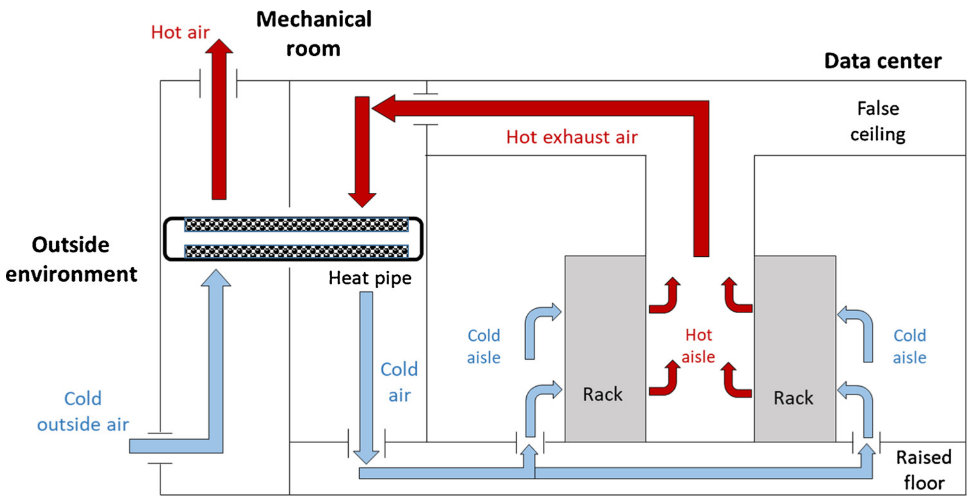


Fig. 15. Indirect free cooling unit with a heat pipe [36].

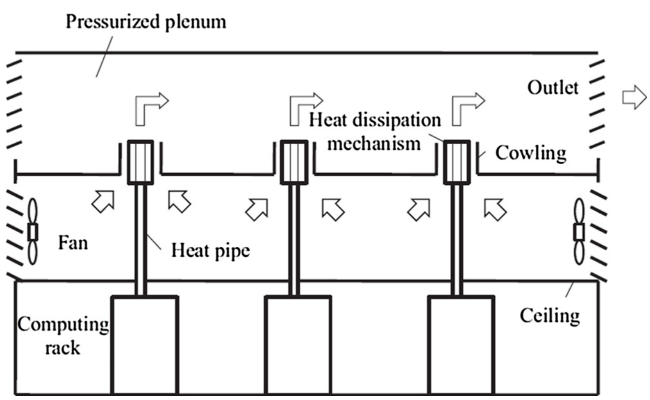


Fig. 16. Heat pipe thermosyphon [21].

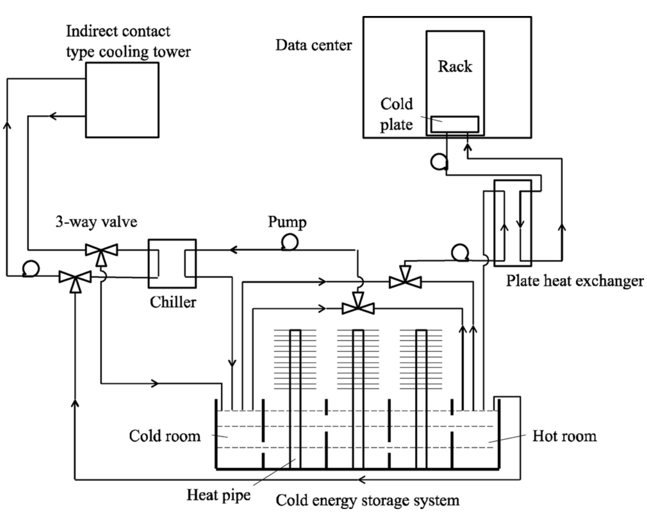


Fig. 17. Pipe based cold storage system combined with a chilled-cooling tower [38].

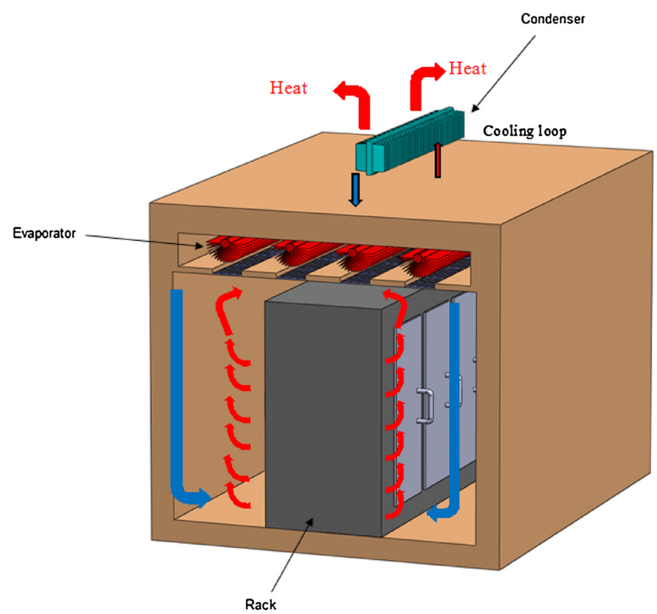


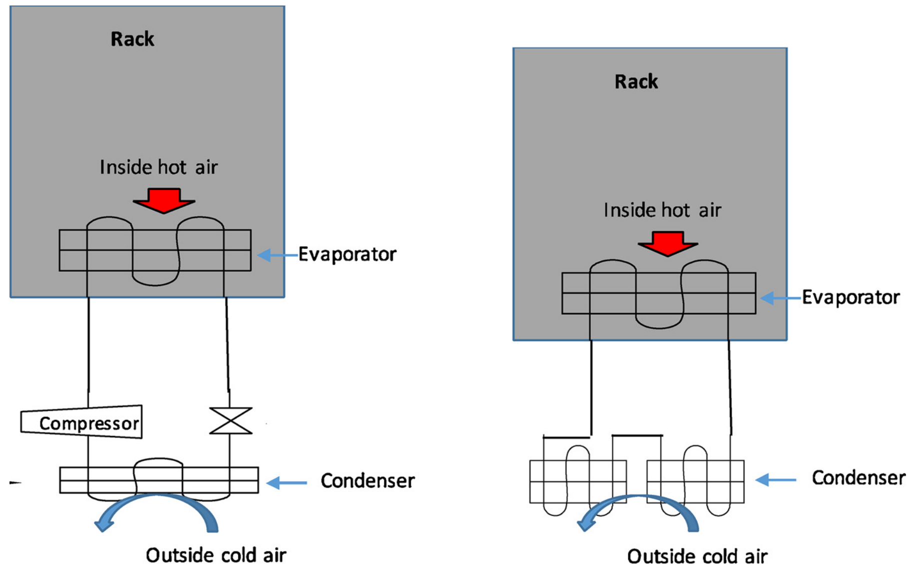
Fig. 18. Experimental setup of a two-phase thermosyphon loop.

investigated. It turns out that the cooling capacity is strongly influenced by evaporator fin pitch, and increased by 135% when the indoor and outdoor temperature difference increased from 6 °C to 8 °C.

4.1.3.3. Integrated system. The thermosyphon needs an independent air conditioner for hot season, which leads to a double installation space, double investment, and double maintenance. An integrated system can avoid two sets of equipment by combining thermosyphon and a mechanical refrigeration system. When the cooling capacity of the thermosyphon is not sufficient, mechanical refrigeration mode is integrated. This will reduce the working time of the thermosyphon cooling and then reduce the energy-saving effect [40]. Fig. 19 schematized the two modes of the integrated system.

Han et al. [41] designed a vapor compression refrigeration with thermosyphon, connected by switching valves. The evaporator and the condenser are located respectively in the indoor and outdoor test rooms. In the vapor compression mode, when the compressor starts, the solenoid valve closes and the three-way valve connects the compressor and condenser. In the thermosyphon mode, the three-way valve by-passes the compressor, connecting condenser and evaporator, and the solenoid valve opens.

To assess daily consumption and energy saving ratio, integrating air conditioning thermosyphon (IATC) and traditional air conditioners (TAC) are installed in two mobile phone base stations. Fig. 20 shows the testing results of energy consumption of the two systems for five months. In Fig. 20a, the outdoor temperature drops from August to December, therefore the thermosyphon mode of the IACT works longer and provides larger cooling capacity. The heat exchange becomes more



(a) (b)

Fig. 19. Integrated air conditioner with thermosyphon: (a) vapor compression mode; (b) thermosyphon mode.

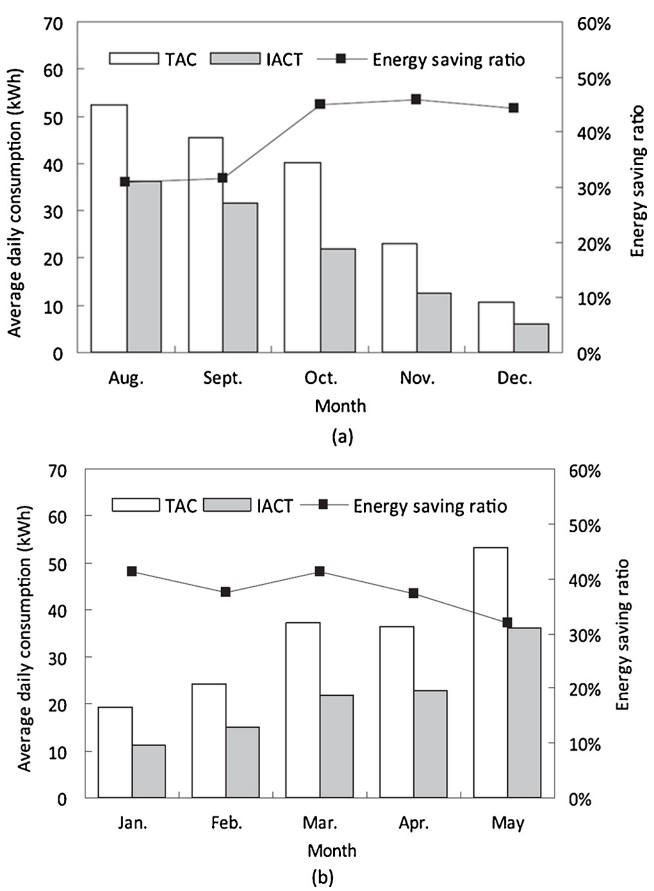


Fig. 20. Energy consumption in two mobile stations: (a) August to December; (b) January to May.

important, the average daily energy consumption decreases and the energy saving ratio rises from 32% to 46%. In Fig. 20b, the daily power consumption of both systems rises from January to May because of the increasing of outdoor temperature. Therefore, the vapor compression mode contributes more often than the thermosyphon mode to provide cooling capacity.

The cooling system studied by Zhang et al. [40], is composed by a thermosyphon loop and a refrigeration system. The indoor and the outdoor test rooms contain respectively hot air and cold air. Unlike the previous system, three-cooling systems, which avoids the reliability risk of mode switching valves, have used: refrigeration loop, thermosyphon loop and for the outdoor air convection. As shown by Fig. 21, each system can work following the outdoor temperature:

- Thermosyphon loop shown in Fig. 21a, works in cold weather (5 °C) where only the fans of the three-fluid heat exchangers and the evaporator operate to cool the data center using outdoor cold air. The working fluid in the thermosyphon absorbs heat and vaporizes in the evaporator, condenses in the three-fluid heat exchanger and then flows back to the evaporator under gravity.
- Refrigeration mode works in hot weather (35 °C) where the fan of the three-fluid heat exchanger stops and the compressor starts (Fig. 21b). Working fluid in the thermosyphon condenses and exchanges heat with the refrigeration working fluid.
- Dual cooling mode (Fig. 21c) in mild weather (15 °C – 20 °C) where all the fans and refrigeration loop works. The compressor helps cool the data center since the cooling capacity of the thermosyphon loop is not sufficient.

Zhang et al. drew the energy efficiency ratio (EER) against the temperature difference in Fig. 22. The EER is defined by the following equation:

$$EER = \frac{Q}{P_{cooling}} \quad (4)$$

Where Q is the cooling capacity of the system, $P_{cooling}$ is the total input power of the cooling system.

The figure shows that the EER of thermosyphon mode is the highest for no energy consumption of mechanical refrigeration. It reaches 10.7 when the indoor and outdoor temperature difference is 10 °C, more than two times of TAC. When the temperature difference is 20 °C, it is 20.8, nearly five times of TAC. The EER of refrigeration mode is almost the same with TAC. The EER of dual mode is not always higher than TAC for its higher input power. When the outdoor temperature is relatively low, its EER are higher for utilizing natural cold source. The

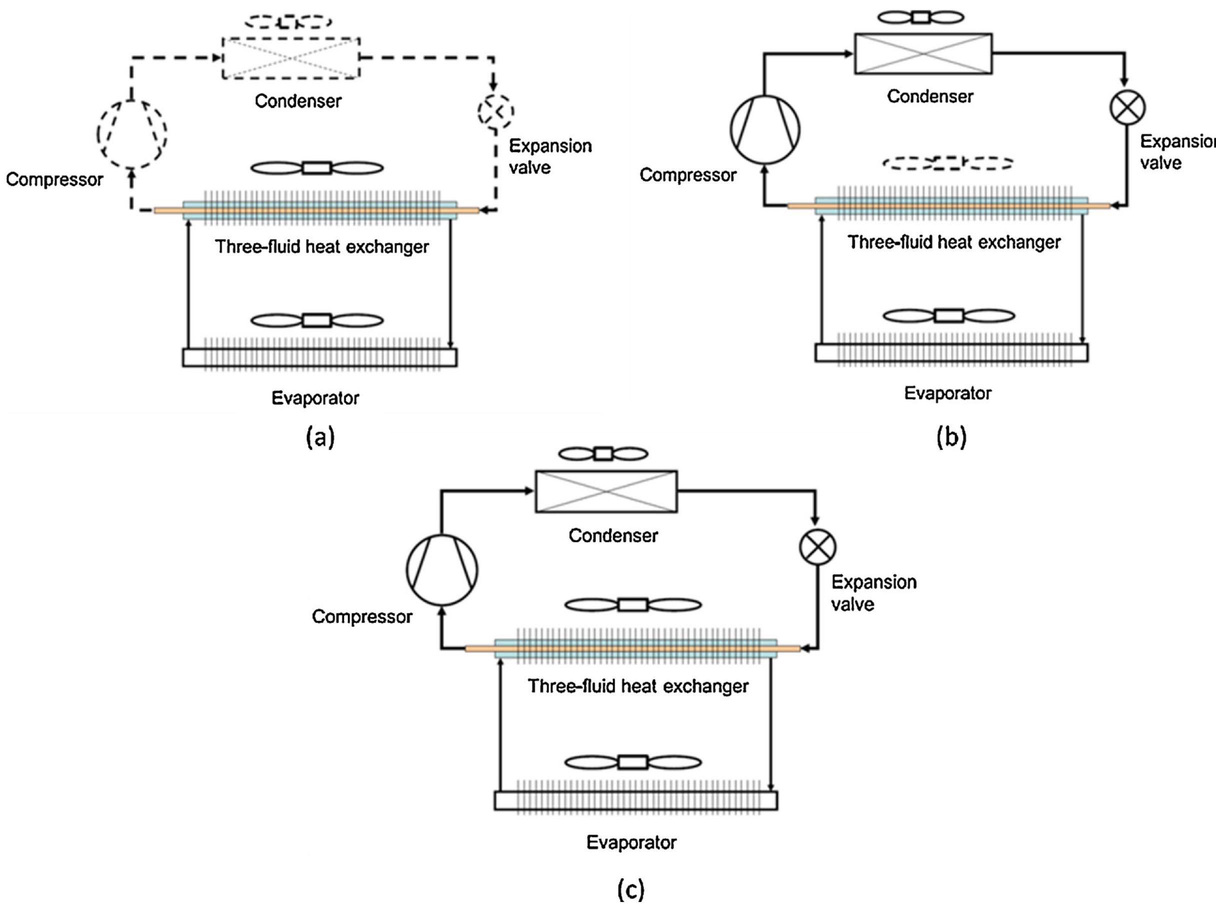


Fig. 21. Configurations of the three-fluid heat exchanger [40].

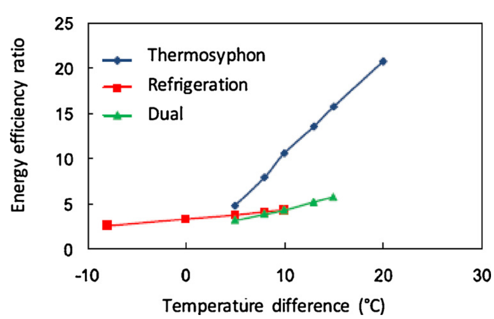


Fig. 22. Energy efficiency ratio against temperature difference.

EER of dual mode is higher than TAC when indoor and outdoor temperature difference is approximately larger than 11 °C.

Wang et al. [42] analyzed the energy efficiency of an integrated heat pipe system in data centers. As shown in Fig. 23, the heat pipe and the vapor compression loops are connected by a plate heat exchanger (HX). Like the previous system, the durability of the system is raised thanks to the non-presence of valves. The refrigerant, which is R22, releases heat to ambient environment in two ways: the first way is the thermosyphon loop where the working fluid circulate between the evaporator and the condenser 1. The second is the thermosyphon-vapor compression where the heat is dissipated through the thermosyphon evaporator and HX of the vapor compression loop used as the second dissipater. An electric heater is set up to simulate the heat source in the data centers. The required temperature of the indoor chamber was set constant as 24 °C while the temperature of the outdoor chamber was varied to simulate the outdoor climate change. Three cooling modes are defined:

- when the outdoor temperature is low enough, the thermosyphon loop works alone;
- when the outdoor temperature is mild, the thermosyphon and the vapor compression system worked together;
- when the ambient temperature is very high, the vapor compression system works alone to provide the required cooling capacity.

Fig. 24 shows that the EER variations are linear in both the heat pipe mode and the compressor-on mode. The heat pipe system provides higher energy efficiency values, which proves that mode is the most efficient. The contribution of the heat pipe system reduces while the contribution of the vapor compression system rises with the outdoor temperature increasing.

These studies on integrated systems are summarized in Table 2.

4.1.3.4. Two-phase immersion. With a heat flux about 100 kW/m^2, two-phase immersion consists of immerging all components and supports and controlling the components temperature by the liquid temperature. The working fluid is selected according to the chemical compatibility with the components [43]. This technology simplifies facility construction by reducing floor space requirements and eliminating the need for air cooling infrastructure such as air economizers. The simplest configuration is presented in Fig. 25 which represents the pool boiling where the produced vapor flows towards the condenser and falls back in the shape of drops to the container [43].

Almaneea et al. [44] analyzed the cooling system when servers are immersed in a dielectric liquid and water is used to transport the heat outside of the data center. The data center cooling system in this study consists of the dry air cooler and buffer heat exchanger to dissipate the heat from a liquid cooled rack. It was found that the PUE is as low as 1.08 for the cooling system.

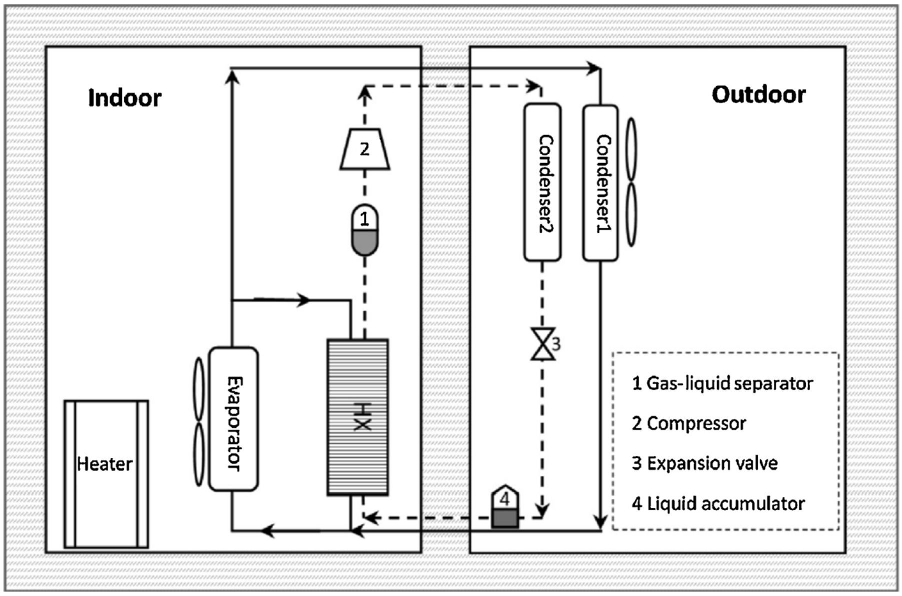


Fig. 23. Integrated system with a plate HX [42].

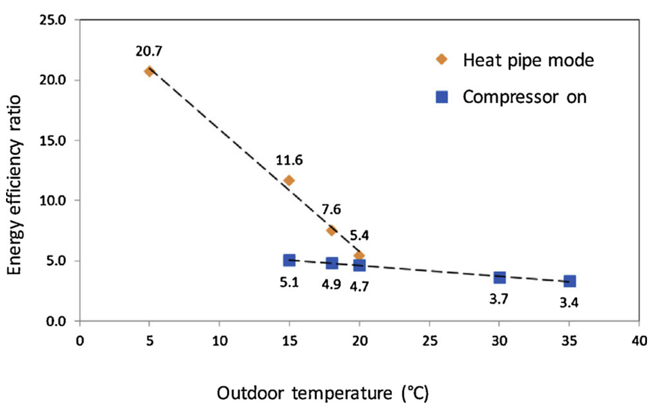


Fig. 24. Energy efficiency ratio against outdoor temperature.

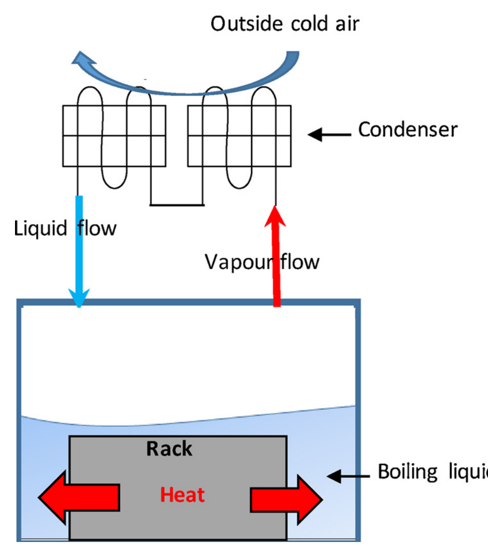


Fig. 25. Immersion cooling process.

Warrier et al. [45] identified among 35 fluids which one could be employed for direct immersion cooling of electronic systems. Tuma et al. [46] discussed about the economic and environmental merits of passive two-phase immersion in semi-open baths for cooling datacom equipment, as shown in Fig. 26. The technique eliminates the need devices associated with immersion cooling and with traditional liquid

Table 2
Summary of studies on integrated system.

Investigator(s)	System description	Working fluid	Temperature conditions	Obtained results		
				Input power (kW)	Cooling capacity (kW)	COP/EER
Han et al. [41]	- Vapor compression refrigeration mode - Thermosyphon mode - Switching valves	R22	- Indoor temperature : 27 °C to 35 °C - Outdoor temperature : 15 °C to 35 °C	- Thermosyphon : P = 0.6 - Refrigeration : - 2 ≤ P ≤ 2.5	- Thermosyphon : 0.8 ≤ Q ≤ 3 - Refrigeration : - 1.9 ≤ Q ≤ 7.5	- Thermosyphon : - 1 ≤ COP ≤ 5 - Refrigeration : - 1 ≤ COP ≤ 3
Zhang et al. [40]	- Vapor compression refrigeration mode - Thermosyphon mode - Three-fluid heat exchanger	NA	- Indoor temperature : 27 °C - Outdoor temperature : 7 °C to 35 °C	- Thermosyphon : P = 0.3 - Refrigeration : 1.3 ≤ P ≤ 2 - Dual : - 1.4 ≤ P ≤ 1.7	- Thermosyphon : 1 ≤ Q ≤ 6.5 - Refrigeration : - 5 ≤ Q ≤ 5.5 - Dual : - 5 ≤ Q ≤ 8	- Thermosyphon : - 5 ≤ EER ≤ 22 - Refrigeration : - 3 ≤ EER ≤ 5 - Dual : - 3 ≤ EER ≤ 5
Wang et al. [42]	- Vapor compression refrigeration mode - Thermosyphon mode - Plate heat exchanger	R22	- Indoor temperature : 24 °C - Outdoor temperature : 5 °C to 35 °C	NA	NA	- Thermosyphon : - 5.4 ≤ EER ≤ 20.7 - Refrigeration : - 3.4 ≤ EER ≤ 5.1

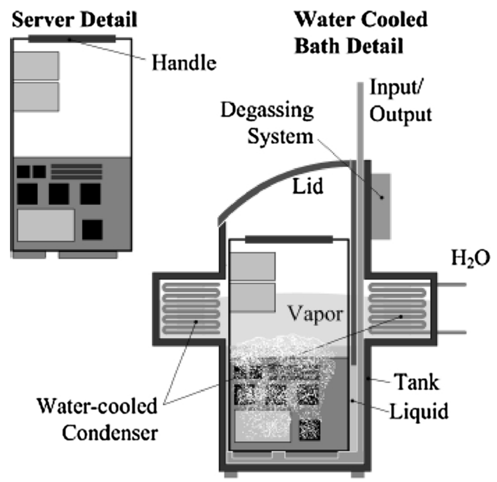


Fig. 26. Water-cooled open bath immersion concept [46].

cooling techniques. The costs and greenhouse gas emissions are found to be less than those associated with the electrical power required for traditional chassis fans and liquid pumps.

4.1.4. *Building envelope*

4.1.4.1. Container-based data center. Container data center (CDC) is a concept which consists of putting racks in containers. These containers are then placed in warehouses or outside. Containers are equipped with traditional cooling systems. Endo et al. [47] worked on energy consumption in a direct fresh-air container data center, illustrated in Fig. 27. The direct-fresh-air-cooled CDC exhibited a 20.8% reduction in the total energy use compared with the estimated use of a CRAC-cooled CDC over one year.

4.1.4.2. Phase change material. The use of phase change materials (PCMs) consists of employing the latent heat storage concept. Heat is absorbed or released when the material changes from solid to liquid and vice versa. It is an efficient way to increase the thermal inertia of building envelopes and controls the indoor environment of a building by reducing temperature fluctuations. Akeiber et al. [48] classified two techniques for PCM operation in buildings: active and passive. In the active technique, the PCM is charged by a conventional cooling system and discharged during the day time to cool the indoor environment. In the passive technique, the temperature difference between night and day cause the charging and discharging processes. Sun et al. [49] built a prototype that combines PCMs with a natural cold source to reduce the space cooling energy of telecommunications base stations. The adjusted energy efficiency ratio (AEER) was used to evaluate the performance of

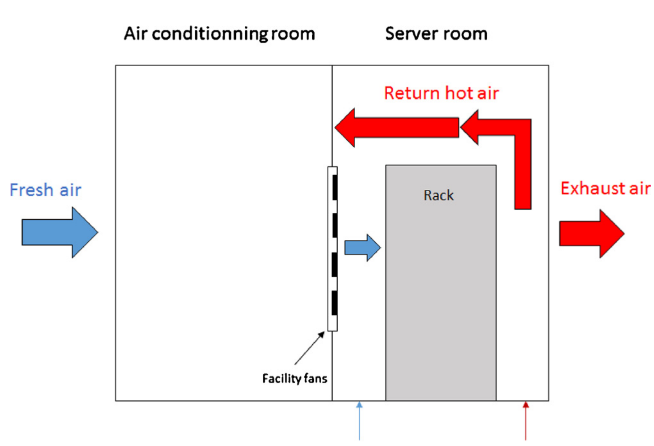


Fig. 27. Fresh-air container data center [47].

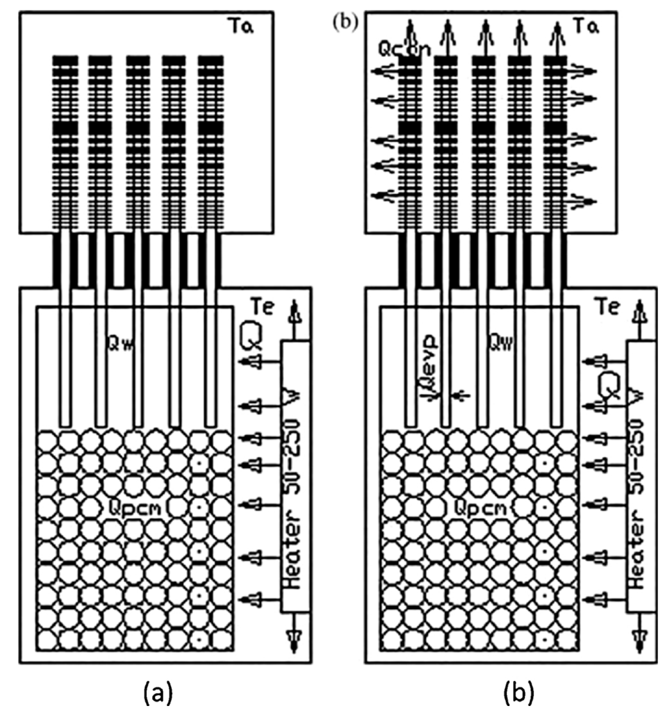


Fig. 28. Passive cooling system combining PCM and two-phase closed thermosyphon [50].

this unit and to compare it with conventional air conditioners. The AEER was 14.04, which is considerably higher than the limiting value of 3.2 for air conditioners with a cooling capacity of less than 4 500 W.

The estimated average energy savings potential of the prototype was 50%. Sundarama et al. [50] developed a new passive cooling system incorporating PCM and two-phase closed thermosyphon heat exchangers to provide thermal management for telecommunication equipment housed in telecom shelters. The newly developed thermal system absorbs the equipment dissipated heat during the hottest part of the day, stores it as latent heat and releases it through thermosyphons during the night to the ambient. Fig. 28 shows this passive cooling system that can save approximately 14 tons of carbon foot print every single year. Therefore, the replacement of conventional air-conditioning system with passive cooling system makes the telecom shelter as a green shelter.

4.1.5. *Comparison with passive cooling solutions*

These four main cooling technologies present benefits to reduce electricity consumption and to improve energy efficiency. Table 3 summarizes the criteria of performance of all cooling technologies introduces above. Each of them is accompanied by an example of system applying the respective solution, the benefits and drawbacks it offers and the energy savings.

Table 3 also indicates that passive cooling technologies have been widely developed over the past few years. According to a survey of the Green Grid in 2011 [51], the direct airside economizer is the most popular, and the waterside economizer is the second. However, the outside air conditions have to be within specified set point. A survey of Intel [52] indicates the waterside economizers are more cost-effective than the airside economizers. The liquid-cooled systems can reduce the overall data center consumption up to 30% in comparison with air cooled data centers [53], but they are expensive and presents fluid leakage risks.

So far, the cooling technology with the higher heat removal capacity is thermosyphon loop. It offers simplicity, compactness and, by associating with micro-channels heat exchangers, the loop thermosyphon is capable of removing higher heat fluxes while working with smaller

Table 3
Passive cooling systems of data centers.

Type	System	Benefits	Drawbacks	Energy savings
Free cooling: Direct airside economizer	Chen et al. [23]	- Low levels of energy consumption - The PUE is grandly reduced	- Humidity has to be taken account - Impurities might bring malfunctions - The outside air has to be cold	49 % energy conservation
Free cooling: Indirect airside economizer	Bao et al. [26]	- Reduced risk of outdoor air impurities - Lower humidification costs and maintain	- Accumulation of quantities in the heat exchanger - Reduction of the effectiveness of the heat exchanger and increasing of its maintenance frequency - Large data center	29 % of energy savings
Free cooling: Indirect waterside economizer: cooling tower	Niemann [24]	Significant energy saving	- The data center has to be close to a natural source of cold water - Large data center - More cost-effective	NA
Liquid cooling system: direct liquid cooling	Zimmermann et al. [29]	- The use of hot water eliminates the need for chillers - Possibility of heat reuse	Tubing connections	PUE = 1.15
Liquid cooling system: rack-level liquid cooling	Almoli et al. [30]	- The removal of the heat is more efficient - Improved working condition	- Hard to maintain - High cost	PUE = 1.3
Liquid cooling system: submerge cooling	Haywood et al. [31]	- No need of CRACS or chiller - Greater heat-absorption capacity - No sealed enclosures and piping are required	- Necessity of pumps to renew the liquid - Complex implementation	Mineral oil cooling holds the potential to eliminate up to 50 % cooling cost.
Two-phase cooling: heat pipe	Jouhara et al. [36]	- No passive component	- Depend of the climatic conditions - Concerns about the wick structure	75% of energy savings
Two-phase cooling: thermosyphon	Ling et al. [39]	Can remove huge heat flux	Depend of the climatic conditions	The cooling capacity increased by 135% with the increasing of the indoor and outdoor temperature difference from 6 °C to 8 °C
Two-phase cooling: integrated system	Zhang et al. [40]	- Huge energy savings - Can operate whatever the climate is	Presence of active component (compressor, valves…)	Thermosyphon : - $5 \le EER \le 22$ - Refrigeration : - $3 \le EER \le 5$ - Dual : - $3 \le EER \le 5$
Two-phase cooling: two-phase immersion	Almaneea et al. [44]	- No pumps, fans, economizers, compressors - Reduced cost and complexity	Fluid leakage	PUE is as low as 1.08
Building envelope: Container-based data center	Endo et al. [47]	Combination of direct fresh-air cooling with evaporative cooling and circulation of waste heat	Necessity of a system to maintain the cleanliness of fresh-air	20.8 % reduction in the total energy
Building envelope: PCM and free cooling	Sun et al. [49]	- Principle of latent heat storage - Combination of PCMs with a natural cold source	Limited by climates like mountains, coastal cities, and cities with desert-like climates	50 % of energy savings

mass flow rate of coolant [27]. If it is properly designed, the thermosyphon loop could provide a more uniform equipment temperature. Still, most are applied into climatic chambers, not in a real data center. Furthermore, they are combined with indirect airside free cooling, so they depend of outdoor conditions, leading to an addition of mechanical refrigeration or fans to provide a sufficient cooling power. The next challenges is to make two-phase cooling system independent of climatic constraints, making them 100% passive, and to apply them into a real data center.

Nowadays, passive cooling systems offer the possibility to the waste heat recovery. It consists of reusing the energy produced by server heat dissipation. Oró et al. [53] designed the liquid cooling configuration of on-chip servers evaluated numerically for a case study of an indoor swimming pool. The indoor swimming pool operator reduces its operational expenses 18%. Ebrahimi et al. [1] reviewed the different system capable of reusing the heat removed by the cooling system. The authors detailed particularly the absorption refrigeration system and organic Rankine cycle, and claimed that these techniques are the most promising technologies for data center waste heat reuse. These systems are represented in Fig. 29.

5. Conclusion

This review points out the most promising solutions to decrease the electrical power consumption:

- The free cooling technology is the most suitable technology to improve energy efficiency. While the airside economization uses natural air to cool the data center, the water economization remove the ejected heat by using the natural cold water ;
- The building envelope technology consists of either putting racks into containers and cool them by traditional cooling systems, or employing the principle of phase change materials by absorbing or releasing heat and thus reducing temperature fluctuations ;
- The liquid cooling technology is employed when data centers provide high power density. The direct liquid cooling consists of attaching the CPU with a cold plate, and the rack-level liquid cooling consists of installing a liquid-cooled door on the back of the rack. It is also possible to submerge servers in liquid to transfer the heat to an external loop ;
- The two-phase cooling technologies are capable of removing high heat flux. This solution uses the principle of evaporation and condensation of a refrigerant to absorb the ejected heat and release it into environment. The heat pipe system uses the capillary action

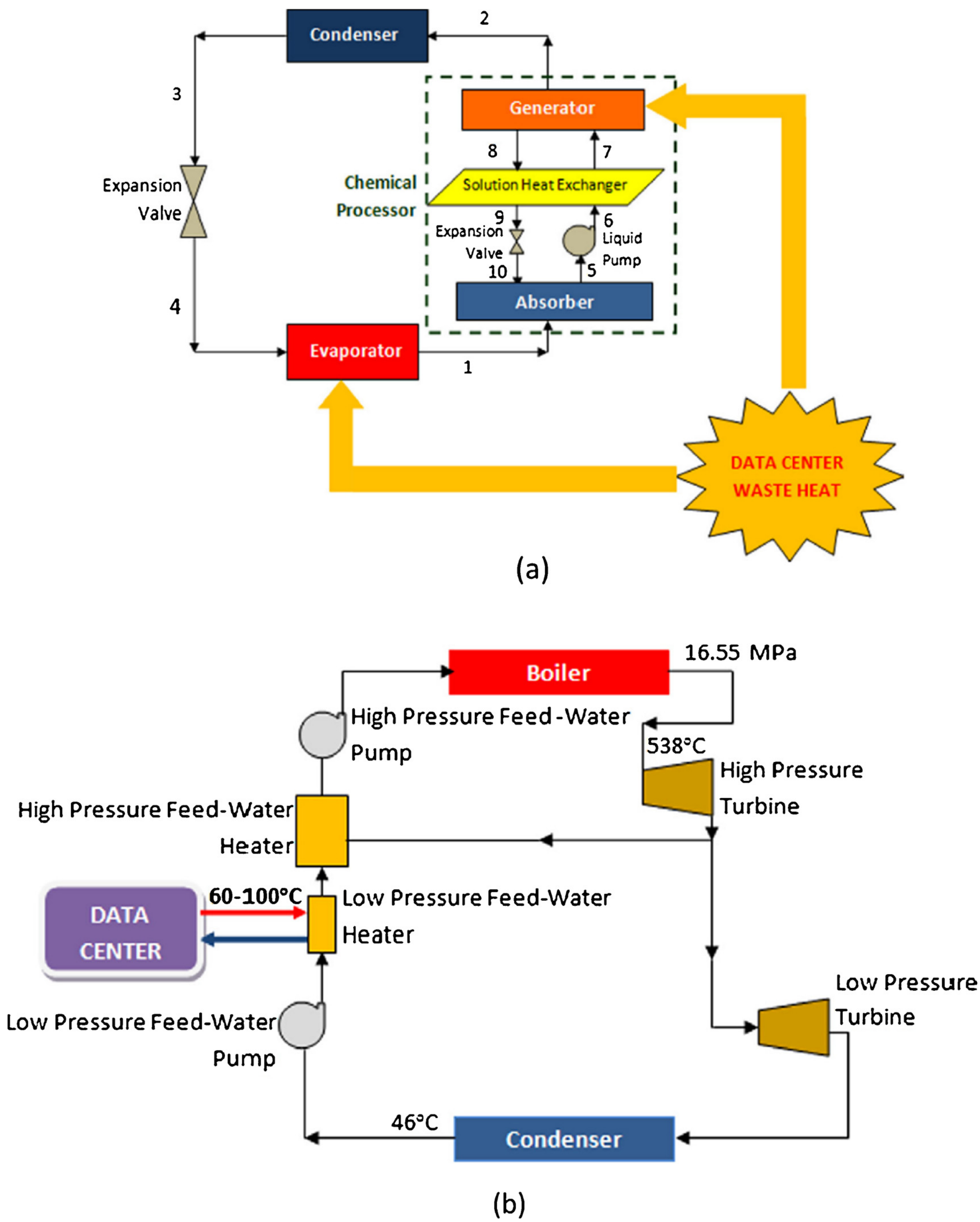


Fig. 29. Waste heat recovery system: (a) Absorption refrigeration system; (b) Schematic diagram of organic Rankine cycle.

while the thermosyphon heat exchanger is composed mainly by an evaporator and a condenser and do not include mechanical components, unlike integrated system. The two-phase immersion consists of immerging all components and controlling the temperature of these components thanks to the temperature of the liquid.

These technologies may be of interest data center operators, since they offer specific benefits. They can potentially allow the reduction of using mechanical equipment and the removing of higher heat fluxes.

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