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INTERNATIONAL INSTITUTE OF REFRIGERATION

AIR SOURCE HEAT PUMPS FOR SPACE HEATING AND COOLING

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“Heat pumps can play an important role in meeting global targets for energy savings and low carbon emissions.”

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Summary

Air source heat pump is an energy-efficient technology that allows heating at different ambient temperatures. The normal heating efficiency of ASHP is 3 to 4 times higher than that of direct electric heating. ASHPs can be used in different climates, from -25°C to +50°C, by developing technologies such as variable frequency compressor, cascade ASHP, two-stage compression and quasi two-stage compression.

This Informatory Note provides detailed information about the principles and state of the art of ASHP technologies. It also outlines anti-frosting strategies and defrosting methods as well as alternative refrigerants with the lowest environmental impact. Finally, it presents the ASHP applications all over the world and highlights the measures to be taken to accelerate the use of ASHPs in buildings.

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Introduction

Since the energy crisis in the 1970s, energy conservation has always been a hot topic for policymakers and practitioners worldwide. Currently, energy consumption in buildings accounts for about 30% of total energy consumption [1]. Owing to the increasing demand for improved thermal comfort in the building environment, the energy use of heating, ventilation and air conditioning (HVAC) systems accounts for almost half of the energy consumption of buildings. Therefore, it is important to increase the energy efficiency of HVAC systems in order to meet energy saving and low carbon emission targets.

Traditionally, both a chiller and a boiler are used in a building for cooling and heating, respectively. However, boilers, such as coal-fired and gas-fired boilers, are not environmentally friendly because of the emissions of greenhouse gases and particles during combustion. The electric boiler, or direct electric heating, is not energy-efficient due to low primary energy efficiency. Thus, as one of the promising technologies for efficient heating and cooling with a single device, the heat pump has been widely developed and used all over the world. Depending on the type of heat source/sink, the heat pump can generally be classified as an air-source heat pump (ASHP), ground-source heat pump (GSHP), water-source heat pump (WSHP), etc.

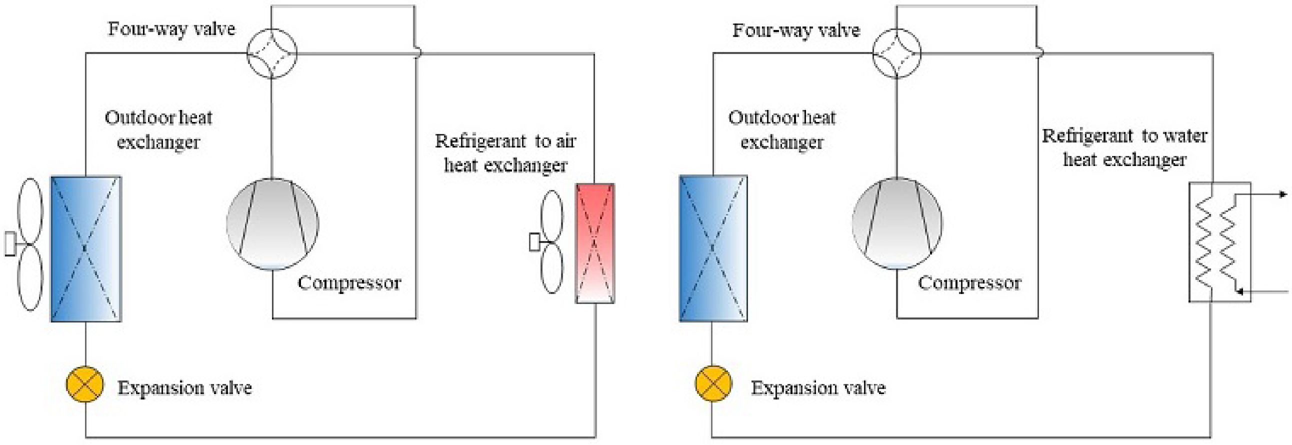
Contrary to WSHP and GSHP, ASHP takes/rejects heat from/into the ambient air, which is cheap and can be implemented anywhere. Therefore, ASHP plays an increasingly important role in cases where both heating and cooling are required. In recent years, many efforts have been devoted to extending the application of reversible ASHP in the heating and cooling of buildings.

This Informatory Note provides detailed information about the principles of ASHP, the state of the art of ASHP technologies and their applications all over the world. Since the research on ASHP cooling has been well developed in recent years, the current challenge comes from heating. Therefore, this Informatory Note focuses mainly on new developments in the field of heating, and some technologies are also applicable to cooling.

The International Institute of Refrigeration is at the disposal of its members and governments, companies, public and private actors, to help them comprehensively understand the potential of ASHP in achieving the Sustainable Development Goals of the United Nations.

Operational principles

The mechanism of a reversible ASHP is quite similar to the typical vapour compression cycle in which the compressor, condenser, throttling valve and evaporator are connected in series. The only difference is the four-way valve located at the outlet of the compressor, as shown in Fig. 1. When the ASHP is operating in cooling mode, the compressed hot gas is directed through the four-way valve to the outdoor condenser where the refrigerant is condensed to a liquid by discharging heat into the ambient air. Then the liquid refrigerant is throttled into low pressure two-phase state and absorbs heat from the air or water in the evaporator to achieve the cooling effect of air or water. The vaporized refrigerant then returns to the compressor and is compressed into hot gas. When the ASHP is operating in heating mode, the four-way valve is switched in its flow direction. The compressed hot gas is directed through the four-way valve to the indoor condenser, where the refrigerant is condensed by discharging heat into the air or water for space heating. Then the liquid refrigerant is throttled into low pressure two-phase state and passes through the outdoor heat exchanger to absorb heat from the ambient air. The ASHP is normally divided into two types based on the heat transfer fluid of space cooling/heating. The air-to-air type mainly refers to split air conditioner, packaged air conditioner, etc. The air-to-water type is used to supply high temperature water or chilled water for heating or cooling indoor air, respectively, by different kinds of indoor terminal units such as air handling unit, fan coil unit, radiator, radiant panel, etc.



(a) Air-to-air type

(b) Air-to-water type

Figure 1

Schematic of the ASHP

Since ASHP extracts heat from the ambient during heating mode, the normal heating efficiency of ASHP is normally 3 to 4 times that of direct electrical heating. However, several factors have a significant impact on the performance of ASHP. Firstly, ASHP performance is significantly reduced at low ambient temperatures. Secondly, the frosting problem heavily affects energy efficiency and reliability during the heating period. In order to solve the problems, many researchers and engineers have devoted a great deal of effort to improve ASHP technology in recent years. The state of the art of the technologies is summarized in the following section.

State of the art of technologies

LOW-TEMPERATURE ASHP

The poor performance of ASHP at low temperatures results in insufficient heating capacity and low coefficient of performance (COP). The low heating capacity can be attributed to the largely reduced refrigerant density at the suction port and the lower volumetric efficiency of the compressor. The poor COP is due to the high pressure ratio, the low isentropic efficiency of the compressor and the high throttling loss. To improve the performance of the compressor, several kinds of new technologies have been developed.

Variable frequency compressor technique is an effective method for increasing the heating capacity of the ASHP [2]. By speeding up the compressor in low temperature conditions, it is possible to rapidly increase the displacement of the compressor and thus the heating capacity of the ASHP. However, inverter technique cannot contribute to the improvement of the COP. To simultaneously improve the heating capacity and COP at low ambient temperatures, multi-stage compression technologies have been developed and implemented. According to the number of compression stages and the cycle configuration, the multi-stage compression ASHP can be classified into cascade type and two-stage compression type. In particular, in order to improve the heating capacity of single-stage compression system at low ambient temperature, a refrigerant can be injected directly into the compressor during the compression process, which is known as quasi two-stage compression. Since the quasi two-stage compression type has the characteristics of two-stage compression type, it can be classified as a two-stage compression type.

- Cascade ASHP

The low ambient temperature leads to a high pressure ratio in the system, which results in high compression work and high throttling loss, and eventually to low energy efficiency of the ASHP. A simple idea to reduce loss and enhance efficiency to use two vapor compression cycles in series to replace the single vapor compression cycle. This is the cascade ASHP system.

As shown in Fig. 2, the cascade compression system consists of two independent vapor compression cycles. One cycle is the low temperature cycle and the other is the high temperature cycle. These two cycles are connected by the shared cascade heat exchanger, which serves the low-temperature cycle as a condenser and the high-temperature cycle as an evaporator. In winter, the low temperature cycle absorbs heat from the environment through the air source evaporator. Through the low-temperature cycle, the heat is raised to a higher temperature and supplied to the high-temperature cycle as a heat source. In the high-temperature cycle, the heat is again brought to the temperature required for space heating.

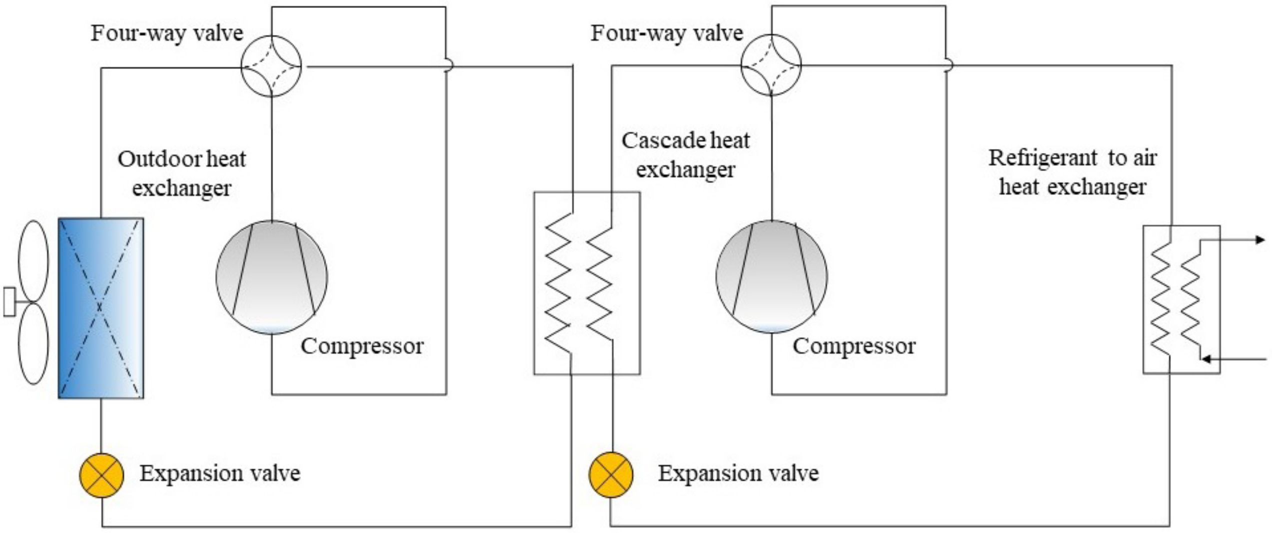


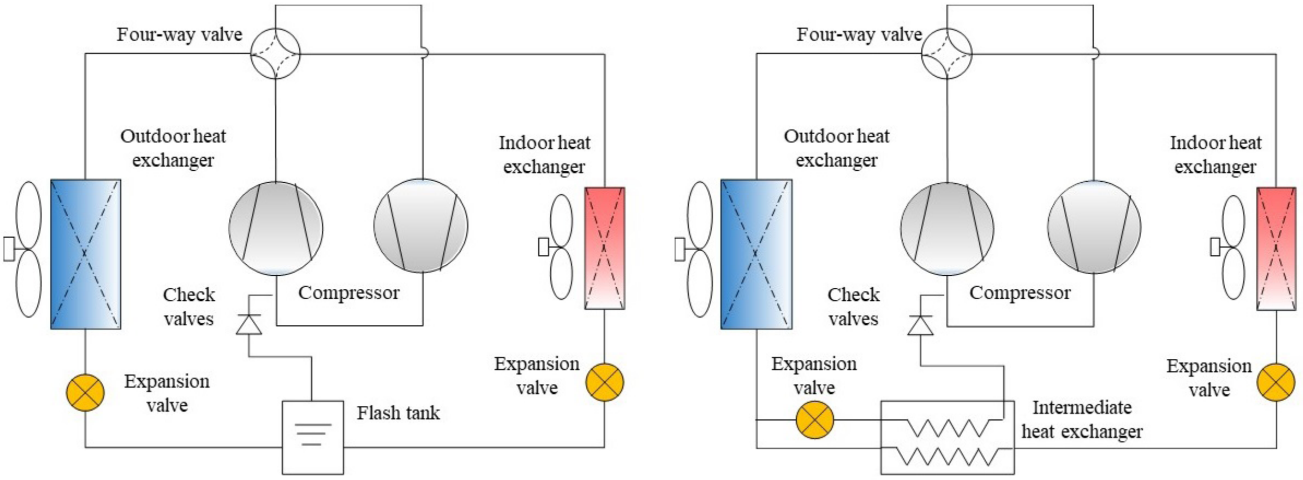
Figure 2

Schematic of the cascade ASHP

With the cascade ASHP, the pressure ratio of each cycle is greatly reduced. Total compression loss and throttling loss are reduced. As a result, the COP of the ASHP can be enhanced. In addition, it is remarkable that different refrigerants can be used in two cycles depending on the working conditions. However, the intermediate heat exchanger imposes a temperature difference that inevitably leads to some loss of efficiency. As the cascade system can be achieved with two well-known single-stage systems, some applications for space or water heating have been available for some years [3, 4]. Unfortunately, this cycle requires the use of two compressors and an extra heat exchanger, which increases the cost compared to the single cycle.

- Two-stage compression ASHP

The two-stage compression ASHP can be considered as a simplification of cascade compression, which connects two refrigerant cycles together. As shown in Fig. 3, the two-stage compression ASHP can be divided into two groups according to the type of economizer, the type of flash tank (FT) [5] and the type of intermediate heat exchanger (IHX) [6].



(a) FT type *(b) IHX type*

Figure 3

Schematic of the two-stage compression ASHP

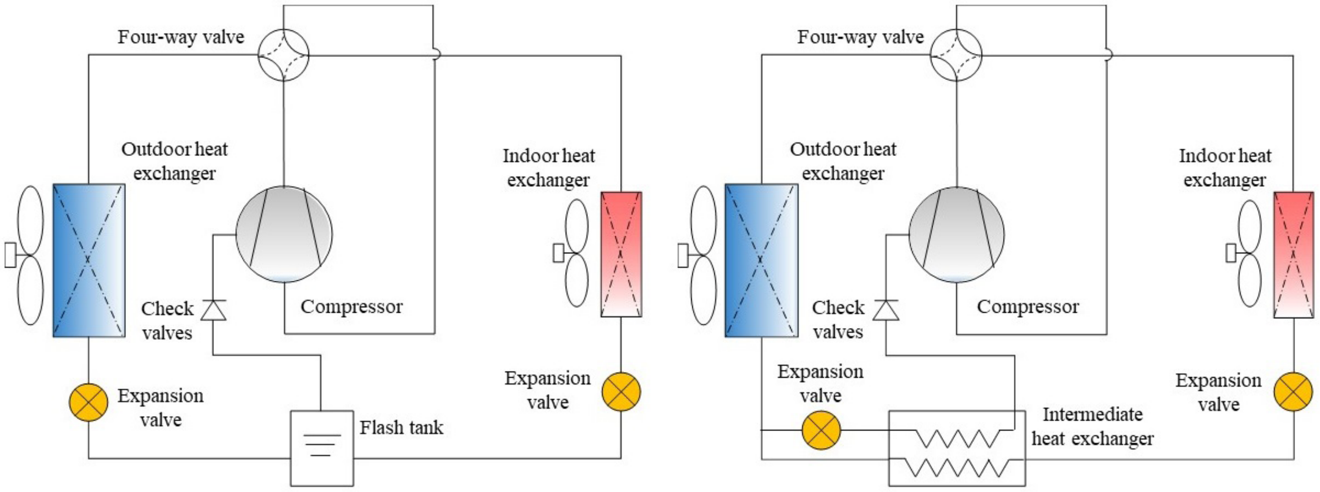
In the FT-type two-stage ASHP, the liquid refrigerant leaving the indoor condenser is throttled in two phases and sent into the FT. In the FT, the two-phase refrigerant is separated into saturated gas and saturated liquid. The saturated gas refrigerant is mixed with the refrigerant discharged from the lower-stage compressor and then recompressed by the upper-stage compressor. The saturated liquid flows into the outdoor evaporator after leaving the second expansion valve. After evaporating in the evaporator, the gas refrigerant is compressed by the lower-stage compressor and mixed with the intermediate pressure gas from the FT.

For the IHX-type two-stage ASHP, the liquid refrigerant at the condenser outlet is directly separated into two paths. The secondary refrigerant is throttled into intermediate pressure. The low-temperature refrigerant cools the mainstream refrigerant to subcooling state in the IHX. Then, the secondary refrigerant becomes saturated or superheated and is mixed with the refrigerant from the lower-stage compressor. The mixture is sucked in by the upper-stage compressor for further compression. The subcooling mainstream refrigerant at the IHX outlet is throttled, then passes through the evaporator, and finally reaches the lower-stage compressor. It is then compressed to an intermediate pressure to mix with the secondary refrigerant.

- Quasi two-stage compression ASHP

As illustrated in Fig. 4, the quasi two-stage compression ASHP, also called a gas injection system, is quite similar to the two-stage compression ASHP. The only difference is that a compressor with an intermediate injection port is used to replace two tandem compressors in a two-stage system. In case of a quasi two-stage ASHP, the saturated gas refrigerant from the FT or the secondary refrigerant from the IHX is injected into the compression chamber of the compressor, instead of in the middle of the two compressors.

It can be seen that the quasi two-stage ASHP is a simplification of two-stage system. It uses a specifically designed gas-injected compressor to replace both compressors, thus avoiding the problem of oil balance between two compressors and reducing the cost of the ASHP. More importantly, by closing the valve on the injection line, the quasi two-stage system can be easily transferred to the single-stage mode, optimising the performance of the quasi two-stage ASHP not only in summer but also in winter. For this reason, quasi two-stage compression technology has been widely adopted in recent years in ASHPs for low ambient temperature [7].



(a) FT type

(b) IHX type

Figure 4

Schematic of the quasi two-stage compression ASHP

ANTI-FROSTING AND DEFROSTING TECHNOLOGIES

When ASHP operates for space heating, frost may form over the fin and tube surface of the outdoor heat exchanger when the surface temperature is below both 0°C and the dew point temperature of the moist air. It is necessary to timely remove the accumulated frost to prevent deterioration of heat transfer of the outdoor unit and to maintain the free circulation of ambient air through the heat transfer coils. It is important to develop effective anti-frosting and/or defrosting technology for ASHPs.

- Anti-frosting technologies

By breaking the key parameters for frost formation, various anti-frosting techniques are proposed, including reducing inlet air moisture by dehumidification with a solid/liquid desiccant, surface treatment, external electric/magnetic field, ultrasonic vibration, etc.

Since humidity level is the key factor affecting frost formation, anti-frosting techniques using solid or liquid desiccant to decrease the humidity level of the heat exchanger inlet air have been well developed. As far as solid desiccants are concerned, silicagel [8], zeolite plates and activated carbon [9] have been more widely investigated. Liquid desiccants include lithium chloride, lithium bromide, calcium chloride and ethylene glycol. Liquid desiccants can be sprayed into the inlet air or directly onto the outdoor heat exchanger. Moreover, pre-dehumidification not only reduces the humidity of the air, but also increases the air temperature by releasing heat during the absorption or adsorption process. However, the main drawback of this anti-frosting method is regeneration. Both the solid/liquid desiccants should be regenerated for continuous operation, which limits its application in ASHPs. Compared with solid desiccants, the regeneration temperatures of liquid desiccants are significantly lower [10].

Another important anti-frosting technology is surface treatment, which modifies the surface microstructure of the fins of the outdoor heat exchanger. Depending on the contact angles (Fig. 5), the surface is classified into hydrophilic, hydrophobic, and super-hydrophobic. Hydrophilic materials inhibit the normal freezing process, both by interfering with the ice crystal formation and by immobilising part of the water molecules. Compared to the bare surface, the hydrophobic surface has sparser condensate droplets distribution, delayed droplet freezing and frost formation. The super-hydrophobic surface is more effective at delaying frosting by "poping-up" tiny water drops before they are frozen, by releasing surface energy. Surface treatments are now highly efficient, inexpensive and environmentally friendly, and the only problem to be solved is the long-term effectiveness of the coating layer.

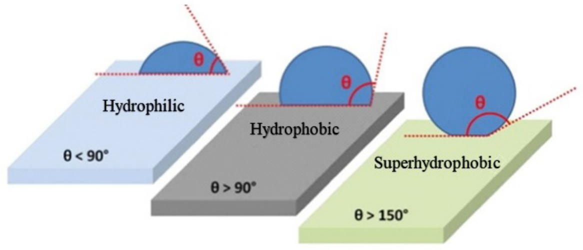


Figure 5

Contact angle of hydrophilic, hydrophobic, and super-hydrophobic surfaces

Moreover, ultrasonic vibration, air jet, external AC or DC electric field [11, 12], external magnitude field are also proposed and investigated for slowing down and destroying frost accumulation. However, all these techniques require expensive additional equipment and energy use, which largely limits their adoption in practical projects.

- Defrosting methods

In contrast to anti-frosting, defrosting technologies attempt to remove frost from the heat exchanger efficiently and in time.

Basically, there are five fundamental defrosting methods:

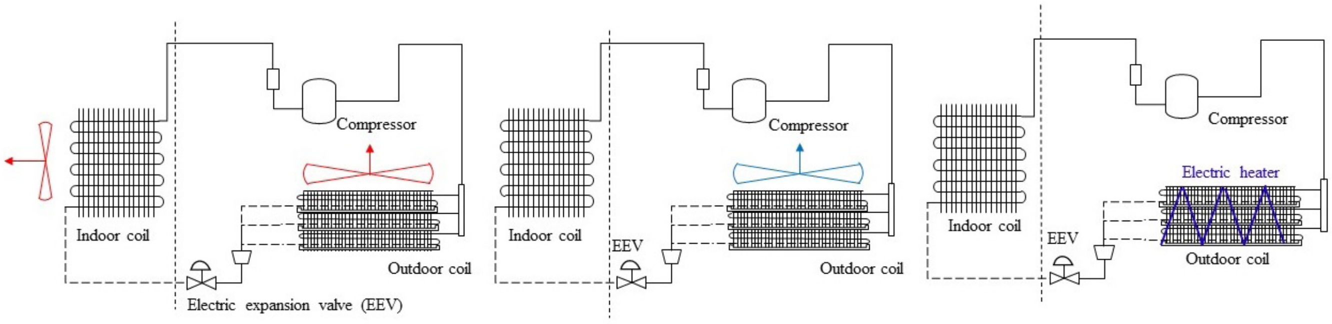
1. compressor shutdown,
2. electric heating,
3. hot water spraying,
4. hot gas bypass, and
5. reverse cycle, as illustrated in Fig. 6 [13].

Reverse cycle and hot gas bypass are the most common defrosting methods for ASHPs.

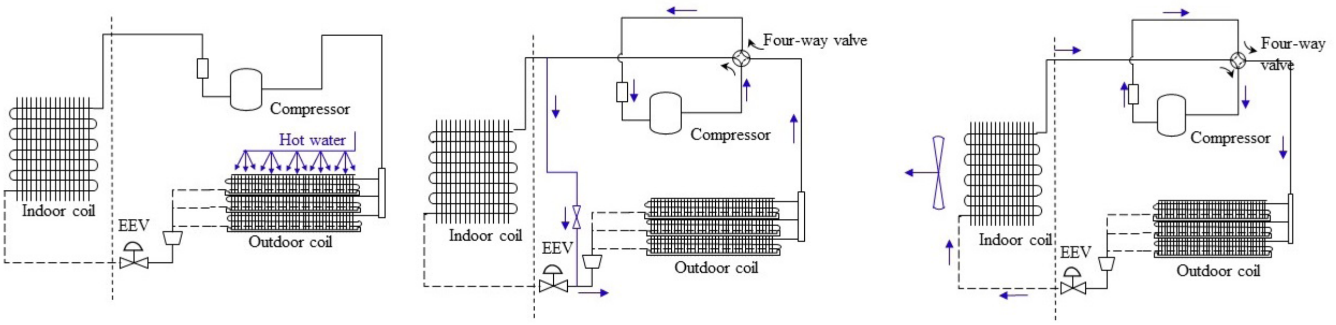
In the compressor shutdown method, the compressor is shut down while the fan of the outdoor unit continuously drives air through the outdoor heat exchanger to melt the frost. It can work only when the outdoor temperature is above 0°C, and its defrosting time is very long but inexpensive. An electric heater can be attached to the outdoor heat exchanger to speed up melting. It should be noted that electricity is a high-grade energy, which limits its application in residential ASHPs. For hot water spraying defrosting, the fan of the outdoor units is switched off while hot water is sprayed on the outdoor heat exchanger. The hot water requirement means that this defrosting method is only used on specific occasions, excluding ASHP.

The reverse cycle defrosting method is the conventional standard method for ASHP. During defrosting, the outdoor heat exchanger operates as a condenser while the indoor heat exchanger works as an evaporator after the four-way valve is reversed, and hot refrigerant flows into the outdoor coil to melt the frost. Meanwhile, the fan in the indoor unit will be stopped to avoid the discomfort sensation when defrosting.

As far as the hot gas bypass defrosting method is concerned, the refrigerant discharged from the compressor is controlled to enter partially into the outdoor heat exchanger to melt the frost and into the indoor unit for heating, which is commonly applied to industrial ASHP units. This method eliminates the adverse shock and "oil rush" occurring during reverse cycle defrosting operations, and maintains good thermal comfort during the defrosting operation.



(a) Heating mode (b) Compressor shutdown defrosting (c) Electric heating defrosting



(d) Hot water spray defrosting (e) Hot gas bypass defrosting (f) Reverse cycle defrosting

Figure 6

Schematic of defrosting methods [13]

As previously mentioned, reverse cycle defrosting and hot gas bypass defrosting are the most widely used fundamental defrosting method for ASHPs. On this basis, some revised techniques for reverse cycle defrosting and hot gas bypass defrosting have been developed.

A typical new method of reverse cycle defrosting is based on thermal storage. In this technology, the phase change material is used to store the heat rejection through the compressor shell during the heating period, and is then utilised as a partial or full heat source for defrosting. This arrangement can effectively shorten the defrosting time, enhance indoor thermal comfort during defrosting, and reduce the risk of wet compression [14, 15]. A sensible heat defrosting method has also been proposed based on the hot gas bypass method [16], in which the partial refrigerant discharged from the compressor is throttled by the expansion valve and flows into the outdoor coil for defrosting, and is more applicable for large capacity units.

- Defrost control strategies

Besides defrosting technologies, the methods for controlling the start and termination of the defrosting operation is another key factor affecting the performance of ASHPs subjected to frost. Poor defrosting, including unnecessary defrosting cycles when little or no frost is accumulated on the outdoor coil, and the lack of defrosting when it is required, are fairly common in actual products.

To find the proper starting time for defrosting, a time control method, a time-temperature control method, a time-temperature difference control method [17] and a superheat degree control method [18] have been developed. Currently, time control is the most widely used control method, which would automatically start defrosting after a predetermined heating time. The time-temperature control method measures the surface temperature of the outdoor coil; and the time-temperature difference control is based on the temperature difference between the outdoor air and the evaporator surface. However, time and temperature are not the only factors that cause frost, as ambient temperature, relative humidity and partial load ratio also affect superheating and the formation of frost.

Smarter defrosting methods focus on starting the defrosting operation only when needed. Those intelligent frost detection methods include:

1. measuring the ice thickness using holographic interferometry technique [19];
2. measuring the frost surface temperature by infrared thermometer [20];
3. detecting refrigerant flow instability [21];
4. sensing frost using photo-coupler, photo-optical systems or fibre-optic sensors [22];
5. neural networks for modeling the amount of frost [23];
6. mass-flow fraction by fin surface temperature [24]; and
7. drop of the outdoor unit [25] or electrical current of the external fan [26].

These technologies are still immature and require further testing and development.

Currently, the methods for terminating a defrosting operation are based on tube or fin surface temperature of the outdoor coil, refrigerant pressure difference across an outdoor coil, or defrosting duration. The tube surface temperature is the most commonly used. The defrosting termination temperature is important to define an accurate termination of the defrosting operation. When the tube surface temperature reaches the setting termination temperature, it switches to the heating mode. The setting termination temperature is different depending on the research carried out under different conditions and requirements [22, 27]. For an ASHP unit with a multi-circuit outdoor coil, the detection of the surface temperature at the outlet of the tube of the lowest circuit is most widely used.

ALTERNATIVE REFRIGERANT

Global warming is motivating researchers, manufacturers and policy-makers to consider alternative refrigerants for all refrigeration, air conditioning, and heat pump systems. Low GWP-refrigerants for ASHP have also been investigated.

Currently, R22 and R410A are the main refrigerants used for ASHPs. The main alternatives being considered are R290, R32, R744, R161 and a number of HFC blends comprising saturated and unsaturated HFCs [28]. However, with the exeption of R744, all medium and low GWP alternatives are flammable and should be applied in accordance with appropriate safety standards or regulations, considering charge amounts and risk, as well as other specific construction requirements.

For pure alternatives, R290 is mainly considered for systems with small charge due to its high flammability, whilst the operating pressures and capacities are similar to R22 and the efficiency is higher than R22. Some manufacturers have introduced split air conditioners with R290 on the market. R32 is currently on the market for different types of air conditioners and has recently been applied in split units in several countries, especially in Japan, China, South Asian countries, and Europe. Some manufacturers are also considering R32 for other types of systems, including VRFs. The operating pressure and capacity of R32 are similar to those of R410A and its efficiency is similar, if not superior, to that of R410A. R744 has limited applicability for common space heating and cooling due to its low efficiency in cooling mode, especially at high ambient temperatures. However, R744 has obvious advantage for high-temperature water production when the supercritical cycle is adopted.

There are also a variety of proprietary mixtures for ASHP applications, which comprise HFC32, HFC125, HFC134a, HFC152a, HFC161, HFC1234yf, HFC1234ze, HC600a, HC600, H1270 and HC290. Some mixtures have been assigned refrigerant numbers such as R444B, R446A and R447A, whilst others are under development. These mixtures tend to have operating pressures and capacities similar to R22 or R410A, with GWPs ranging from 150 to approximately 1000 and flammability class 1 (for higher GWPs) and 2L (medium GWPs). Currently, most of these mixtures are not widely available on the market, and the relevant technical data are not yet in the public domain.

Applications

As a promising technology for space cooling and heating, ASHP has been applied in various commercial and residential buildings worldwide. Over the past decades, the radiator has been used as the main terminal for space heating, resulting in high supply water temperatures. However, in recent years, the increasing use of fan coil and floor heating has led to a decrease in the temperature of supply water. This has contributed to an increase in ASHP applications in recent years. Besides, another reason for the increase in ASHP applications is the growing demand for both cooling and heating equipment.

According to statistics by International Energy Agency [29], the global stock of air conditioning (including room air conditioner, VRF system, packaged window units, etc.) reached about 1.5 billion units in 2016 (Fig. 7). Among all types of air-conditioning systems, room air conditioners and VRF systems account for the majority, as shown in Fig. 8a. In addition, the stock in China and the United States accounts for more than half of total sales (Fig. 8b). Other countries with more than 20 million units include Japan, Korea, Brazil and India.

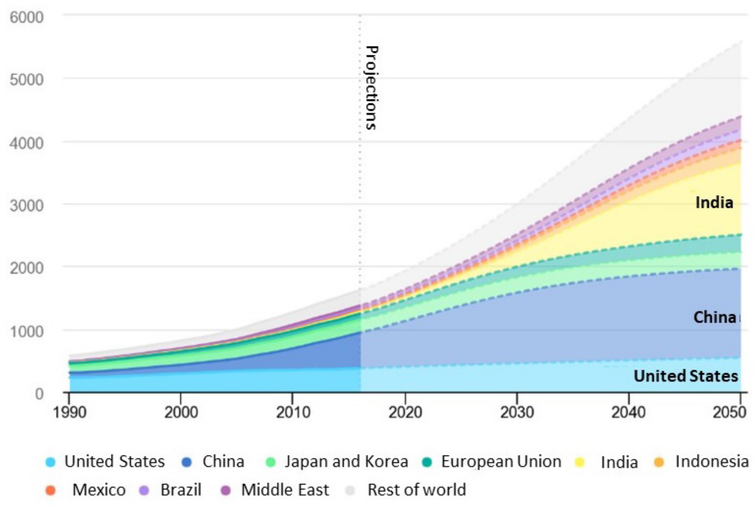
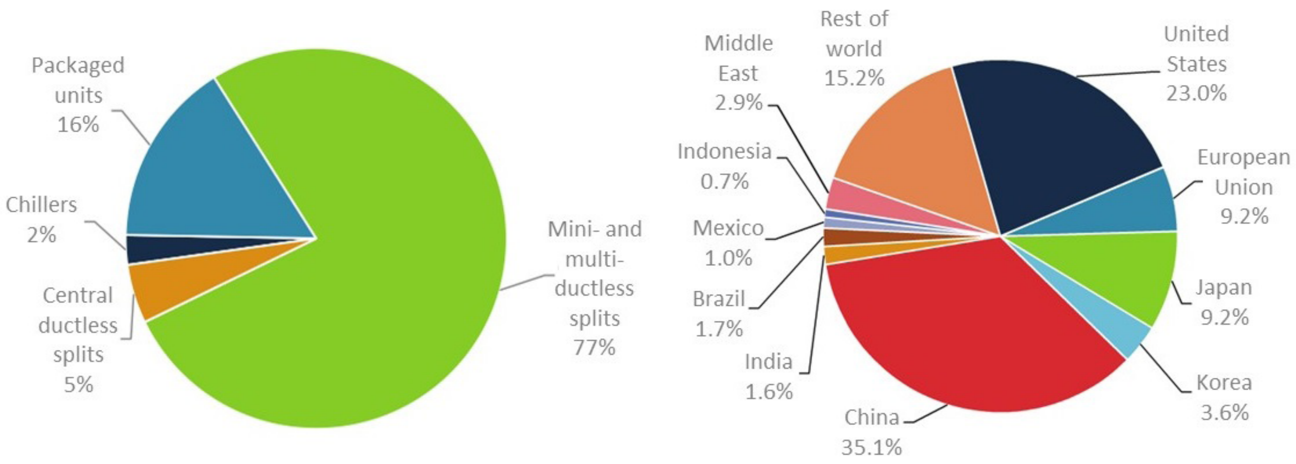


Figure 7

Global air conditioner stock, 1990-2050 (million units) [29]



(a) Stock of ACs by type, end 2016

(b) Stock of ACs by country/region, end 2016

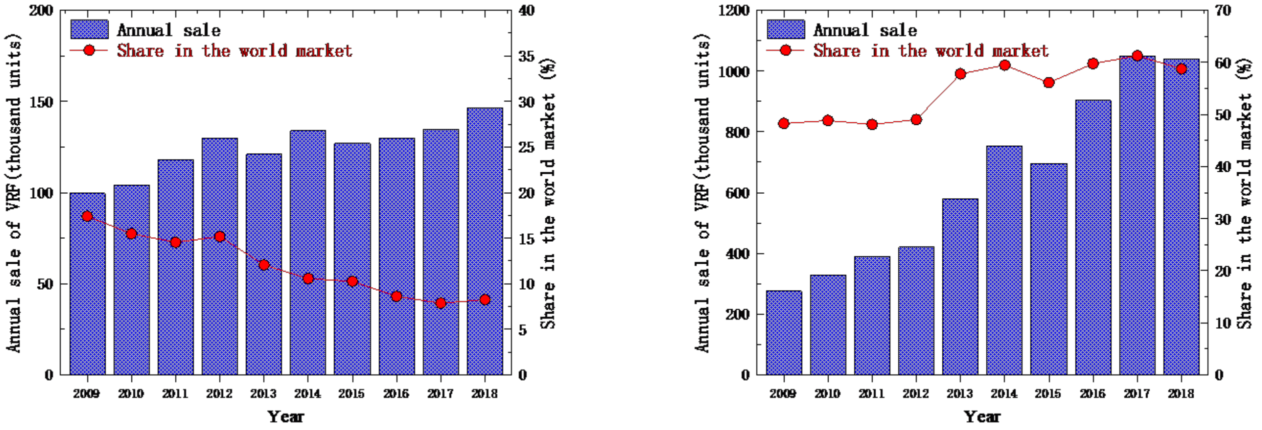
Figure 8

Global air conditioner stock, 1990-2050 [29]

The application of multi-split VRF system has developped rapidly all over the world since its creation in 1982 in Japan. The multi-split VRF system reached the European market in 1987, the Chinese market at the end of the 1990s, and the American market after 2000, successively [30]. In 2018, the annual sale volume of multi-split VRF systems in Japan reached 146,000 units (Fig. 9a) [31]. In China, VRF systems have for many years maintained the highest share and growth rate among the central air-conditioning market, which is used in about half of medium-sized commercial buildings and one third of large commercial buildings [32]. According to statistics, VRF sales volume in China in 2018 reached about 1 million units, which accounts for 58.8% of the world market (Fig. 9 b). Moreover, such a huge sales volume in the Chinese market has promoted the development of VRFs in European and American markets.

(b) China

In order to combat air pollution from traditional boilers, low-temperature ASHPs have been widely used in cold regions around the world, including northern Europe, northern China and Canada. In recent years, northern Chinese provincial administrations have launched programmes to accelerate the phase-out of coal in rural domestic heating [33], which has led to the booming development of low-temperature ASHP. Among the main alternative options, direct expansion heat pumps designed for heating in very cold regions have experienced rapid growth in recent years. In addition, novel heating equipment such as ASHP air heaters [34] are widely applied in northern China. In 2017, the output value of ASHP used for space heating in China reached RMB 5.6 billion (USD 850 million) [35]. Low-temperature ASHPs with quasi two-stage or two-stage compression have been widely applied in northern China, even in areas with ambient temperatures as low as –35°C.



(a) Japan

(b) China

Figure 9

Market sales of the multi-split VRF system in Japan and China [29]

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IIR recommendations

Heat pumps can play an important role in decreasing the energy consumption of buildings and in meeting global targets for energy savings and low carbon emissions. Because it extracts heat directly from the ambient air or rejects it into the air, the convenient air source heat pump is the most widely used type of heat pump, and is expected to become an essential part of the green heating objective.

Although ASHPs have been investigated and implemented for decades, their total installed capacity worldwide is still much lower than that of direct burning of fossil fuels and direct heating with electricity. Many measures still need to be taken to accelerate the use of ASHPs in buildings. The main conclusions and recommendations are as follows:

- Over a year (2018), buildings account for 30% of global energy consumption and 28% of global greenhouse gas emissions. About 40% of the energy consumed by buildings is used for space heating and cooling. ASHPs can play an important role in reducing greenhouse gas emissions.

- ASHP is an energy-efficient technology that allows heating at different ambient temperatures. The normal heating efficiency of ASHP is 3 to 4 times higher than that of direct electric heating. ASHPs can be used in different climates, from -25°C to +50°C, by developing technologies such as variable frequency compressor, cascade ASHP, two-stage compression and quasi two-stage compression.

- ASHPs with higher energy efficiency should be continuously developped, adapted to local ambient conditions and the economic situation. International communication and cooperation should be encouraged.

- The actual performance in the field is the most important factor to consider in order to reduce real energy consumption, as it is generally lower than the performance under nominal conditions. Developing field-adaptive intelligent controls is necessary.

- Further efforts should be made to raise awareness among decision-makers and the public about the benefits of air-source heat pumps.

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