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Advances in heat pump systems: A review

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ABSTRACT

Heat pump systems offer economical alternatives of recovering heat from different sources for use in various industrial, commercial and residential applications. As the cost of energy continues to rise, it becomes imperative to save energy and improve overall energy efficiency. In this light, the heat pump becomes a key component in an energy recovery system with great potential for energy saving. Improving heat pump performance, reliability, and its environmental impact has been an ongoing concern. Recent progresses in heat pump systems have centred upon advanced cycle designs for both heat- and work-actuated systems, improved cycle components (including choice of working fluid), and exploiting utilisation in a wider range of applications. For the heat pump to be an economical proposition, continuous efforts need to be devoted to improving its performance and reliability while discovering novel applications. Some recent research efforts have markedly improved the energy efficiency of heat pump. For example, the incorporation of a heat-driven ejector to the heat pump has improved system efficiency by more than 20%. Additionally, the development of better compressor technology has the potential to reduce energy consumption of heat pump systems by as much as 80%. The evolution of new hybrid systems has also enabled the heat pump to perform efficiently with wider applications. For example, incorporating a desiccant to a heat pump cycle allowed better humidity and temperature controls with achievable COP as high as 6. This review paper provides an update on recent developments in heat pump systems, and is intended to be a "one-stop" archive of known practical heat pump solutions. The paper, broadly divided into three main sections, begins with a review of the various methods of enhancing the performance of heat pumps. This is followed by a review of the major hybrid heat pump systems suitable for application with various heat sources. Lastly, the paper presents novel applications of heat pump systems used in select industries.

Contents

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1. Introduction

The heat pump (HP) has evolved to become a mature technology over the past two decades. However, it is not applied as widely as it should or could be. Initial costs, system design and integration remain to be challenging problems, since few major vendors of refrigeration systems offer large-scale heat pumps. Efficient use of energy in such energy-intensive operations as district cooling/heating, drying and cogeneration is crucial to the reduction of net energy consumption and hence emissions of greenhouse gases. With the eventual acceptance of a carbon/energy tax around the world energy, energy conservation will become a key concern in many industrial operations.

With raising cost of fuel and global warming at the forefront of world attention, the interest in HP as a means of energy recovery appears to have been resurrected. Heat pumps offer one of the most practicable solutions to the greenhouse effect. It is the only known process that recirculates environmental and waste heat back into a heat production process; offering energy efficient and environmentally friendly heating and cooling in applications ranging from domestic and commercial buildings to process industries [1]. Practical studies have shown the potential of heat pumps to drastically reduce greenhouse gases, in particular CO_2 emissions, in space heating and heat generation. The positive impact on environment depends on the type of heat pump and the energy-mix and efficiency of driving power used.

One key approach to improving the energy efficiency of many industrial operations is to recover every possible sources of waste heat and turn them to useful outputs. To facilitate this approach, the HP becomes a critical heat system as it possesses the capacity to recover thermal energy, otherwise exhausted to environment, and channel it to places where this heat energy can be converted to produce useful outcomes such as producing hot water to provide heat to occupants in buildings or even for the noble purpose of

Table 1
Representative overview of heat pump applications in industrial manufacturing activities (adapted from US Department of Energy [3]).

Industry	Manufacturing activity	Process	Heat pump type
Petroleum refining and petrochemicals	Distillation of petroleum and petrochemical products	Separation of propane/propylene, butane/butylene and ethane/ethylene	Mechanical vapour compression, open cycle
Chemicals	Inorganic salt manufacture including salt, sodium sulphate, sodium carbonate, boric acid	Concentration of waste streams to reduce hydraulic load on waste treatment facilities	Mechanical vapour compression, open cycle
	Treatment of process effluent	Concentration of waste streams to reduce hydraulic load on waste treatment facilities	Mechanical vapour compression, open cycle
	Heat recovery	Compression of low-pressure steam or vapour for use as a heating medium	Mechanical vapour compression, open cycle
	Pharmaceuticals	Process water heating	Mechanical vapour compression, closed cycle
Wood products	Pulp manufacturing	Concentration of black liquor	Mechanical vapour compression, open cycle
	Paper manufacturing	Process water heating	Mechanical compression
	Paper manufacturing	Flash-steam recovery	Thermocompression, open cycle
	Lumber manufacturing	Product drying	
Food and beverage	Manufacturing of alcohol	Concentration of waste liquids	Mechanical vapour compression, open cycle
	Beer brewing	Concentration of waste beer	Mechanical vapour compression, open cycle
	Wet corn milling/corn syrup manufacturing	Concentration of deep water and syrup	Mechanical vapour compression, open cycle, thermocompression, open cycle
	Sugar refining	Concentration of sugar solution	Mechanical vapour compression, open cycle, thermocompression, open cycle
	Dairy products	Concentration of milk and whey	Mechanical vapour compression, open cycle
	Juice manufacturing	Juice concentration	Mechanical vapour compression, open cycle
	General food-product manufacturing	Heating of process and cleaning water	Mechanical vapour compression, closed cycle
	Soft drink manufacturing	Concentration of effluent	Mechanical vapour compression, closed cycle
Utilities	Nuclear power	Concentration of radioactive waste	Mechanical vapour compression, open cycle
		Concentration of cooling tower blowdown	Mechanical vapour compression, open cycle
Miscellaneous	Manufacturing of drinking water	Desalination of sea water	Mechanical vapour compression, open cycle
	Steam-stripping of waste water or process streams	Flash steam recovery	Thermocompression, open cycle
	Electroplating industries	Heating of process solutions	Mechanical vapour compression, closed cycle
		Concentration of effluent	Mechanical vapour compression, open cycle
	Textiles	Process and wash-water heating	Mechanical vapour compression
		Space heating	Mechanical vapour compression
		Concentration of dilute dope stream	Mechanical vapour compression
	General manufacturing	Process and wash-water heating	Mechanical vapour compression
		Space heating	Mechanical vapour compression
	District heating	Large-scale space heating	Mechanical vapour compression
	Solvent recovery	Removal of solvent from air streams	Mechanical vapour compression, open cycle

desalination. As heat pump continues to find new novel applications in various energy-related industries, research efforts have been expanding to make it more energy efficient while evolving new hybrid systems that improve overall system efficiency. While enough is known about heat pumps and various thermal systems, optimal integration of the technologies remains a challenging R&D task.

Several heat pump types exist; some require external mechanical work while others require external thermal energy. Commercial heat pumps based on the vapour compression cycle or the absorption cycle are operational in numerous applications in various industries. New HP technologies such as the adsorption cycle or the chemical reaction cycle are emerging rapidly, although they have yet to find major industrial applications [2]. In this paper, selected recent works on heat pump systems in various applications and their impact on energy efficiency are reviewed. For the purpose of discussing key heat pump characteristics and applications, this paper focuses on the mechanical variety rather than the thermal types. Table 1 presents an overview of heat pump applications in industrial processes [3]. In contrast to heat actuated systems, it is readily observed that mechanical vapour compression heat pumps are extensively applied in many manufacturing industries. Though this table may not be entirely comprehensive, it highlights the most common industrial applications and heat pump types.

The structure and elements of the review are portrayed in Fig. 1. It begins with a section describing various techniques that currently are being employed to improve the performance of heat pump. Next, it presents several hybrid heat pump systems that have the capacity to recover heat from various thermal sources. Lastly, it offers some novel applications of heat pump systems in various energy-intensive industries. Through this review paper on heat pump, we hope to convey one key message, that is, continuous efforts in improving heat pump performance will directly optimise energy use and reduce carbon footprint of many energy-intensive operating industries.

2. Improving energy efficiency

2.1. Multistage cycles

A multistage system employs more than one compression stage. Multistage vapour compression systems can be classified as compound or cascade systems [4] as shown in Fig. 2. A compound system consists of two or more compression stages connected in series. It may have one high-stage compressor (higher pressure) and one low-stage compressor (lower pressure) or several compressors connected in series. Compared to a single-stage system, a multistage has a smaller compression ratio and higher compression efficiency for each stage of compression, greater refrigeration effect, lower discharge temperature at the high-stage compressor, and greater flexibility [5,6]. The pressure between the discharge pressure of the high-stage compressor and the suction pressure of the low-stage compressor of a multistage system is called interstage pressure. Interstage pressure for a two-stage system is usually determined so that the compression ratios are nearly equal between two stages to realize a higher coefficient of performance (COP) [6]. Tanaka and Kotoh [7] investigated the performance of a double-stage compressor heat pump water heaters using CO_2 refrigerant for cold districts in Japan. They noted that the ratio of suction pressure (low pressure) of the compressor to the discharge pressure (high pressure) is large and subjects the compressor to harsh operating conditions in cold district where the lowest temperatures range from −10 to −20 °C. This lowers both the water-heating capacity and the system COP. To improve the performance and reliability of their HP system, they divided the compression stroke into two stages and the refrigerant injection at intermediate pressure [7]. Therefore, a compound multi-staging HP system presents a favourable option to improve system COP when operating in extreme cold conditions.

A cascade system consists of two independently operated single-stage refrigeration systems: a lower system that maintains a

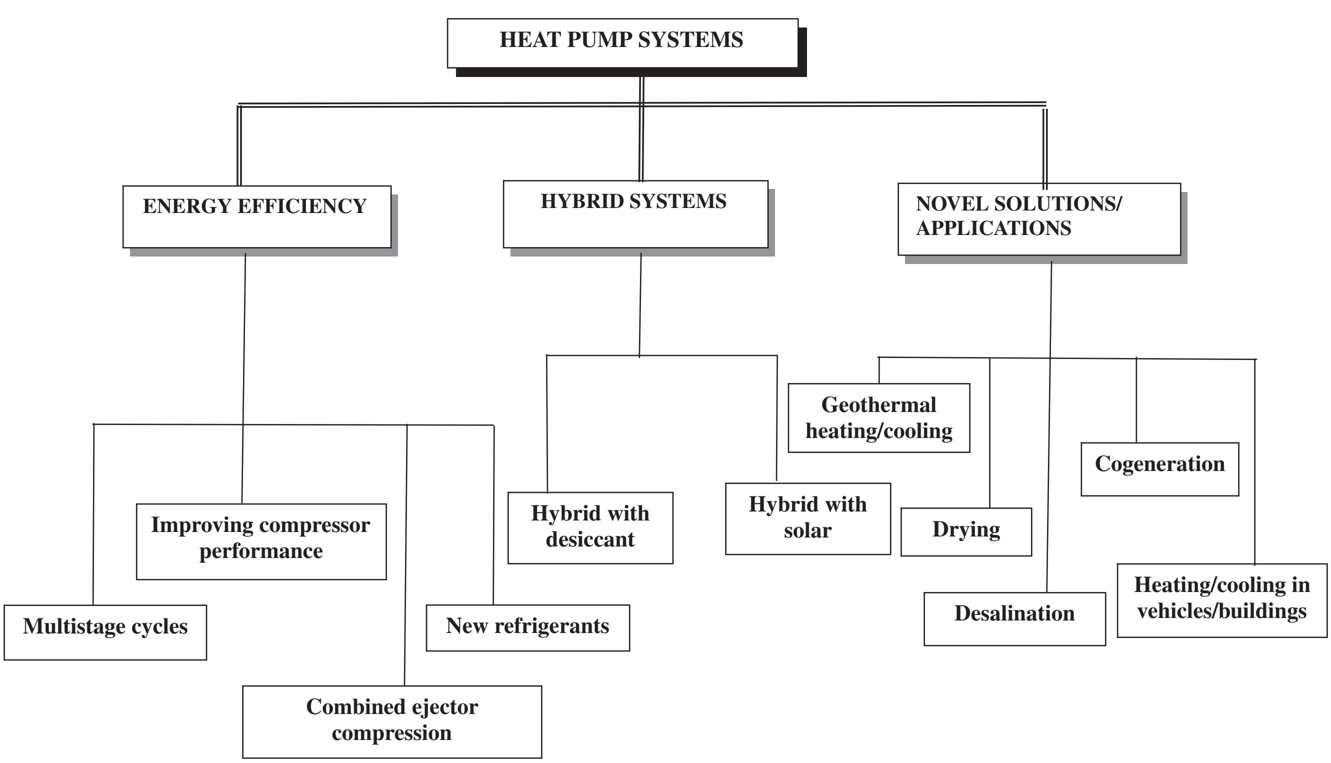

Fig. 1. A generalised classification of the recent development in heat pump technologies.

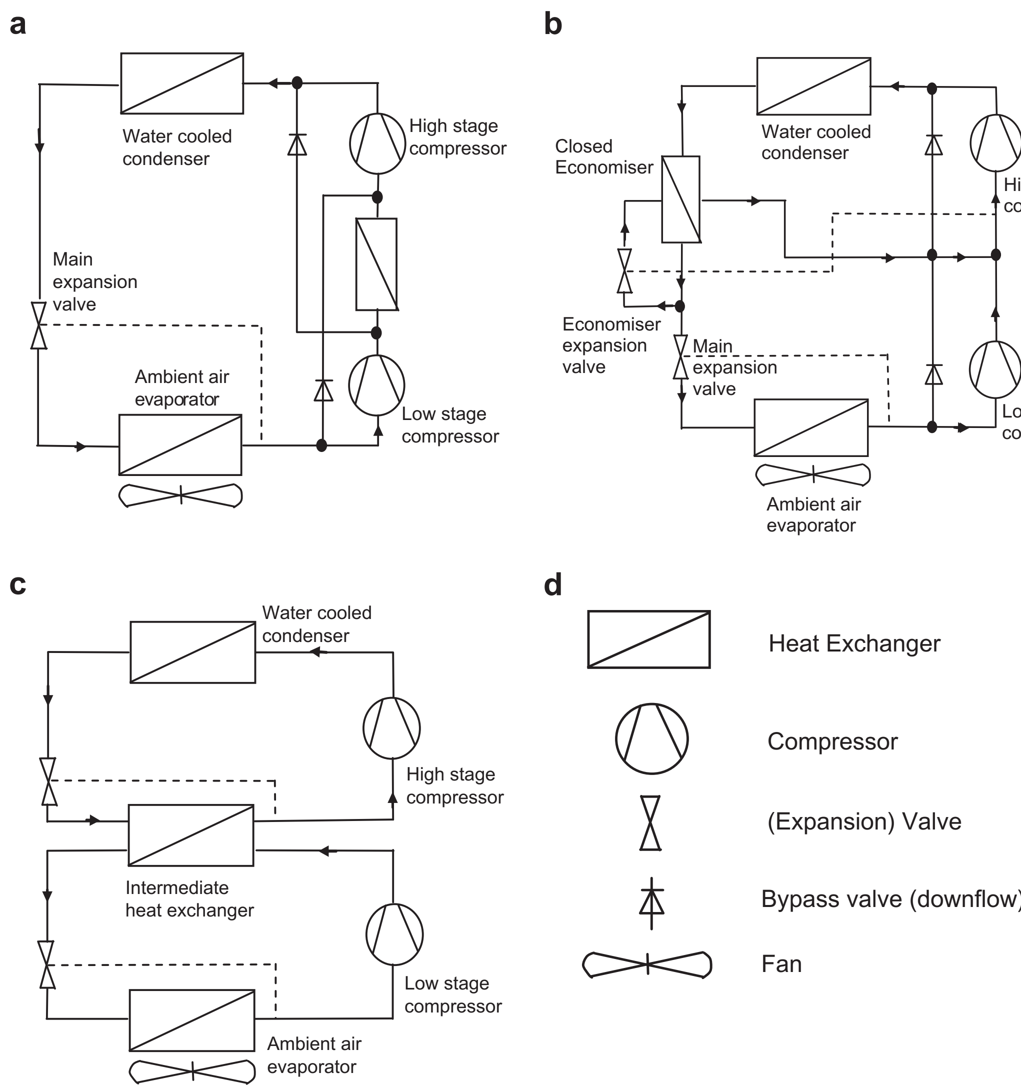

Fig. 2. Schematics of (a) two-stage cycle with intercooler, (b) two-stage cycle with closed economizer, (c) cascade cycle, and (d) legend [4].

lower evaporating temperature and produces a refrigeration effect and a higher system that operates at a higher evaporating temperature as shown in Fig. 2c [4]. These two separate systems are connected by a cascade condenser in which the heat released by the condenser in the lower system is extracted by the evaporator in the higher system. Wang et al. [8] examined the potential of a double-stage coupled heat pumps heating system, whereby an air source heat pump was coupled to a water source heat pump. Comparatively, they found that such a coupling process improved energy efficiency ratio by 20% compared to a purely air source heat pump [8].

Many of the commercial heat pump systems comprise a single-stage vapour compression cycle. In such systems only one evaporator is used for cooling and dehumidifying, and recovering the heat from a heat source. A mechanical constraint is, therefore, imposed on the amount of heat recovered because of the physical area available for heat transfer. Chua and co-workers have conducted studies on a two-stage evaporator heat pump system as shown in Fig. 3 [9]. In their system, the refrigerant vapour was split into two streams at the exit of the condenser. One stream entered an expansion valve with a higher discharge capacity to regulate to the “low” evaporator temperature while the other entered another expansion valve to be expanded to a higher temperature [9]. At the high and low pressure evaporators, the evaporation processes took place. The pressure of the refrigerant vapour at the exit of the high pressure evaporator was regulated by a back pressure regulator to that of the low pressure evaporator before mixing at a vapour chamber. Tests conducted the on a prototype two-stage evaporator heat-pump-assisted mechanical drying system highlighted one key finding: up to 35% more heat could be recovered via a two-stage evaporator heat pump drying cycle in comparison to one having only a single evaporator. The result was an appreciable improvement of the heat pump performance [9].

2.2. Improving compressor performance

To minimize the energy consumption of the vapour compression cycle, one key approach is to reduce the energy consumption of the compressor for a required compression ratio. In other words, improve the performance of the compressor. In recent years, one can consider the invention of the scroll compressor to be a major technological breakthrough in compressor technology [10]. The scroll compressor is approximately 10 percent more efficient than the standard reciprocating compressor. There are three chief reasons for this improvement [11]. Firstly, the suction and discharge processes are separate, meaning that no heat is added

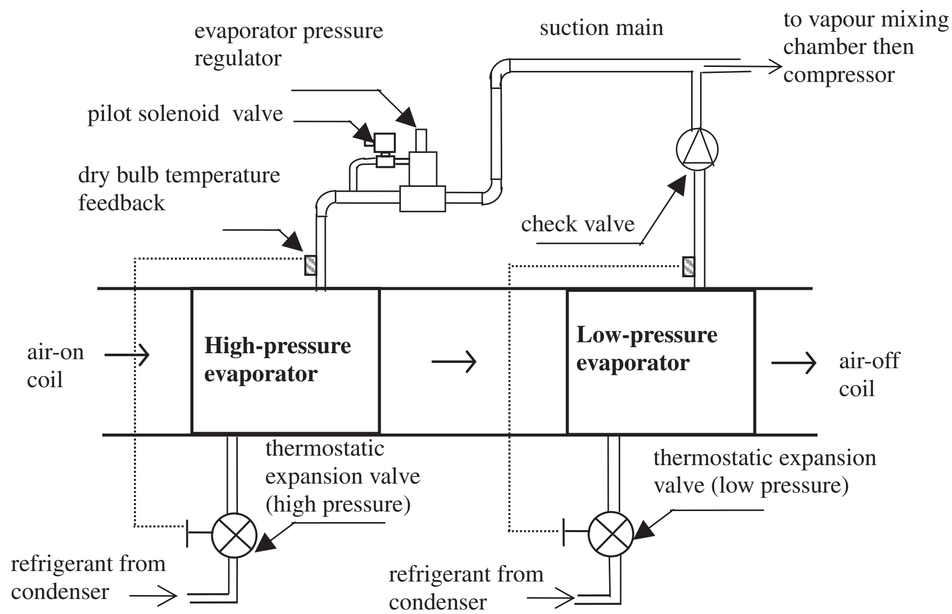

Fig. 3. Schematics of a two-stage evaporator system [9].

to the suction gas as it enters the compressor in contrast to the reciprocating compressors. Secondly, the compression process is performed slowly over 540 degrees of rotation versus 180 degrees of rotation for a reciprocating compressor. Therefore, fluctuations in driven torque are only 10 percent those of a reciprocating compressor. Thirdly, the scroll compression mechanism enables the elimination of the suction and discharge valves which are a source of pressure losses in reciprocating compressors. In additional, scroll compressors have better reliability because they have fewer moving parts and can operate better under liquid slugging conditions. Recent works coupling the heat pump with the scroll compressor demonstrated the energy efficiency of such an integration [12,13].

Recently, a new refrigeration compressor, named ‘Revolving Vane (RV) compressor’, has been developed by a group of researchers [14–17]. According to them, the salient feature of their innovative design involved the radical use of a rotating cylinder that moved together with the compressing mechanism to cut down on energy loss [14]. Consequently, frictional and leakage losses were effectively reduced [14]. Compared to piston type, the leakage loss at the radial clearance in the RV compressor was typically found to be 40% lesser than that of the former with anticipated volumetric efficiencies reaching as high as 95% [15–17]. The green and novel compressor significantly lowered input energy to perform similar refrigerant compression. Data from experiments have shown energy reduction as high as 80% when compared to current systems on the market [14].

A less active approach to enhance compressor performance is to ensure the compressor temperature is kept low during operations. Wang et al. [18] have studied two methods to achieve this. The first option involved cooling the compressor’s motor by external means other than using the suction gas. The second option subjected the compressor to undergo an isothermal process by transferring heat from the compression chamber. Results have shown that this strategy can potentially reduce the compression work by up to 14% as compared to the isentropic compression process for a R22 refrigeration system. A combination of both methods can yield energy savings up to 16% depending on operating conditions and fluid choice [18].

2.3. Ejector system

The ejector, which is the heart of the jet refrigeration system, was invented by Sir Charles Parsons around 1901 for removing air from a steam engine’s condenser. In 1910, an ejector was used by Maurice Leblanc in the first steam jet refrigeration system [19]. The ejector is an essential part in refrigeration and air conditioning, desalination, petroleum refining and chemical industries [20]. Also, the ejector forms an integral part of distillation columns, condensers and other heat exchange processes. Several recent published works have focused on various aspects of the ejector-compression system, namely, ejector-expansion transcritical CO_2 heat pump cycle [21], two-phase ejector system [22,23], ejectors in a multi-evaporator refrigeration [24], and performance of ejector refrigeration system powered by low grade waste heat or solar [25,26]. The following section highlights one significant recent development of an ejector heat pump system.

An ejector-compression heat pump employs low-grade thermal energy to provide space cooling and heating [22,23,25]. A versatile ejector-compression augmented system is shown in Fig. 4. It employs an ejector to perform various degree of compression of the refrigerant, depending on the quality and pressure of the exit refrigerant from the condenser as well as the available of high temperature waste heat. A gas–liquid separator separates expanded refrigerant into gas and liquid so that gas refrigerant is directly drawn into the compressor at a higher pressure while liquid refrigerant flows into the evaporator to exchange heat with the cooled space. The ejector undertakes part of the compression load, enabling the power requirement for the compressor to be significantly reduced. When high temperature waste heat is available, the ejector is able to undertake the entire compression duty as shown by the dotted-line cycle in Fig. 4. Depending on the geometrical, aerodynamical, and mechanical design of the ejector, theoretical study have shown that COP of an ejector-compression heat pump can yield improved performance of up to 21% over the vapour compression standard cycle [27]. To validate the energy performance of an ejector-compression heat pump, Chaiwongsa and Wongwises [23] designed an experimental setup with motive nozzles having three different outlet diameters. Fig. 5 shows the coefficient of performance of their

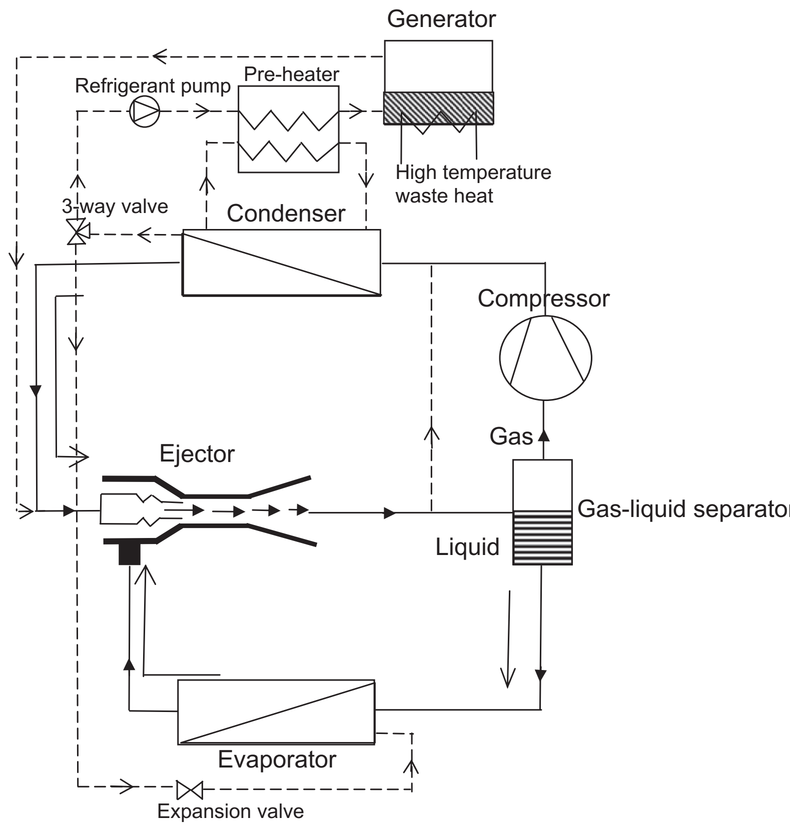

Fig. 4. A novel versatile ejector-compression augmented system.

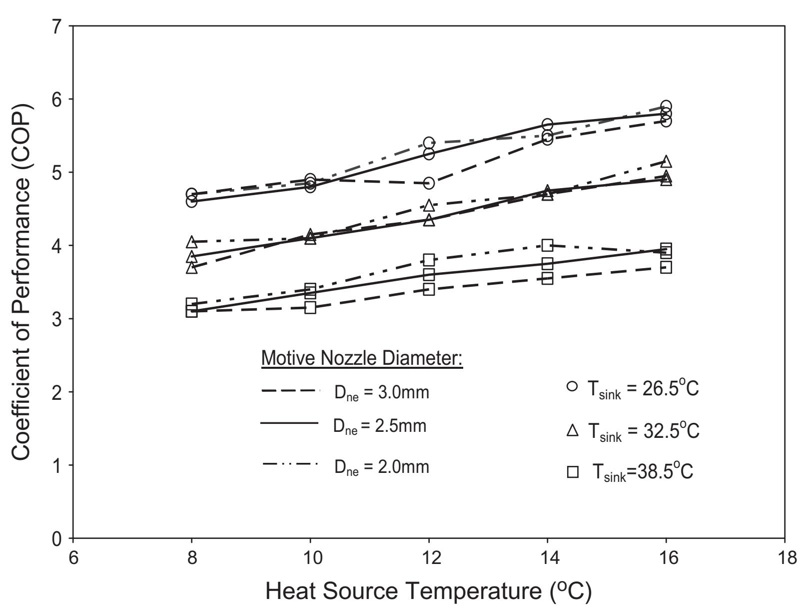

Fig. 5. Coefficient of performance of an ejector-HP system operating with different nozzle diameters and at various heat sink temperatures [23].

ejector-HP system operating at various heat sink temperatures [23]. Indeed, their study demonstrated marked improvement in energy efficiency with COP approaching as high a value as 6.

2.4. New refrigerants

HCFC-22 is perhaps the most widely used fluid in heat pump and air conditioning applications. It has a relatively low ozone-depletion potential, but since it contains chlorine, therefore, a replacement fluid is being sought. In seeking for a potential replacement refrigerant, it is important to select one that has thermodynamic properties similar to the fluids being replaced. It should also possess the desirable attribute in terms of matching the enthalpy of vaporization. Only when these parameters can be matched closely, the need for system redesign or re-configuration would be minimal.

Efforts to identify a replacement fluid that has thermodynamic properties similar to HCFC-22 have not been particularly successful. This has led researchers to investigate the possibility of concocting mixtures of HFCs to replace HCFC-22 [28]. The use of refrigerant mixtures in heat pump and air conditioning systems constantly poses new challenges to engineers. A pure single-component refrigerant will condense or boil at a constant temperature. In comparison, a refrigerant mixture changes temperature during a constant-pressure condensation or boiling process leading to what is often known as temperature "glide." The occurrence of glide during the phase change present problems to heat transfer engineers, among which incomplete condensation is considered the most important one [29]. Research continues to foray into refrigeration-system component design that can use these phase-change characteristics of refrigerant mixtures.

Besides the issue of environment impact caused by refrigerants, extensive works continue to progress in testing new refrigerant mixtures to improve the energy efficiency and operation of heat pumps [30]. Recently, performance tests have been conducted on an array of new refrigerant mixtures, namely, R404A [31], R407C [32], R410A [33], R433A [34], R32/R134a [35] and R170/R290 [36]. Chen [37] conducted R410A performance evaluation and found that the efficiency of the R410A air conditioning unit was observed to about 12% higher than that of R22 unit. Heat pump systems using the new chemical are more efficient because compressors that use R410A run cooler. This means they use less energy and are less likely to burn out. In additional, R410A absorbs and releases heat more efficiently which means systems using it will use less electricity and operates more efficiency [33]. Besides positive energy benefits, R410A has the potential to reduce heat exchanger sizes, particularly evaporator and condenser, since it captures and releases heat better than R22 [37]. Another new refrigerant R433A has shown tremendous potential in improving energy efficiency of heat pump. Park et al. [34] have conducted R433A and R22 comparative test using a heat pump bench testing facility. Key results from their work indicated that the coefficient of performance of R433A is 4.9–7.6% higher than that of HCFC-22 with significantly lower discharge temperature. An extension of this work, they studied the thermodynamic performance of R170/R290 mixture as a potential substitute to R22 [36]. In terms of energy performance, they demonstrated that the COP of R170/R290 mixture was higher than that of R22 in the composition range of up to 6% R170 under typical heat pump operations.

Researchers, such as Atipoang et al. [38] and Gorozabel Chata et al. [39], have studied the performance of hybrid heat pump systems employing refrigerant mixture. They were able determined the best performance of their systems with the right mass mixture of refrigerants.

The future poses a number of challenges and opportunities for manufacturers of HP systems. Most notably is the sustained effort to develop new refrigerants. Concurrently, there will be pressure to improve efficiency to maintain the competitive edge over new technologies such as gas heat pumps and to satisfy minimum efficiency requirements imposed by legislations. New performance enhanced refrigerants must compliment improved cycle controls, higher-efficiency motors and compressors, and new cycles to realize optimum cycle efficiencies to meet varying refrigerating capacities.

3. Hybrid systems

3.1. Hybrid desiccant system

A desiccant heat pump hybrid system offers an effective means of controlling space humidity while providing energy-efficient air temperature control. Such hybrid systems combine an electric vapour compression cycle with desiccant material. The desiccant material is regenerated from the waste condenser heat off of the vapour compression cycle. Desiccant systems in HVAC applications, an alternative or supplement to traditional air conditioning systems, are used primarily where the latent load is high or where independent control of temperature and humidity is an important factor [40]. Some key advantages of a desiccant heat pump hybrid system include: (1) allowing independent control of humidity and temperatures control for improved comfort and control of space conditions; (2) producing lower humidity levels in occupied spaces provides equivalent comfort levels at space temperatures; and (3) lowering capacity cost by eliminating expensive over-cooling and reheat devices required to dehumidify.

Some commercial applications of such hybrid system include schools, auditoriums, hospitals, low-rise office buildings, supermarkets, restaurants, etc. For example, Lazzarina and Castellotti [41] studied how a desiccant heat pump hybrid system performed when employed in a supermarket. In their system, a self-regenerating liquid desiccant cooling system was integrated to an electric heat pump. Their work demonstrated possible energy savings of such as hybrid system, compared to a traditional mechanical dehumidification [41]. In another independent study, performance measurement of a desiccant heat pump was conducted [41]. The achievable COP of the unit for low dehumidification capacity (4–6 g/kg) was around 5–6. However, lower COP was observed with increasing dehumidification capacity. Exploring a novel hybrid system by the integration of the variable refrigerant flow and heat pump desiccant (HPD) systems, Aynur et al. [42] conducted field performance tests during a heating season. They presented results that demonstrated such a novel system allows significant energy savings while providing the best indoor thermal comfort and indoor quality conditions.

3.2. Hybrid solar

The integration of heat pump with solar technology presents a novel hybrid system whereby the performance of the heat pump can be significantly enhanced by taking heat from a natural source – solar energy [43]. The applications for solar-assisted heat pump system include water heating [44–46], heat storage [47] and drying [48].

Among the works conducted on SAHP in recent years, new ideas related to the integrations of solar-thermal, photovoltaic (PV) and heat pump have been conceived to yield novel hybrid systems [49–51]. This is primarily due to sustained interest in employing renewable energy to improve heat pumping processes. Pei et al. [52] have described a novel photovoltaic solar-assisted heat pump (PV-SAHP) system whereby a Photovoltaic Thermal (PVT) was incorporated onto the evaporator to realise an evaporator–collector plate. In their setup, a portion of the solar energy received was converted to electricity while the rest was converted as heat. The heat energy was then absorbed by the refrigerant and carried over to the condenser. The generated electricity serves to augment the compressor power. The COP of the heat pump was also substantially improved because of the solar energy absorption [52]. The results indicated that the PV-SAHP system performed superiorly over conventional heat pump system while achieving a higher photovoltaic efficiency.

As far as the application of SAHP for drying of agricultural products is concern, it has been observed that coupling the heat pump to a solar collector improved the thermal efficiency of the air collector with values spanning 0.7–0.75 while efficiencies of the evaporator–collector were found to vary between 0.8–0.86. Improved efficiencies were primarily due to the reduction of losses from the collector [48]. Recent works have been devoted to investigating

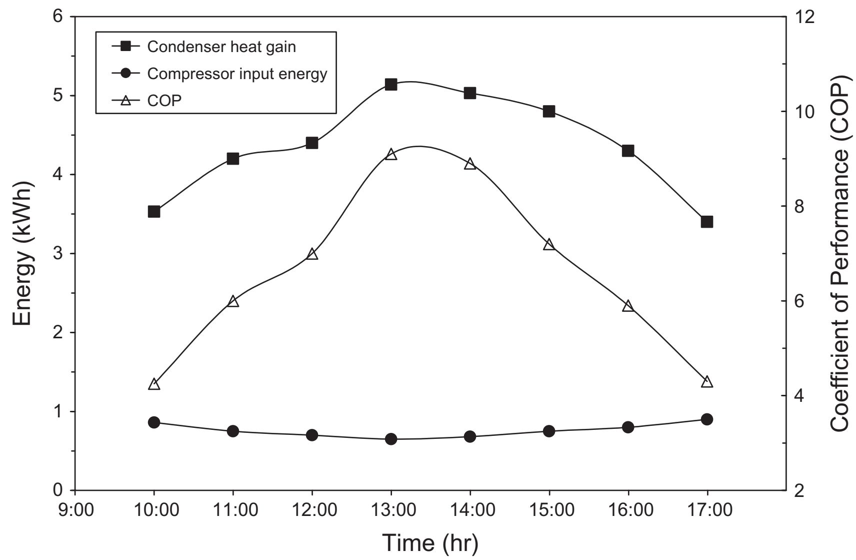

Fig. 6. Variation of condenser heat gain, compressor input power and system COP during winter system of a direct-expansion solar-assisted heat pump for water heating in subtropical Hong Kong [45].

the performance of a SAHP for hot water production [45,46]. In these works, the solar-assisted heat pump was specifically applied to water heating in Hong Kong. A mathematical system model was developed to study its performance under varying operating conditions. Results from the model highlighted several key points – SAHP system performance was strongly governed by the change of circulation flow-rate, solar collector area and initial water temperature in the preheating solar tank. It was further demonstrated that the SAHP system could achieve a year-long average COP of 6.46, which is considerably higher than the conventional heat pump system [45]. Fig. 6 illustrates the varying condenser heat gain, compressor input power and system COP during winter system for water heating in subtropical Hong Kong [45]. It was also observed that the amount of hot water produced in summer can be more than double of that in winter. With such favourable energy indicators attributed to its heat recovery capability, the SAHP system is deemed to be economically superior to electrical heating and solar-only systems, and is considered to be competitive with conventional energy-efficient fuel burning systems.

4. Novel applications/solutions

4.1. Desalination

Desalination is the process of converting sea water to fresh water. HPs employ heat energy effectively at desalination plants. Several works have been conducted to study the deployment of heat pump systems for producing fresh water [53,54]. Desalination plants based on mechanical vapour compression (MVC) technology are inherently the most thermodynamically efficient [55]. The thermodynamic efficiency of the MVC process is derived from the application of the HP principle. A single unit of a two-effect MVC desalination pilot plant of 50 m^3/day capacity was commissioned at Trombay, Mumbai [55]. Horizontal tube thin-film spray desalination evaporators were used for efficient heat transfer. The HP application was adeptly applied as the feed water was deemed to be highly saline and condenser cooling water was absent, and where a thermal heat source was not available. The unit produces high-quality water, nearly demineralised quality, directly from seawater. Gao et al. (2008) have demonstrated the energy efficiency of a MVC system to produce freshwater [56]. Results from their test-rig demonstrated that freshwater could be produced at a rate 60 kg/day with a conservative power of 500 W.

Thermal desalination requires lots of energy. One hybrid technology that can potentially lower energy consumption is solar-assisted heat pump as it operates at low temperature and utilizes solar energy, ambient energy and waste heat. Hawlader et al. [57] have analyzed the performance of a novel solar-assisted heat pump system test-rig and obtained good water production. Their experimental system had the capacity to produce 1 litre of water per hour. In terms of energy efficiency, the hybrid system performed efficiently had a COP spanning 5–9, and a performance ratio of 0.6–1.38. By virtue of integrating the HP and solar energy, a hybrid system can reduce operating costs with the added benefit of maintenance being simple and convenient [57].

4.2. Geothermal

A geothermal heat pump or ground-source heat pump (GSHP) is a central heating and/or cooling system that pumps heat to or from the ground to provide heating, air conditioning and, in most cases, hot water [58]. They are ideally suited to tap the ubiquitous shallow geothermal resources. GSHPs include those in which heating/cooling coils are placed in horizontal and vertical configurations, under a building or parking lot as shown in Fig. 7. Geothermal HP heating and cooling systems operate as follow: During winter period, they move the heat from the earth into buildings and pump the heat from buildings and discharge it into the ground during summer season. Studies have shown that approximately 70 percent of the energy used in a geothermal heat pump system is renewable energy from the ground [59]. The earth's constant temperature is what makes geothermal heat pumps one of the most efficient, comfortable, and quiet heating and cooling technologies available today [59]. Zamfirescu and Dincer [60] and Granowskii et al. [61] have developed new mechanical compression heat pumps using organic fluids to upgrade the heat and increase the temperature to a level which can run a thermochemical or hybrid cycle. Their heat pumps have demonstrated favourable efficiency in applications with a temperature difference of about 50 °C and where available constant heat source is available, as in the case of the ground-source.

As a renewable energy technology, the GSHP's high energy efficiency and low environmental impact characteristics have already

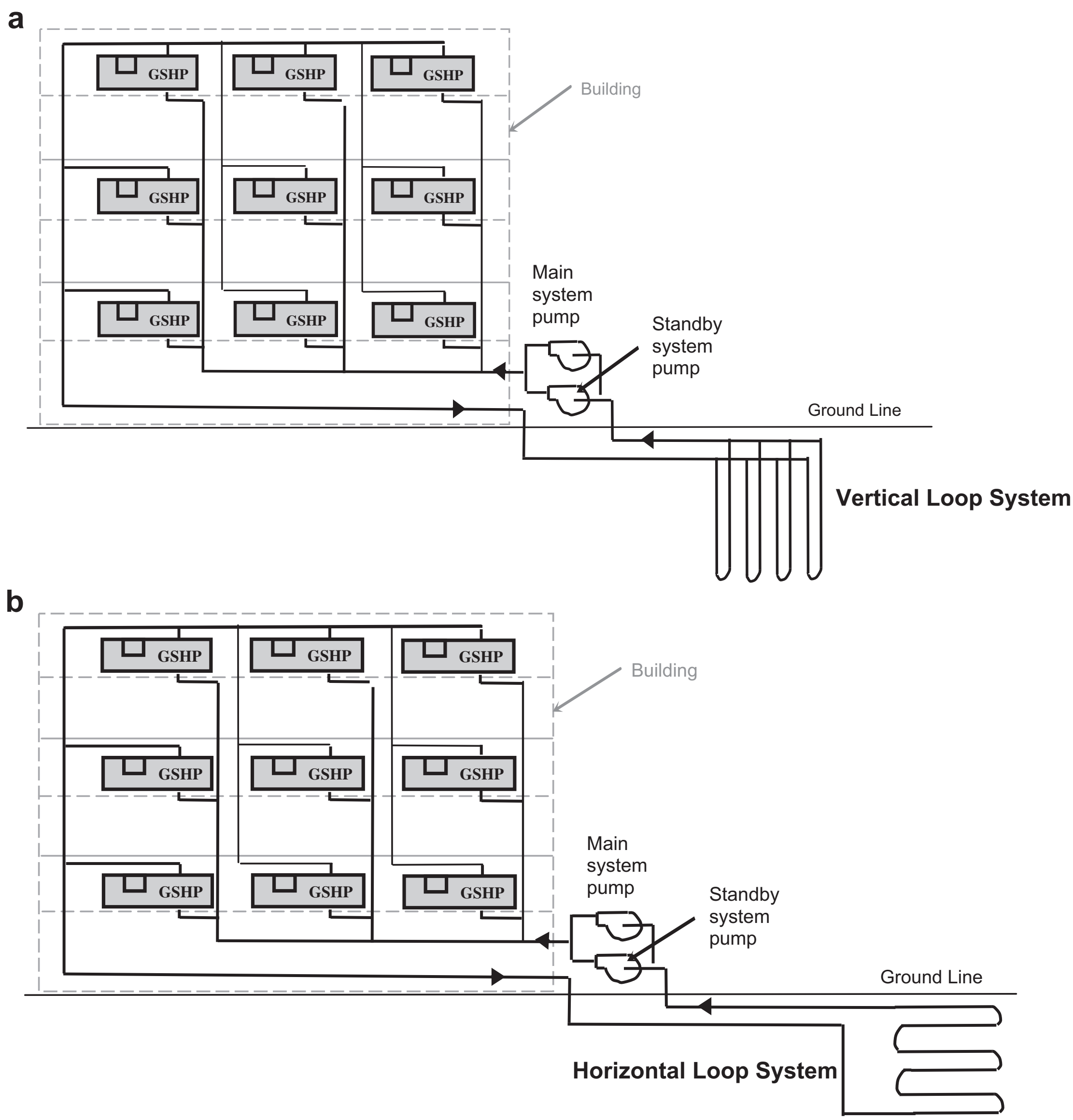

Fig. 7. Schematics of (a) vertical layout of a geothermal heat pump, and (b) horizontal layout of a geothermal heat pump.

drawn a fair amount of attention in huge energy-consuming nation like China [62]. GSHP can employ both the earth and buried underground water as potential heat sources/sinks as shown in Fig. 8. The water below the ground level can be the waste water from power plants (e.g. chemical, fossil fuel, etc.) to the wastewater treatment plant [63]. The primary advantage of the GSHP technology is that the both the earth and water stream provides a relatively constant temperature for heat transfer, thereby, improving the energy efficiency (COP) over that of conventional air systems. Work has also been carried out to integrate ground-coupled heat pump (GCHP) system with a fluid cooler, a cooling tower or surface heat rejecters in cooling-dominated buildings [64]. The operation principle of the GCHP system with a cooling tower involves the cooling tower being connected in series with the ground heat exchanger loop and is isolated from the building and ground loops with a plate heat exchanger. The ground loop is judiciously sized to meet the building heating load and the cooling load in excess of the heating load is met through the supplemental heat rejection [64].

Recent studies have focused on the evaluating the effectiveness of GCHP for heating/cooling applications in buildings while resolving related technical problems [65,66]. One study dealt with the modelling and performance evaluation of a heat pump system utilizing a low temperature geothermal resource [66]. The system was then designed, constructed and tested in Nigde, Turkey, and has been in operation since 2005. Energy and exergy analysis methods were used to assess the system performance based on the experimental data. Data analysis illustrated respective energy and exergy efficiency values to be ranging from 73.9% to 73.3% and 63.3% to 51.7%, respectively [66]. Recent research works have also been devoted to studying key parameters that will influence the performance of GCHP [67–70]. One study emphasized the importance of axial effects for borehole design of geothermal heat pump systems [69]. Another study has identified running time, shank spacing, depth of borehole, velocity in the pipe, thermal conductivity of grout, inlet temperature and soil type, on the thermal resistance and heat exchange rate, as key parameters that impact on GCHP performance [67].

Better quality of ground-coupled heat pump system installations has also occurred in recent years. Today's systems typically consist of thermally fused polyethylene or polybutylene piping with an expected lifetime of at least 50 years [71]. Engineers,

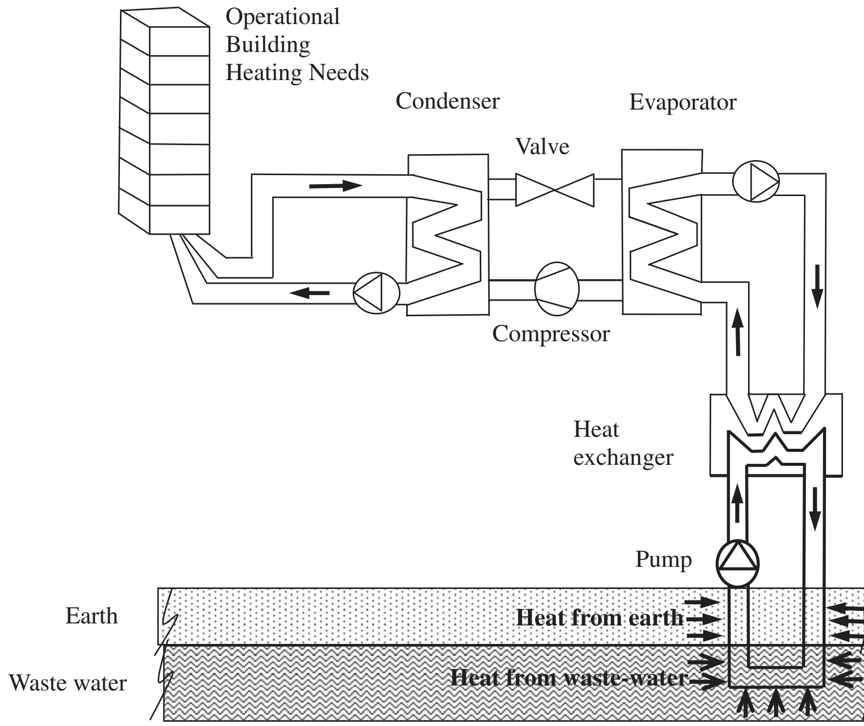

Fig. 8. Schematic of a hybrid ground-source heat pump that employs both the earth and buried underground water as potential heat sources/sinks.

architects, manufacturers, and installers have supported standardization of design methods and installation techniques for systems that use horizontal trenches and vertical boreholes [64]. Accordingly, GSHP's performance as well as the reliability of the system have improved.

Geothermal heat pumps are durable and require little maintenance. They have fewer mechanical components than other systems, and most of those components are underground, sheltered from the weather. The underground piping used in the system is often guaranteed to last 25–50 years and is virtually worry-free. Geothermal heat pumps are also known to be economically attractive in terms of reducing operating cost to provide heating [70,72]. Employing ground-coupled heat pumps for residential heating and cooling benefits the environment. In a CO_2 emission study conducted in Japan, it has shown that a typical residential GSHP produces 2038 kg-CO_2/year [73]. This emission amount is less than half compared to conventional oil boiler systems. It is noteworthy that a geothermal heat pump does not create heat by burning fuel like a furnace does. Instead, it collects the earth's natural heat for various heating applications. As a result, it is one of the cleanest technologies available for transferring heat to and from a natural heat source or sink. To date, geothermal heat pump remains an under-used technology, due mainly to the limited awareness of its potential. Therefore, continuous research and publicity efforts will serve to create greater public awareness about its benefits and promote end-users confidence in using it for different heating/cooling applications.

4.3. Drying

Heat pump dryers have been known to be energy efficient when used in conjunction with drying operations [9]. The principal advantages of heat pump dryers emerge from the ability of heat pumps to recover energy from the exhaust gas as well as their ability to control the drying gas temperature and humidity [74,75]. Researchers have demonstrated the importance of producing a range of precise drying conditions to dry a wide range of products and improve their quality [2,76,77]. Clearly, any dryer that uses convection as the primary mode of heat input to the dryer (with or without supplementary heat input by other modes of heat transfer) can be fitted with a suitably designed heat pump (HP). Although batch shelf or tray dryers or kilns (for wood) are the most commonly reported dryers used in conjunction with heat pumps, other types may also be used e.g. fluid beds, rotary dryers etc. The ability of heat pump dryers to convert the latent heat of condensation into sensible heat at the hot condenser makes them unique heat recovering devices for drying applications. The energy efficiency of HPD can be reflected by the higher SMER values and drying efficiency when compared to other drying systems as shown in Table 2 [78]. Consequently, higher SMER would then be translated to lower operating cost, making the pay-back period for initial capital considerably shorter.

The key advantages of the heat pump dryer [2] are: (1) heat pump drying (HPD) offers one of the highest Specific Moisture Extraction Ratio (SMER), often in the range of 1.0–4.0, since heat can be recovered from the moisture-laden air; (2) heat pump dryers can significantly improve product quality via drying at low temperatures. At low temperatures, the drying potential of the air can be maintained by further reduction of the air humidity;

Table 2
Comparing heat pump drying with other drying systems (adapted from Perera and Rahman [78]).

Parameter	Hot air-drying	Vacuum drying	Heat pump drying
SMER (kg water/kW h)	0.12–1.28	0.72–1.2	1.0–4.0
Drying efficiency (%)	35–40	⩽70	95
Operating temperature range (°C)	40–90	30–60	10–65
Operating % RH range	Variable	Low	10–65
Capital cost	Low	High	Moderate
Running cost	High	Very high	Low

(3) a wide range of drying conditions typically −20 to 100 °C (with auxiliary heating) and relative humidity 15–80% (with humidification system) can be generated; and (4) excellent control of environment for high-value products and reduced electrical energy consumption for low-value products.

Chua and co-workers have demonstrated the enormous potential of HPD for drying of various bioproducts [79]. Besides being energy efficient, it provides closed control of the drying conditions in terms of air temperature, humidity and flow-rate. Instead of employing a constant drying condition throughout the entire process, heat pump time-varying drying regulates drying temperatures in step-wise, intermittent or any cyclic fashions to yield high-quality end bioproducts [79].

In a recent review of heat pump drying technology, HPD and heat pump hybrid systems have clearly proven their capabilities to improve energy efficiency for removing similar amount of moisture for different products [80]. Various researchers involved in drying have found that the HPD uses energy more efficiently compared with conventional drying systems [2]. Hepbasli et al. [81] utilized a gas engine-driven heat pump (GEHP) for food drying purposes for the first time. The system consists of four key components, namely: (1) a GEHP unit with heating capacity of 18 kW, (2) a HP unit with scroll modified for compression with enhanced vapour injection, (3) an air solar collector, and (4) a band conveyor dryer. Preliminary study has indicated that the heat gained by heat recovery can be provided approximately by 30% of the total heating capacity for GEHP systems.

There has been a raising trend in applying HPD to various heat-sensitive herbs [82]. In comparison to various conventional dryer, heat pump-dried herbs yielded improved colour and aroma of herbs (e.g. parsley, rosemary, and sweet fennel). The sensory values were nearly doubled in case of heat pump-dried herbs compared to commercially dried products [2]. The specific energy consumption (kg/kWh) for herbs drying was also found be low particularly with moisture-laden herbs because greater amount of latent heat is available for recovery [2].

The use of modified atmospheres for drying of sensitive materials such as food products is another important aspect of the HPD technology [83]. Drying with oxygen-sensitive materials such as flavour compounds and fatty acids can undergo oxidation, giving rise to poor flavour, colour, and rehydration properties. Using modified atmospheres to replace air would allow new dry products to be developed without oxidative reactions occurring [83].

4.4. Heating/cooling

One of the primary applications of heat pump is to provide heating and cooling to a designated space. The space can vary from a modest size such as a motor vehicle to as large as a township whereby heat can be pumped from one sector to another. Although the application of heat pump technology for heating/cooling is not new, novel applications are still constantly being developed. For example, heating and cooling of space and provision of hot water in a building can be simultaneously being carried out [84]. On a larger scale, novel designs of district heating/cooling systems have been recently looked at to support township operations. With improved heat pump heating/cooling system designs, energy efficiency for district heating/cooling is significantly enhanced with significant reduction in carbon footprint.

Heat pumps for heating and cooling buildings can be divided into four main categories depending on their operational function and needs. The categories include: (1) heating-only heat pumps, providing space heating and/or water heating; (2) heating and cooling heat pumps, providing both space heating and cooling; (3) integrated heat pump systems, providing space heating, cooling, water heating and sometimes exhaust air heat recovery; and (4) heat pump water heaters, fully dedicated to water heating [84].

Heat pumps can be both monovalent and bivalent [85]. A monovalent heat pump heating system is one whereby the heat pump alone supplies heat during the heating season. In a bivalent heat pump heating system, the heat pump heat capacity may be supplemented by other heating equipment to meet or assist in meeting heating demand on unusually cold days. In other words, a hybrid heating system comprising heat pump and another heating system, such as gas or oil boiler, is borne out. Typically, monovalent heat pumps are sized to meet the entire annual heating and cooling demand, while bivalent heat pumps are sized for 20–60% of the maximum heat load and meet around 50–95% of the annual heating demand [85].

A district heating and cooling system is expected to be a promising energy-saving measure for high-density cities and heat pump systems play an essential role in such large-scale heat transfer operations [86,87]. For example, coastal areas are ideal sites for the application of seawater-source heat pump technology (SWHP) to provide district cooling and heating. Recently, Zhen et al. [88] conducted a study on employing heat pumps to deliver thermal energy from the ocean thermal energy to a district in Dalian, China. The district has an estimated 68 MW heating load and 76 MW cooling load plant capacity. In this study, the economic, energy and environmental impacts of the SWHP technology were analyzed. Key results from the study indicated that Dalian has great potential for applying SWHP system. It is both technically and economically feasible because of the favourable geographical location and urban environmental setting [89]. Economically, district heating with heat pump system has demonstrated significant reduction in annual energy bill.

Several works have conducted on the performance of heat pump systems employed for motor vehicles [90–92]. Antonijevic and Heckt [92] developed a prototype heat pump system for performance evaluation in a test vehicle. Test results were obtained, analyzed and compared with other current supplemental vehicle heating systems. The proposed automotive heat pump heating system performed superiorly compared to other automotive supplemental heating solutions by demonstrating better performance parameters, lower fuel consumption and stable operational behaviour. In investigating the performance characteristics of an R134a automotive air conditioning system capable of operating as an air-to-air heat pump using ambient air as a heat source, Hosoz and Direk [90] observed that the heat pump operation provided adequate heating only in mild weather conditions, and the heating capacity dropped sharply with decreasing outdoor temperature. Also, the heat pump yielded a higher coefficient of performance compared to operating the system purely for air conditioning with a lower rate of exergy destruction per unit capacity. A simple approach to improve the energy efficiency of heat pumps in vehicles is by recovering heat from a better heat source such as the engine coolant, exhaust gases [90] or even from the fuel cell stack in the case of fuel cell vehicles [91].

4.5. Cogeneration

At a time of soaring energy costs, cogeneration is one way to ease operating cost. The value of the waste heat dumped into the air or water by power plants can, at times, be worth about twice as much as the electricity that's generated and sold. Cogeneration systems have a large potential for energy saving, especially when they simultaneously produce heat, cold and power as useful energy outputs. Because of its capacity to recover heat from any heat sources, heat pump plays a critical role in cogeneration.

Typically, cogeneration systems for combined heat, cold and power production are designed mainly incorporating absorption

Table 3
Summary of energy performance of different HP systems.

#	Year	Investigator(s)	Type of study		Type of system		Application			Result(s)
			Theoretical (simulation)	Experimental	Heating	Cooling	Water heating	A/C[a]	Other	
1	2010	Chow et al. [45]	√		√		√			SAHP system – mean achievable COP of 6.46
2	2009	Park and Jung [36]		√	√		√			Improved COP about 6% with the use of new refrigerant mixture
3	2008	Chaiwongsa and Wongwises [23]		√		√		√		HP with ejector – COP approaching as high a value as 6
4	2008	Aynur et al. [42]		√		√		√		HP with dehumidifier – COP approaches 5 to 6
5	2007	Yari and Sirousazar [27]	√			√		√		HP with ejector –improved COP of 21%
6	2005	Chua and Chou [9]		√	√				√ (drying)	Improved HP energy efficiency approaching 35% via multi-staging

[a] A/C: air conditioning.

heat pumps. But as compression heat pumps become more energy efficient, attention has recently been focused at employing them for cogeneration purpose. One such example is the application of heat pump whereby the compression driven by gas engine [93]. Cogeneration systems associated with gas engine-driven heat pump have higher efficiency. A recent study on a gas engine heat pump applied to a specific building for cogeneration demonstrated effective energy usage. Result of the energy consumption showed that the primary energy ratio of such system was 1.49, a performance index that was much higher than that of the conventional separated production system [93].

A cogeneration system combined with a heat pump can yield impressive carbon savings. Micro-cogeneration, also termed micro combined heat and power or residential cogeneration, is an emerging technology with the potential to provide energy efficiency and environmental benefits by reducing primary energy consumption and associated greenhouse gas emissions [94]. Dorer and Weber [95] compared several micro-cogeneration devices, namely, solid oxide fuel cell, Stirling engine, internal combustion engine, gas boiler and ground-coupled heat pump. Taking the gas boiler as the benchmark, they found that CO_2 mission was the most significant with the heat pump system achieving an appreciable value of up to 29%. Mancarella [96] presented a novel approach to modelling the energy and CO_2 emission of cogeneration systems coupled to electric heat pumps. One key result from their findings was that for small-scale distributed applications heat pump coupled cogeneration system exhibited energy saving and emission reduction of the order of up to 50%.

Cogeneration can dramatically increase energy efficiency, slash carbon emissions, and save money. Heat pump brings about even greater opportunities for enhanced energy efficiency. In designing a cogeneration, heat pumps readily compliment with many renewable energy technologies to produce desired heat and power at reduced basic fuel input. Thus, integrating heat pumps with clean technologies becomes a potent tool in combating carbon emission. This is the direction energy engineering should be moving with all deliberate speed.

5. Conclusions

Heat pump technologies are widely used for upgrading ambient heat from sustainable sources, such as air, water, the ground and waste heat, to heating temperatures. They can be used for residential and commercial space heating, cooling and water heating, refrigeration and in many industrial processes. In producing heat, they are called heat pumps and they compete with fossil fired boilers and direct electric heating. This paper has portrayed HP as an energy-efficient technology with enormous potential to contribute to various energy-intensive industries. Table 3 summarises the key performance values of several reviewed HP works presented in this paper. We have demonstrated through various literature sources how recent efforts have improved heat pump energy efficiency by 35% through multi-staging and enhanced COP by 20% thorough ejector-augmentation. In additional, various recently developed hybrid heat pump systems have further improved efficient use of thermal heat, extended the application of HP and markedly reduced carbon emission. Employing HP for residential heating and cooling produces about 2038 kg-CO_2/year, an amount is less than half compared to conventional boiler systems.

With abundant amount of heat available in various natural sources and waste heat generated in various process industries, HP becomes an indispensable technology that can contribute towards a cleaner environment. It is important, when pursing new green technologies to combat climate change, to not lose sight of available conventional technology like the heat pump. Much work has been done but more is still required to integrate HP in innovative systems. It is hoped that this review will help increase awareness and spur efforts in exploring and maximizing the potential of HP to realize greater energy efficiency.

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