Chillers of air-conditioning systems: An overview

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ABSTRACT

In tropical and subtropical regions, air-conditioning commonly consumes the most energy in buildings. The chillers used in existing air-conditioning systems are largely based on thermodynamic vapour compression cycle because the cycle is highly effective, efficient and practical. Moreover, the system installation and operation are convenient when grid electricity is available. Popular vapour compression chiller types include air-cooled, water-cooled, seawater-cooled and oil-free chillers. In addition, thermal-driven absorption and adsorption chillers have become available in the market. Viable sources of thermal energy input include fuel combustion, renewable solar energy, waste heat, and so on. This paper provides an overview of different types of chillers and system configurations in terms of mechanisms, characteristics, energy efficiency, environmental performance and costs. The technical information and comparisons should help engineers select the chiller type in air-conditioning system design for achieving high sustainability.

KEYWORDS Vapour compression cycle; oil free chiller; absorption cooling; adsorption cooling; energy efficiency; carbon footprint; cost analysis

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Received 21 November 2019

1. Introduction

Air-conditioning is the major form of energy consumption in Hong Kong buildings (Figure 1). Similar energy consumption distribution is found in other cities in the tropical and subtropical regions. Due to global urbanisation and economic growth, the energy demand for air-conditioning will continue to increase worldwide (Figure 2). Therefore, energy-efficient air-conditioning has a high energy saving potential as well as carbon emission reduction potential among other energy consumers in the building sector.

In a central heating, ventilation and air-conditioning (HVAC) system, the chillers are considered as key units as they produce the cooling effect required and account for most of the electricity consumption. There are different types of chillers available in the market, including conventional vapour compression chiller, oil-free chiller, absorption chiller and adsorption chiller. Each type has its own unique features, advantages and limitations. Depending on the specific site conditions and requirements, one chiller type may fit better than the others. In this paper, the cooling mechanisms of each chiller type and their characteristics, energy efficiency, environmental impacts and costs will be discussed. The technical information can facilitate selection of chillers in HVAC system design, and thus, yield significant energy saving, carbon emission reduction as well as cost saving.

Figure 1. Annual electricity consumption distribution in Hong Kong (HKSAR Government, 2018: pp.63-68).

Figure 2. Energy demand for air-conditioning worldwide (Paris: International Energy Agency, 2018: p.1).

2. Vapour compression chiller

2.1. Vapour compression cycle

Vapour compression (VC) cycle, as illustrated in Figure 3, is the most commonly used refrigeration cycle in air-conditioning systems from small-scale domestic units to large-scale central chiller plants (ASHRAE Handbook-Fundamentals, 2017). The four main components of the VC cycle are compressor, condenser, expansion device and evaporator. As the refrigerant passes through the expansion device, it undergoes expansion from liquid to saturated liquid and vapour. In this process, the temperature of the refrigerant drops to a low level (1°C - 5°C). Then, the cooling effect occurs at the evaporator as the cold refrigerant absorbs heat from the chilled water return (11°C - 15°C) to produce low-temperature chilled water supply (6°C - 10°C). The energy efficiency of the cycle can be measured in terms of the coefficient of performance (COP), defined as the ratio of the cooling effect to the compressor work. It is noted that the air-conditioning system performance can be measured in terms of system COP, defined as the ratio of the cooling effect to the energy consumed by the chiller and other components, e.g. pumps and fans (Aprea and Greco, 2002).

2.2. Refrigerant

There are many different refrigerants that can work effectively as the working fluid in VC cycle. Choosing the right refrigerant yields high COP as well as low carbon footprint. In the past, chlorodifluoromethane, also known as R22, was widely used from domestic to large-scale applications due to its excellent thermodynamic properties to achieve high COP. However, as it has a considerable level of ozone depletion potential (ODP), R22 has been phased out under the Montreal Protocol on Substances that Deplete the Ozone Layer. Various hydrofluorocarbons (HFCs) became available in the market as substitutes to R22, e.g. R410A and R134a. Recently, the use of HFCs has also been increasingly restricted since they are greenhouse gases (GHGs) with high global warming potential (GWP). In case of leakage, the fugitive emission of GHG will adversely contribute to climate change. Refrigerants for the next generation have been proposed although each substance has its limitations as summarised in Table 1.

R32 has been adopted by some manufacturers in the air-conditioning industry. Refrigerant blends have also been suggested for additional advantages.

Figure 3. Vapour compression chiller: (a) schematics; (b) pressure-enthalpy ($P-h$) diagram; and (c) temperature-entropy ($T-s$) diagram of typical operation using refrigerant R134a.

Table 1. Potential environmental-friendly refrigerants for future air-conditioning industry.

Potential refrigerant	Refrigerant type	Advantages	Disadvantages
R290, R1270	Hydrocarbon (HC)	Very low GWP; zero ODP	Flammable
R32	Hydrofluorocarbon (HFC)	Low GWP; zero ODP; minimum changes required to existing equipment	Mildly flammable
R1234ze(E), R1234yf	Hydrofluoroolefin (HFO)	Very low GWP; zero ODP	Flammable
R717 (Ammonia)	Natural refrigerant	Zero GWP; zero ODP	Mildly flammable; toxic
R744 (CO_2)	Natural refrigerant	Negligible GWP; zero ODP; non-flammable	High working pressure

2.3. Compressor

Compressor is the most important component in a chiller as it is responsible for driving the flow of refrigerant in the VC cycle (ASHRAE Handbook-Fundamentals, 2017). It is similar to the heart in our blood circulation system. The compressor accounts for most of the electricity consumed by the entire air-conditioning system. There are different types of compressors available in the industry, including scroll, reciprocating, screw and centrifugal compressors. Their characteristics are summarised in Table 2. Based on the initial costs and operating costs, each compressor type has a favourable range of cooling capacity.

2.4. Condenser

The COP of a chiller highly depends on the heat rejection effectiveness of the condenser. An air-cooled condenser (Figure 4(a)) is a heat exchanger that uses ambient air to cool the hot superheated vapour refrigerant until it fully turns to liquid. In a water-cooled condenser (Figure 4(b)), the condenser is directly cooled by water and a cooling tower is used to reject the heat from the condensing water by latent heat of vaporisation. It is more convenient to install and operate an air-cooled condenser than a water-cooled condenser because the cooling tower occupies more space and requires condensing water treatment. However, the water-cooled condenser is a more effective heat exchanger than the air-cooled condenser as water has a much higher specific heat capacity than air. A seawater-cooled condenser (Figure 4(c)) uses seawater to cool the refrigerant and then the seawater is discharged back to the sea. Seawater-cooled condenser is more effective than water-cooled condenser because the seawater intake is colder than the counterpart. However, fouling problem occurs in seawater-cooled condenser. Automatic condenser tube cleaning devices can solve the fouling problem effectively (ASHRAE Handbook-Fundamentals, 2017). The typical COP values of chillers using different heat rejecting media are shown in Figure 5 (Bitzer Software, 2019). Figure 6 further presents the COP of chillers using different compressors and condensers based on specifications provided by major manufacturers. The standard test conditions of water-cooled chillers are as follows: the entering and leaving water temperatures of the evaporator are 12°C and 7°C, respectively; and the entering and leaving water temperatures of the cooling tower are 30°C and 35°C, respectively.

Figure 4. Chillers using different condenser types: (a) air-cooled condenser; (b) water-cooled condenser; and (c) seawater-cooled condenser.

Figure 5. Typical COP of air-cooled, water-cooled and seawater-cooled chillers.

Figure 6. COP of chillers using different compressors and condensers.

2.5. Component enhancement

Many attempts in component enhancement for conventional vapour compression chillers have achieved encouraging results. Recently, modification on the heat exchanger structure has received much attention. Cao et al. (2020) utilised passive two-phase heat transfer devices to reduce the need for variable frequency operation. Singhal et al. (2019) designed a porous wick cloth for the condenser to improve its heat transfer capability, resulting in about

32.4% enhancement in COP with a maximum ambient temperature of 35°C. Abubaker et al. (2020) proposed the use of innovative fin-tube heat exchanger as the condenser of a cooling system and the COP increased by 4.7%.

3. Oil-free chiller

3.1. Magnetic bearing

Oil-free chillers are similar to conventional VC chillers. The main difference between oil-free chillers and VC chillers is in the compressors. In an oil-free chiller, the compressor is equipped with magnetic bearings. As shown in Figure 7, the magnetic bearings are non-contacting devices, and thus, they do not require lubricating oil. The magnetic bearing compressor is more energy efficient because the VC chiller using oil-lubricated compressor consumes more energy to drive the flow of refrigerant as the lubricating oil is miscible with the refrigerant (Yu et al., 2015). Moreover, the deposition of lubricating oil onto the heat exchanger surfaces declines the overall heat transfer coefficient due to its low thermal conductivity (Kedzierski, 2001). Furthermore, the presence of the lubricating oil reduces the bubble size of departure in the phase change process, resulting in poor heat transfer.

In oil-free chillers, there are two major types of magnetic bearing systems, namely, active magnetic bearing

Table 2. Characteristics of chillers using different compressor types (HKSAR government, 2015: pp.5-10; Johnson Controls, 2018: pp.8-12; GEA North America, 2020: pp.11-19; Carrier Corporation, 2019: pp.2-5; Aprea et al., 2003: pp.653-669; Aprea et al., 2009: pp.1995-1997).

Compressor type	Operating principle	Cooling capacity	Full-load performance	Part-load operation	Equipment cost per kW cooling (HKD)	Maintenance cost
Scroll	Compressing gas using two inter-fitting, spiral-shaped scroll members	50 kW - 1,300 kW	Good	Mostly via speed variation or with a multiple-compressor arrangement	900 - 2,000	Low
Reciprocating	Using pistons driven by a crankshaft to deliver gas at higher pressure	200 kW - 2,400 kW	Good	Staged capacity control via cylinder unloaders; COP not affected during part-load operation	600 - 1,300	High
Screw	Using helical rotors to reduce the refrigerant gas volume as they rotate to achieve compression	200 kW - 5,800 kW	Excellent	Poor COP via slide valve capacity control; can be improved via variable speed capacity control	600 - 1,400	Medium
Centrifugal	Refrigerant gas compressed via rotating impellers	500 kW - 21,000 kW	Excellent	Mostly via speed variation and COP remains high	700 - 1,400 ($\leq 1,500$ kW); 350 - 800 ($> 1,500$ kW)	Low

and passive magnetic bearing (Figure 7). The active magnetic bearing is formed by coils which generate a magnetic field by an alternating current. The properties of the active magnetic bearing include good controllability and damping effect, but poor reliability and availability because of the complicated control (Du et al., 2019; Guan et al., 2019; Sun et al., 2019).

Passive magnetic bearing using permanent magnets has a simpler structure (Jinji et al., 2011; Ohji et al., 2011). The advantages include high reliability and low energy consumption because a passive magnetic bearing system does not involve any electronic control. However, it is not favourable to high speed rotation due to the lack of damping. Without damping, the rotor is vulnerable to synchronous vibration excitation.

Figure 7. (a) Active and (b) passive magnetic bearing systems for oil-free chillers.

3.2. Operation and performance

Similar to VC chillers, the oil-free chillers can operate with variable speed so that it can significantly save 20% of the energy consumption (Aprea et al., 2006). Yu and Chan (2008) consistently found that the annual savings in energy consumption and water usage of the variable speed oil-free chiller were 19.7% and 15.9%, respectively. However, the initial cost of the oil-free chillers is about twice of that of

conventional VC chillers (Yu et al., 2015). Low economic benefit is the major barrier to commercialisation of oil-free chillers in the present market. The COP of oil-free chillers normally lies between 5 and 6 at the full load condition.

Integrated part load value (IPLV) is another parameter for evaluating the performance of a chiller operating in part load. IPLV is defined as the weighted average of COP at 25%, 50%, 75% and 100% of the full capacity and the weighting factors are 0.12, 0.45, 0.42 and 0.01, respectively. Yu et al. (2017) compared the IPLV between a constant speed centrifugal chiller and a variable speed oil-free chiller, and the values were 8.7 and 10.7, respectively. It means that variable speed oil-free chillers have a better performance than constant speed centrifugal chillers in different loading conditions. The average system COP increased from 6.2 to 10.3 in the chiller replacement. Yu et al. (2017) also conducted a retrofit project in which constant speed centrifugal chillers were replaced by variable speed oil-free chillers in a shopping arcade in Hong Kong. They found that an energy saving of 9.6% was achieved. The total capital cost of the chiller replacement was about 6 million HKD and the annual cost saving was approximately 1 million HKD, resulting in a payback period of around six years. It should be noted that the variable speed oil-free chillers normally have a ten-year life span.

It is also found that oil-free chillers require less maintenance services (Parker and Blanchard, 2012) and thus the downtime is low. In principle, the maintenance cost is also low. However, since presently there are few trained suppliers offering maintenance contracts of oil-free chillers, the maintenance cost may be high in the less competitive market. Replacement of conventional VC chillers by variable speed oil-free chillers is a profitable long-term investment.

3.3. Feasibility

The use of oil-free chillers in Hong Kong is effective because of the high demand for air-conditioning and the potential energy saving is high with a short payback period. Moreover, the electricity indirect GHG emissions, such as carbon dioxide and nitrous oxide, can be reduced. Therefore, the use of oil-free chillers is an environmentally friendly strategy. The oil-free chillers are relatively not susceptible to ambient temperature and humidity, so they are applicable to Hong Kong in which the climate is relatively hot and humid. Similar to VC chillers, the space requirement of oil-free chillers is low. Since space in Hong Kong is very limited, compact oil-free chillers are favourable. It is noted that active magnetic regenerative refrigeration, another advanced technology adopting magnetism to produce cooling effect, also has a high potential for achieving energy efficient air-conditioning (Aprea et al., 2012; Aprea et al., 2014). The choice of magnetic material is of crucial importance and the development of advanced magnetic materials has received much attention (Aprea et al., 2015; Pecharsky and Gschneidner, 2006).

4. Absorption chiller

4.1. Absorption cooling

Absorption chiller is a thermal-driven chiller, in which the cooling effect is produced by heat utilisation as the main energy input (Sarbu and Sebarchievici, 2013). The basic single-effect absorption cycle is illustrated in Figure 8. There are similarities between the absorption cooling cycle and the VC cycle. The main difference is that instead of vapour compression driven by electric compressor in VC, the refrigerant vapour in the absorption cycle is raised to high pressure by the following sequential process: (1) absorption into liquid form, (2) pumping of liquid to high pressure and (3) heating desorption to release high-pressure refrigerant vapour. In the absorption cycle, the main energy input is the thermal energy consumed in the heating process. Therefore, the COP can be defined as the ratio of the cooling effect to the heat input. Single-effect absorption chillers are designed for medium-temperature heat sources (80°C - 120°C). The typical COP is 0.5 - 0.7.

Multi-effect absorption chillers can enhance the cycle performance when high-temperature heat source is available, with the double-effect and triple-effect cycles being the majority (Gebreslassie et al., 2010). Double-effect absorption chillers are driven by heat at high temperature (120°C - 170°C) and yield high COP (1.0 - 1.2). Triple-effect absorption chillers are driven by heat at even higher temperature (200°C - 230°C) and yield even higher COP (1.4 - 1.7).

Comparing with a VC chiller of the same cooling capacity, an absorption chiller requires a considerably larger condenser to accommodate its higher heat rejection. Thus, the space requirement of the entire absorption cooling system is much higher.

4.2. Working fluids

Working fluids, consisting of refrigerant and absorbent, play an important role in the performance of absorption chillers. H_2O -based working fluids are the most widely used for absorption chillers, with H_2O (refrigerant)-LiBr(absorbent) being the majority (Herold et al., 2016). H_2O -based working fluids feature high efficiency, low cost and safe operation (Horuz, 1998). However, they also have some limitations: (1) high freezing point of H_2O does not facilitate subfreezing refrigeration (Karamangil et al., 2010; Muthu et al., 2008); (2) H_2O -LiBr solution is subject to crystallisation affecting the reliability of the chiller (Izquierdo et al., 2004; Wang et al., 2011); and (3) high vacuum condition is required for efficient operation of the H_2O -LiBr chiller. Various alternatives have been explored to reduce crystallisation of H_2O -salt pairs, e.g. adding salts (Jian et al., 2010; Kim et al., 1999) and using H_2O -ionic liquid (IL) mixtures (Dong et al., 2013; Yokozeki and Shiflett, 2010).

NH_3 -based working fluids are also popular for absorption chillers, with NH_3 (refrigerant)- H_2O (absorbent) being the majority (Wu et al., 2014a). Compared with H_2O -LiBr, NH_3 - H_2O shows slightly lower COP and requires

Figure 8. Single-effect absorption chiller.

a rectifier for refrigerant purification due to the small difference in boiling points of NH_3 and H_2O (Berlitz et al., 1998). However, there are advantages of the NH_3 - H_2O chillers (Wu et al., 2013; Wu et al., 2014c): (1) subfreezing refrigeration is possible due to low freezing point of NH_3 ; (2) there is no concern of crystallisation; and (3) operating pressures are higher than the atmospheric pressure to avoid air infiltration. Various novel NH_3 -based working fluids have been studied to remove the rectifier and reduce the complexity (Wu et al., 2012; Wu et al., 2014a). These working fluids include NH_3 -NaSCN, NH_3 - LiNO_3 (Cai et al., 2016; Cerezo et al., 2011) and NH_3 -IL mixtures (Wu et al., 2018; Yokozeki and Shiflett, 2007).

The biggest concern for NH_3 -based absorption chillers is that the working fluid, i.e. NH_3 , is toxic and flammable. Additional safety measures are therefore required in the design and operation of the chiller plants. For H_2O -LiBr chillers, the corrosion issue needs to be noted as it may cause the failure of system pipelines.

4.3. Heat sources

Fossil fuels are the most widely used energy source due to the wide availability and high stability. Among various fossil fuels, natural gas and oil can be used for direct-fired absorption chillers, of which fuels are combusted directly in the burners (Wang and Li, 2007; Wu et al., 2014b). Direct-fired absorption chillers usually adopt the double-effect, triple-effect or generator-absorber-heat-exchange (GAX) cycles due to the high combustion temperatures. Direct-fired absorption chillers can also supply hot water as a by-product (Yoon et al., 2003). As for coal, it is used by boilers to produce hot water or steam, which then drives the absorption chillers.

Renewable energy sources, including solar energy (Fan et al., 2007; Zhai et al., 2011), geothermal energy (Keçeciler et al., 2000) and biomass energy (Anbazhagan et al., 2005), have also been used for absorption chillers. Normally, due to low temperature level, conventional solar

collectors and geothermal wells can only power single-stage or multi-stage absorption chillers to obtain a low COP. With high-temperature solar thermal collectors (Fernández-García et al., 2010; Tian et al. 2018), solar energy can also be used for multi-effect or GAX cycles. As for biomass energy, similar to natural gas, it is suitable for multi-effect or GAX cycles due to the high combustion temperature.

Waste heat is available in the flue gas of boilers and the processes of industries, with temperatures typically in the range of 80°C - 200°C . Depending on the actual temperature levels, the waste heat can be recovered to drive single-stage, multi-stage, multi-effect or GAX cycles (Cao et al., 2015; Kang et al., 1999; Manzela et al., 2010). As renewable energy and waste heat are often intermittent, energy storage technologies are essential (Sharma et al., 2009; N'Tsoukpoe et al., 2009; Zhang et al., 1999); otherwise, auxiliary fossil fuels are required.

For direct-fired absorption chillers, emission control measures should be implemented to ensure the exhaust gas of the combustion of fuel does not cause air pollution. Additional space is also required for exhaust discharge components, such as chimneys.

4.4. Chiller performance

The operating conditions and performance of different absorption chillers are summarised in Table 3. The typical COP of absorption chillers is much lower than that of VC chillers. Therefore, the use of absorption chillers is justified only if the heat source is at low or zero cost, such as waste heat or renewable source.

Compared with VC chillers, absorption chillers have a longer start-up time and slow response to load variation, which may cause a reduction of its performance for applications with rapidly changing load profile and frequent system start/stop. Moreover, the energy consumption by auxiliary equipment is higher for an absorption chiller since the system is composed of large cooling tower fans and additional fans and motors in the combustion part.

Table 3. Performance of absorption chillers (Alobaid et al., 2017: p.735; Deng et al., 2011: p.177; Ghafoor and Munir, 2015: pp.779-770; Kim and Intante Ferreira, 2008: pp.9-11).

Working fluids	Cycle configuration	Chilled water supply temperature ($^\circ\text{C}$)	Heat source temperature ($^\circ\text{C}$)	Capacity (kW)	COP	Cost (HKD/kW)
H_2O -LiBr	Single-effect	5 - 10	80 - 120	35 - 7000	0.5 - 0.7	11,900 - 15,800
H_2O -LiBr	Double-effect	5 - 10	120 - 170	20 - 11630	1.0 - 1.2	-
H_2O -LiBr	Triple-effect	5 - 10	200 - 230	530 - 1400	1.4 - 1.7	-
NH_3 - H_2O	Single-effect	5 - 10	80 - 120	10 - 30	0.5 - 0.6	19,800 - 23,700
NH_3 - H_2O	Double-effect	5 - 10	160 - 200	10 - 90	0.7 - 0.9	-
NH_3 - H_2O	Triple-effect	5 - 10	170 - 200	< 110	0.8 - 1.2	-
NH_3 - H_2O	Single-effect	-60 - 0	100 - 200	10 - 6500	0.25 - 0.6	-

5. Adsorption chiller

5.1. Adsorption cooling

Adsorption chiller, as illustrated in Figure 9, is also based on thermal-driven refrigeration mechanisms. Absorption and adsorption chillers share the similar working principle that both systems can be powered by thermal sources. The major difference is in the sorbent. Solid adsorbent (e.g. zeolite) is used in adsorption chillers and the refrigerant is adsorbed on the surface and internal voids of the adsorbent by physical phenomenon. Unlike absorption cooling, adsorption cooling does not utilise any toxic or corrosive sorbents. In other words, the refrigerant-adsorbent working pairs are usually chemically inert and have little environmental impact (Chua and Chou, 2003). Besides, the adsorption chillers can be powered by a larger range of heat source temperature (Wang and Oliveira, 2006). The COP is usually very low, i.e. < 1 . However, the energy efficient ratio (EER), defined as a ratio of cooling effect to the electrical power consumed by pumps and fans, is relatively high, i.e. > 5 .

Figure 9. Adsorption chiller with sorption chamber 1 for (a) adsorption and (b) desorption.

5.2. Ongoing development

Adsorption chillers have not been widely commercialised at the current stage due to the following drawbacks: (1) long adsorption/desorption time, (2) low COP and (3) large size, leading to an increased energy consumption and cost. These problems can be overcome by enhancing the heat and mass transfer performance in the adsorber, evaporator and condenser, by improving the adsorption/desorption properties of the refrigerant-adsorbent working pairs and by better thermal management during the adsorption-desorption cycle. Most recent research efforts on adsorption chillers are related to (1) high adsorption capacity/rate composite adsorbent (Allouhi et al., 2015; Gong et al., 2011; Tso and Chao, 2012; Ugale and Pitale, 2015; Xu et al., 2016), (2) design optimisation of adsorber (Rezk and Al-Dadah, 2012; Zhu et al., 2017), (3) modelling for predicting adsorption chiller behavior in different working/operating conditions (Hassan et al., 2011; Nasruddin et al., 2015; Sharafian et al., 2015; Zhu et al., 2018a), (4) enhanced heat and mass transfer performance in evaporator and condenser (Thimmaiah et al., 2016; Xia et al., 2008; Zhu et al., 2018b) and (5) integration with clean energy and waste heat (Alam et al., 2013; Fadar, 2015; Koronaki et al., 2016; Tso et al., 2014; Zhu et al., 2018b). Up to the current stage, different types of adsorption chillers are built mostly based on the double-bed type (Alahmer et al., 2019; Alam et al., 2003; Chan et al., 2018; Chua et al., 2004; Habib et al., 2013; Hassan et al., 2011; Rezk and Al-Dadah, 2012; Rouf et al., 2013; Voyiatzis et al., 2008; Wang et al., 2004; Xia et al., 2008).

It is noted that the solar-powered adsorption chillers are effective as the daily cooling demand matches well with the availability of solar radiation (Oluleye and Boukhanouf, 2019). Both experimental study and modelling simulation have proven that a solar-powered adsorption chiller is more effective as well as economical in comparison with other adsorption chillers using clean energy (Li et al., 2019; Qadir et al., 2020).

5.3. Practicality

Practical applications of adsorption chillers in Hong Kong are limited at the current stage mainly due to its large size, which is around two to three times larger than conventional VC chillers. The mechanical floors of commercial buildings often cannot fulfil the space requirement for adsorption chillers. However, adsorption chillers can be considered for premises where large space is available, such as industrial buildings, remote areas, etc. Other factors favourable to adsorption chillers include unavailability of grid electricity and availability of renewable thermal energy and waste heat.

6. Practical applications and case studies

In this section, the operational parameters, energy consumption, GHG emissions and costs of 1,000-RT VC chiller, oil-free chiller and double-effect absorption chiller are presented for direct comparisons (Ahmad et al., 2020; Simbolon and Hikmat, 2020). The analyses are based on actual chiller applications and system operations in Hong Kong. The results are summarised in Table 4. Taking the VC chiller as the base case, it is found that the oil-free chiller is able to achieve a payback in six years with a net present value of around 508,000 HKD. For an absorption chiller using town gas as the heat source, both capital and operational costs are significantly higher, indicating that it is not financially viable in Hong Kong at this stage. The absorption chiller also yields higher GHG emission. However, it may become sensible when a renewable or waste heat source is available, which will largely reduce its operating cost as well as GHG emission.

7. Conclusions

Different types of chillers in terms of cooling mechanisms, operational conditions, energy efficiency, environmental impacts, costs, etc. were discussed. The comparisons show that oil-free chillers have higher COP and possess other advantages for implementation in urban city. The high energy efficiency implies significant reduction in indirect GHG emissions. Conventional VC chillers are still highly competitive due to the low installation cost. Both thermal-driven absorption and adsorption chillers are more environmentally friendly when renewable or waste heat sources are used as the primary energy inputs. Absorption chillers are readily available as commercial products while adsorption chillers are under active research and development.

One apparent challenge the chiller industry faces is to identify the next generation refrigerant with a minimal GWP, non-flammability and excellent thermodynamic properties. For high-capacity units, the existing products have a reasonably high performance; however, the performance for small-scale units tends to drop significantly due to multiple factors, such as the type of compressor, capability of the heat exchanger and system control. Continual efforts are needed to mitigate the above shortcomings. For thermal-driven chillers, it is crucial to overcome the disadvantages of thermal source compared with electricity, e.g. reliability, stability, storage and long-distance transmission.

Table 4. Comparison of VC chiller, oil-free chill and absorption chiller on energy and costs.

Parameter	VC chiller	Oil-free chiller	Absorption chiller
Cooling capacity (RT)	1,000	1,000	1,000
Full load COP	6	6.6	1.36
Input energy (kW)	586	535	2,586
Daily operating hour (hours)	16	16	16
Daily energy consumption (kWh)	9,379	8,557	41,376
Daily GHG emission (kgCO ₂)	4,783	4,364	9,748
Daily energy cost (HKD)	11,254 (Electricity rate: 1.2/kWh)	10,269 (Electricity rate: 1.2/kWh)	42,204 (Town gas rate: 1.02/kWh)
Condensing water pump power (kW)	38	38	55
Cooling tower fan power (kW)	18.5	18.5	30
Burner fan & accessories (kW)	N/A	N/A	22
Daily auxiliary power consumption (kW)	904	904	1,712
Daily auxiliary power cost (kW) (HKD)	1,085	1,085	2,054
Daily auxiliary GHG emission (kgCO ₂)	461	461	873
Daily water consumption (m ³)	212	212	307
Daily water cost (HKD)	1,590	1,590	2,303
Daily total auxiliary cost (HKD)	2,675	2,675	4,357
Annual operating days	150	150	150
Annual operating cost (HKD)	2,089,380	1,941,512	6,984,135
Annual GHG emission (kgCO ₂)	786,624	723,780	1,593,212
Equipment capital cost (HKD)	3,000,000	4,000,000	4,500,000
Annual maintenance cost (HKD)	100,000	80,000	150,000
Payback (years)	Base case	6.0	N/A
Equipment lifespan (years)	10	10	10
Net present value (HKD) (assumed interest rate of 2%)	Base case	507,888	N/A

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