Green Energy and Technology

Y. H. Venus Lun
S. L. Dennis Tung

Heat Pumps for Sustainable Heating and Cooling

Springer

Green Energy and Technology

Climate change, environmental impact and the limited natural resources urge scientific research and novel technical solutions. The monograph series Green Energy and Technology serves as a publishing platform for scientific and technological approaches to "green"—i.e. environmentally friendly and sustainable—technologies. While a focus lies on energy and power supply, it also covers "green" solutions in industrial engineering and engineering design. Green Energy and Technology addresses researchers, advanced students, technical consultants as well as decision makers in industries and politics. Hence, the level of presentation spans from instructional to highly technical.

Indexed in Scopus.

More information about this series at http://www.springer.com/series/8059

Y. H. Venus Lun · S. L. Dennis Tung

Heat Pumps for Sustainable Heating and Cooling

Springer

Y. H. Venus Lun
Sustainable Energy Limited
Hong Kong, PR China

S. L. Dennis Tung
Sustainable Energy Limited
Hong Kong, PR China

ISSN 1865-3529 ISSN 1865-3537 (electronic)
Green Energy and Technology
ISBN 978-3-030-31386-9 ISBN 978-3-030-31387-6 (eBook)
https://doi.org/10.1007/978-3-030-31387-6

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

This book aims to highlight the significance of using sustainable energy to prevent degradation of the globe. Energy sustainability can be achieved through improved energy efficiency. Heat pump provides an energy-efficient alternative for heating and cooling. To this end, we focus on examining sustainable practices in heat pump system design for sustainable buildings.

This book consists of the following parts:

– To begin, we define sustainable energy and discuss the trend of “think green.” In designing new HVAC (heating, ventilation, and air-conditioning) system or renovating existing buildings, the use of sustainable energy is appropriate in furnishing comfortable indoor temperature and humidity. The first part focuses on exploring topics of sustainability in heating and cooling.
– We then investigate sustainable practices in mapping out HVAC system. As temperature and humidity affect indoor air quality, it is desirable to control indoor air temperature and relative humidity via heating and cooling system. To this end, we investigate sustainable heat pump equipment. Innovation in heating and cooling is also covered in this part.
– Green operations are examined to promote sustainable practices in heat pump operations. Topics in this part include various operating modes, reverse cycle operations, and heat pump system configuration to meet user requirements.

Hong Kong, PR China

Y. H. Venus Lun
S. L. Dennis Tung

Contents

About the Authors

Dr. Y. H. Venus Lun received her Ph.D. from the University of London. She is Co-founder of Sustainable Energy Limited which is located in Hong Kong Science and Technology Park. She has been invited by various global bodies (e.g., APEC, ASEAN, and United Nations) to deliver talks at international events. She was the founding director of Research Center of Hong Kong Polytechnic University. She held visiting positions of Adjunct Professor, University of Tasmania in Australia; Erasmus Mundus Scholar (funded by European Commission), City University of London in UK; Visiting Fellow, Curtin University in Australia; and Visiting Scientist, Nanyang Technological University in Singapore.

Ir. Dr. S. L. Dennis Tung received his Doctor of Business Administration from Hong Kong Polytechnic University. He is Co-founder of Sustainable Energy Limited which is a manufacturer producing heat pumps and HVAC products for sustainable buildings. With a strong mechanical engineering background, he is professional engineer and registered energy assessor with substantial experience in building services engineering and heat pump manufacturing. He is Past President of ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Hong Kong Chapter. He actively involves in ASHRAE research promotion and related activities.

Part I
Principles of Heat Pump

Chapter 1
Think Green

Nomenclature

dI	Entropy caused by irreversibility (always positive)
dS_{sys}	Total change within system in time dt during process
$(\delta Q)/T$	Change caused by reversible heat transfer between system and surroundings at temperature T
$\delta m_e s_e$	Entropy decease caused by mass leaving (exiting)
$\delta m_i s_i$	Entropy increase caused by mass entering (incoming)

1.1 Renewable Energy as Heat Source

Sustainable energy consists of two main elements. First, energy is consumed at insignificant rates compared to its supply capacity with manageable environmental effects. Another element of sustainable energy is that the system serves the existing needs without compromising future generations. Both sustainable energy and renewable energy are important topics in energy efficiency. While renewable energy collects energy from natural resources, sustainable energy can be achieved through improved energy conservation and efficiency. As shown in Fig. 1.1, the benefits of using heat pump are not only from the renewable energy source but also from the generation of sustainable energy.

From the aspect of energy sources, heat pump uses renewable energy (e.g., air) as sources to provide heating and/or cooling. From the aspect of heat pump applications in buildings to provide heating and/or cooling, the unit produces sustainable energy because the same input power for heat pump generates much more useful energy as compared to traditional heating system (e.g., electric heater or gas boiler). The use of heat pump technology is getting more popular. According to the European Parliament on the energy performance of buildings, heat pump is defined as “a machine, a device,

Y. H. V. Lun and S. L. D. Tung, *Heat Pumps for Sustainable Heating and Cooling*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-31387-6_1

Fig. 1.1 Renewable energy and sustainable energy

or installation that transfers heat from natural surroundings, e.g., air or water, to buildings or industrial applications by reversing the natural flow of heat such that it flows from a lower to a higher temperature" [1]. For reversible heat pump, it moves heat from buildings to the natural surroundings. Typical heat pump transforms energy from source to useful energy via refrigeration cycle. For heat generation, air source heat pump is useful to absorb heat from outside cold air and discharge heat at higher temperature for space or water heating. Air source heat pump can also cool down air or water for cooling and rejecting heat to outside air. Heat pump technology enables the use of renewable aerothermal or hydrothermal heat at a useful temperature level for the generation of required heating and/or cooling for buildings and other industrial applications. Using heat pump for heating and cooling is energy efficient as heat pump technology requires less electrical energy to achieve the same heating and cooling functions.

Although heat pump transfers renewable energy from natural surroundings, the generation of useful energy requires auxiliary energy (e.g., electricity). To classify as sustainable energy, the power input to operate the heat pump should be significantly lower than the total output capacity. As shown in Fig. 1.2, in addition to renewable energy as heat source, energy input from electricity or other sources are required for the refrigeration cycle operations. Depending on climate conditions and level of technology, the ratio between energy input and energy transfer from renewable source varies. For instance, the efficiency of aerothermal heat pump drops dramatically in extreme cold climate. Hence, a minimum efficiency level should be established to

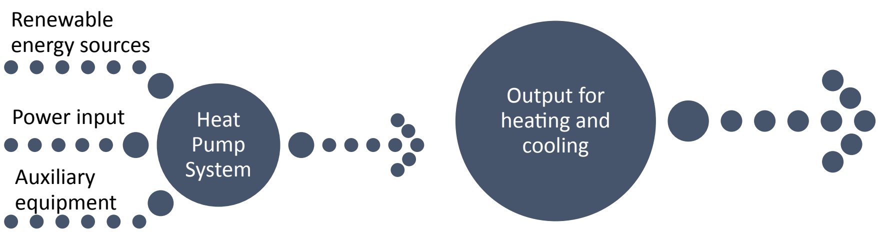


Fig. 1.2 Principle of heat pump operations

ensure heat pump deserves to be a sustainable energy device. Coefficient of performance (COP) is the ratio of useful output in terms of heating and/or cooling capacity to energy input [2]. The higher the COP, the more the saving in energy consumption.

Heat pump generally operates on an electrically driven compression cycle and pumps energy from the air in the natural surroundings to useful energy for heating and cooling. The key factor for heat pump to be important in the development renewable energy and sustainable energy is the available of abundant and reliable sources for heating, cooling, and dehumidification. Researches on heat pumps have been conducted since 1950s. The first commercial heat pump was installed in the Equitable Building located in Portland of the USA [3]. Commercialized in the early 1950s, the use of heat pump declined in the 1960s due to poor reliability. The oil crisis and high energy costs in the 1970s led researchers to look into heat pump as an energy-efficient alternative. Nowadays, heat pumps became popular for heating and cooling for residential, commercial, and industrial applications.

Heat pump is essential for the development of sustainable energy system. Sustainable energy system is energy-efficient and reliable energy system that effectively utilizes available resources [4, 5]:

- Energy sustainability can be achieved through improved energy efficiency. The coefficient of performance (COP) is an indicator of energy efficiency. The COP of traditional heating system is generally less than 1.0 as losses exist during the energy generation process. In general, ratio of useful energy generated from heat pump to its power input is three times higher than traditional heat-generating devices. There are several factors affecting the COP of heat pump system. Examples include the temperature of energy source, the temperature of delivery useful heat, the working medium used, and the components of heat pump system.
- Reliability can be viewed from the aspects of sources to generate energy and system operations. Heat pump uses renewable energy sources from natural surroundings or non-natural processed wasted heat. Typical heat pump is air source operated uses energy source from aerothermal which is reliable as air is free and abundant to absorb for energy generation to meet heating and cooling demands. From the perspective of heat pump system operations, reliability has been a key issue since the first unit installed in 1950s. Today, the heat pump production is moving to high-efficiency operations with advanced control system and safety protection to ensure smooth running throughout the life cycle. Current technology allows the use of heat pumps in severe climatic condition.

Renewable energy is collected from renewable sources, which are naturally replenished. Renewable energy is important for HVAC (heating, ventilation, and air-conditioning) operations, which account for approximately one-third of global energy consumption. Renewable energy resources exist over wide geographical areas. To mitigate climate change and improve energy efficiency, the promotion of the use of renewable energy source is essential. The use of renewable energy resource is a significant opportunity for energy efficiency with rapid technological development. Heat pump employs technologies using renewable energy as heat source to suit the needs for providing heating and cooling for various applications. Heat pump systems are rapidly becoming more efficient and cheaper, and their share of total energy consumption is increasing throughout the world.

1.2 Heat Pump and Refrigeration Cycle

Based on the physical characteristics of energy transfer, heat pump uses renewable energy with power input to generate useful energy via refrigeration cycle. In addition to refrigerant and refrigerant pipe, key components of a refrigerant system include compressor, expansion device, evaporator, and condenser. As shown in Fig. 1.3, the refrigeration cycle generally consists of four stages.

The four stages refrigeration cycle are:

- The first stage is the refrigerant in the form of gas enters the compressor and superheated after existing the compressor.
- The second stage is the superheated gas goes through the condenser to remove the heat. The condenser removes heat and condenses the gas into liquid.
- In the next stage, the liquid refrigerant travel through the expansion valve resulting in a mixture of liquid and gas at lower pressure and lower temperature.
- The cold liquid-gas mixture then goes through the evaporator for completely vaporized in the final stage before returning to the compressor to start the cycle again.

There are different types of refrigerants as working fluids for heat pumps. Although there is no general rule governing the selection of working fluid in heat pumps, the criteria are based on the aspects of chemical stability, thermophysical properties, and safety and environmental factors:

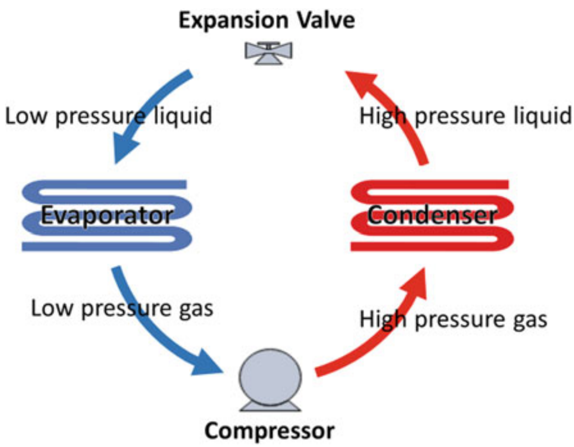


Fig. 1.3 Four-stage refrigerant cycle

- Chemical stability: The refrigerant should operate stably within the refrigeration system.
- Thermodynamic properties: Freezing temperature should be well below normal operating conditions. Critical point and boiling point temperatures should be appropriate for the application. Reasonable operating pressures should be set to keep operating costs at minimum level.
- Safety factor: The use of flammable and toxic refrigerants should be limited.
- Environmental factor: The refrigerant should be decomposed quickly with harmless substances in the atmosphere, and direct emissions (i.e., leakage) must be kept at the minimum level.

Heat pump is generally defined as a machine that transfers heat from natural surroundings to buildings. In refrigeration system, circulating refrigerant facilitates the heat transfer from one area to another area. Refrigeration cycle is associated with the first and second laws of thermodynamics [6]. The first law and second law of thermodynamics are useful to explain the heat pump operations. According to ASHARE [7], the first law of thermodynamics is called the law of conservation of energy. For any system, open or closed, there is an energy balance as:

$$\left[\text{Energy in}\right] - \left[\text{Energy out}\right] = \left[\text{Net increase of stored energy in system}\right]$$

The first law states that energy cannot be created or destroyed but can change form and location. In the process of heat pump operations, the refrigeration system absorbs heat from renewable energy source to produce useful higher temperature heat for space heating and domestic hot water supply. The cycle can produce lower temperature air or chilled water for space cooling and reject heat outside the building.

According to the theory of thermodynamics, energy must flow from an object at a higher temperature to an object at a lower temperature. ASHARE [7] describes the concept of thermodynamics in terms of entropy changes as

$$\mathrm{d}S_{\mathrm{sys}} = (\delta Q)/T + \delta m_{\mathrm{i}} s_{\mathrm{i}} - \delta m_{\mathrm{e}} s_{\mathrm{e}} + \mathrm{d}I \tag{1.1}$$

By rearranging Eq. (1.1), the equation becomes

$$\delta Q = T\,[(\delta m_{\mathrm{e}} s_{\mathrm{e}} - \delta m_{\mathrm{i}} s_{\mathrm{i}}) + \mathrm{d}S_{\mathrm{sys}} - \mathrm{d}I] \tag{1.2}$$

where

$\mathrm{d}I$ is entropy caused by irreversibility (always positive)

$\mathrm{d}S_{\mathrm{sys}}$is total change within system in time $\mathrm{d}t$ during process

$(\delta Q)/T$ is change caused by reversible heat transfer between system and surroundings at temperature T

$\delta m_{\mathrm{e}} s_{\mathrm{e}}$ entropy decease caused by mass leaving (exiting)

$\delta m_{\mathrm{i}} s_{\mathrm{i}}$ entropy increase caused by mass entering (incoming).

According to Eq. (1.2), it is essential to have a difference in temperature for heat transfer. In the refrigeration cycle, there are two sections that can produce a pressure

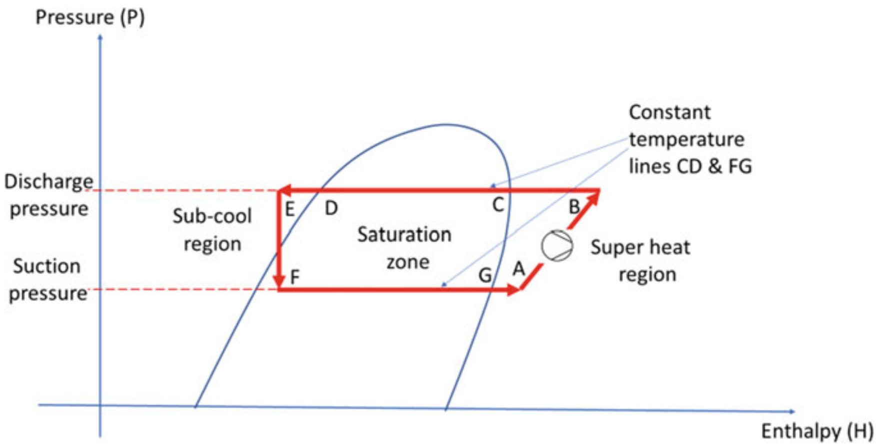


Fig. 1.4 PH (pressure-enthalpy) diagram

difference, i.e., condenser (high pressure and high temperature) and evaporator (low pressure and low temperature). The PH diagram explains the relationship between pressure and enthalpy of a refrigeration cycle [8].

Figure 1.4 illustrates the PH diagram plotting the pressure and enthalpy of the refrigeration cycle. The constant high temperature line CD of the PH diagram is condensing latent heat, and the constant low temperature line FG is the evaporator latent. The refrigerant system removes heat from evaporator into condenser. When the cold refrigerant flows through evaporator and the temperature of air surrounding is higher, the refrigerant absorbs the heat from air to cool the space. The evaporation of the refrigeration occurs at a constant low pressure, and the condensation of the refrigeration occurs at a constant high pressure [9].

The four red lines (AB, BE, EF, and FA) explains the operations of the refrigeration system. The first stage (from A to B) is compressing refrigerant in compressor in the form of gas enters and superheated. The second stage is de-supering heat (from B to C) and condensation (from C to D) at constant pressure to subcool region (from D to E). The next stage (from E to F) is the liquid refrigerant travel through the expansion valve resulting in a mixture of liquid and gas at lower pressure. The final stage (from F to A) is evaporation at constant pressure to super heat region. The PH diagram illustrates the operating principles of heat pump in which heat is moved from a one place to another place.

Heat pump transfers heat from/to natural renewable energy to useful energy for heating or cooling to ensure the quality of indoor climate. Renewable natural energy sources for heat pump can be aerothermal, geothermal, hydrothermal heat, or non-natural processed wasted heat. A heat pump is a machine that transfers heat from heat source to heat sink through a refrigeration cycle. Air source heat pump is the most popular system used in sustainable buildings and industrial applications. This is a system to absorb heat from outside to inside a building to supply domestic hot

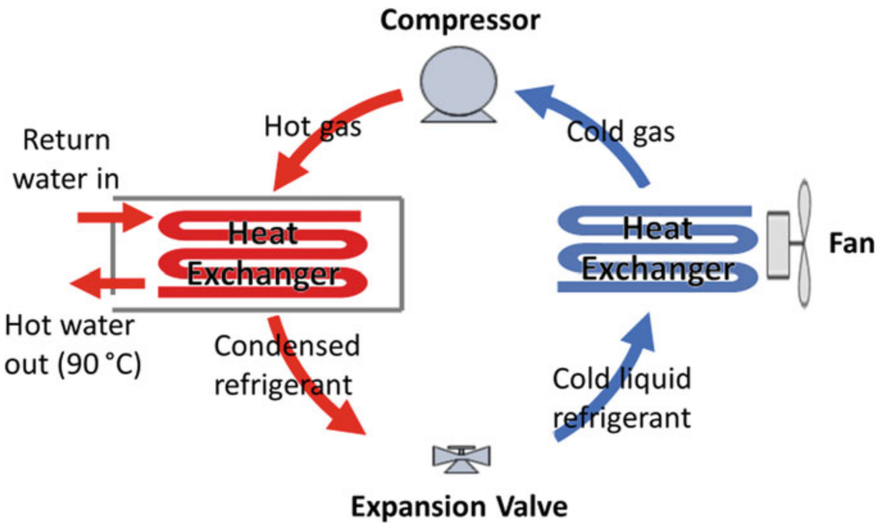


Fig. 1.5 Air-to-water heat pump

water supply and provide space heating. In hot climate, the reversible operations for outside heat rejection are possible to provide indoor space cooling.

Figure 1.5 illustrates the principle of air source heat pump. Basic components used in the refrigeration systems are compressor, expansion valve, refrigerant-to-water heat exchanger, refrigerant-to-air heat exchanger, and blower. Air-to-water heat pump absorbs heat from outside cold air to heat water. The heat can be used for space heating or domestic hot water supply in cold climate. The heat pump can operate reversely. Therefore, it can also generate chilled water for space cooling and reject heat to outside in hot climate. With advanced technology, air-to-water heat pump can be a device to integrate advanced programmable logic controller and sensors to provide constant indoor temperature solutions for cooling in summer and heating in winter.

In general, air-to-water heat pump can generate either cooling or heating to generate chilled water or hot water. With improved technology on precision control, air-to-water heat pump can also generate constant temperature for special needs. For instance, air-to-water heat pump provides precision constant temperature control on aquarium water. Aquarium water temperature is important in the health of fishes. To keep aquarium water temperature consistent, the products can provide water heating when the water temperature is below setpoint and water cooling when the water temperature above the setpoint.

The capability of producing specific outlet water temperature is significantly enhanced in the past decade. In the early twenty-first century, the maximum outlet water temperature of heat pump is around 45 °C. Due to technology improvement, most of the heat pumps nowadays can generate hot water up to 60 °C. With advanced heat pump technologies, high performance heat pump can produce hot water up to

90 °C by using environmental refrigerant (e.g., R134a). High temperature heat pump can potentially replace steam boiler and electric heater with much higher coefficient of performance (COP). With the application of high temperature heat pump, the acceleration in energy efficiency can be achieved.

In addition to renewable heat source, there are several benefits to use refrigeration system-based high temperature heat pump. Advantages of using high temperature heat pump to replace boiler include:

- High energy efficiency,
- Easy for maintenance,
- Low cost to operate,
- Lower CO_2 emission due to lesser electricity consumption,
- No combustion of explosive gases,
- No fuel gas pipe connection,
- No fuel tank required for fuel storage.

While aerothermal heat pump system uses outdoor air to keep indoor warm in winter, hydrothermal heat is also an important source of energy for heat pump to generate useful energy for heating and cooling in sustainable buildings. Using air source heat pump and water source heat pump are environmentally friendly as both air and water are renewable energy. Heat recovery water-to-water heat pump is one of the most energy-efficient devices with the capability to produce both chilled water for cooling and hot water to heating. In such case, the heat pump uses evaporator to produce cold water for cooling and condenser to produce hot water for heating simultaneously. Operations of water source heat pump are similar to air source heat pump except that the heat source is water instead of air.

Figure 1.6 illustrates the principle of water source heat pump. Basic components used in the refrigeration systems are expansion valve, compressor, and two

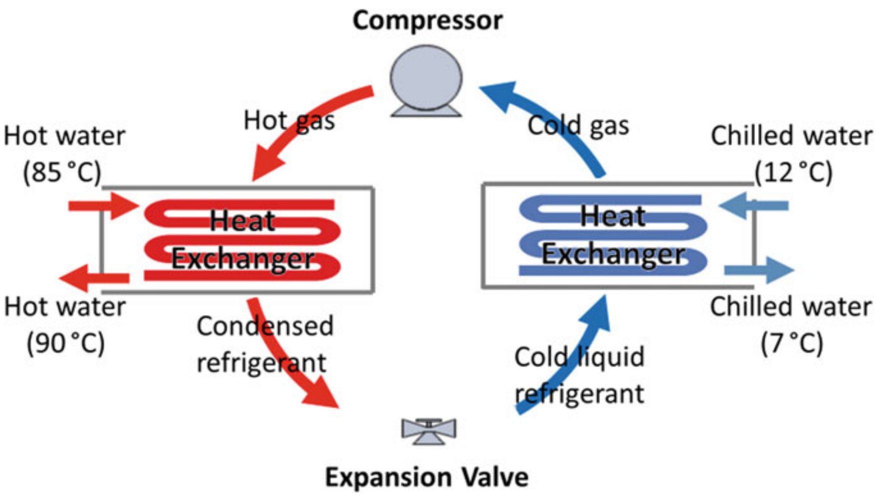


Fig. 1.6 Water-to-water heat pump

refrigerant-to-water heat exchangers (one for hot water and one for chilled water). Water source heat pump systems have become a popular choice for sustainable buildings. Commercial water-to-water heat pump systems are popular because they can supply heating and cooling simultaneously. It can bring comfortable indoor condition to meet different requirements. There are two major types of water source heat pump systems: i.e., closed-loop and open-loop systems. The most commonly used one is a standard closed-loop system where the loop piping runs inside the building and connects the two heat exchangers to supply hot water for heating and chilled water for cooling.

1.3 Economic Growth and Environmental Quality

According to Brundtland [10], sustainable is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." There are three mutually dependent areas of sustainability: i.e., economy, environment, and society. These three areas are interrelated. For instance, economic growth requires natural resources and produces emissions which negatively affect both environment and social well-beings. Historically, researches on the relationship between economic growth and environmental degradation generally agreed that "communities grow with environment declines." Conventional economics focuses on economic growth and efficient allocation of resources. With increased concern on the co-exist of economic production and environmental quality, it is essential to promote the sustainability studies on community growing without incurring corresponding negative impact on environmental quality. Sustainability studies examine different ways to minimize resource needed for the production and consumption.

Environmental protection represents the fundamental condition of sustainable development of economy. The aim of environmental protection is to maintain be ecological balance for the present and future generations [11]. Concern on environment degrade is accelerated as economies grow due to overexploitation of globe's resources. Environmental deteriorate and economic development are closely associated [12]. According to Arrow et al. [13], the relation between economic growth with industrial development and level of environmental degradation has an initial positive relationship up to a turning point. After the post-industrial stage, the level of environmental degradation is negatively associated with economic growth.

Figure 1.7 illustrates the relationship between economic growth and environmental quality. There are four stages in the level of environmental degradation:

- Stage 1: The first stage is pre-industrial economies. Increased pollution can be an acceptable side effect of economic development at an early stage of economic development. Hence, economic development is positively associated with environmental degradation.

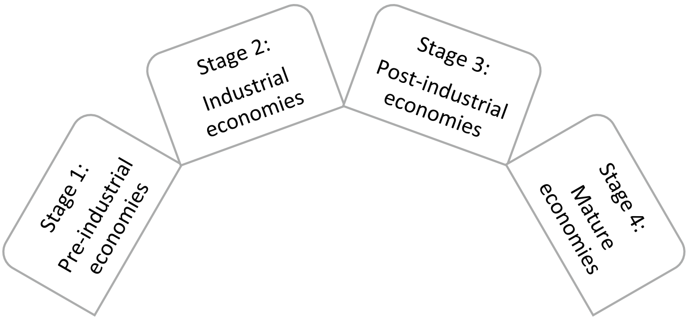


Fig. 1.7 Stages of environmental degradation and economic development

- Stage 2: The second stage is industrial economies. When the economic development is up to this point, the GDP per capita reaches an acceptable level reaching a turning point to aware of the environmental quality.
- Stage 3: The next stage is post-industrial economies. In this stage, the community is concern about the environmental quality. The relationship between economic development and level of environmental degradation changes from positive relationship to negative relationship.
- Stage 4: This stage is mature economies with service based. When an economy has attained a higher living standard and more affordable to allocate resources to improve environmental quality, tolerance on environmental degradation reduces.

While conventional economics deals with efficient allocation of resources and economic growth, ecological economies focuses on sustainable development with balance between environmental quality and economic production [14]. In advanced economy, sustainability studies have become a main theme. One key focus of sustainability studies is the improvements in technological efficiency and innovation to enable a complete decoupling of economic growth from environmental degradation. There are conflicting views on the effectiveness of technological efficiency and innovation. On the one hand, efficiency experts propose that resources used for development can be significantly reduced for continued economic growth with the use of resources sustainably. On the other hand, several studies conclude that the use of materials and energy are increased with economic growth.

Nevertheless, the natural environment is being degraded due to overconsumption on resources [15]. Green is related to the natural capability of the plant to recover. The globe can still be green provided that environmental degrade that does not go beyond the recovering capability. Green energy is generated from renewable sources. Energy sustainability involves not only from the energy source but also the way it is consumed. Energy consumption patterns can be very different throughout the world. Heating requirements are high in northern climates as the ambient air temperature is negative in winter. On the other hand, cooling requirements are high in regions close to the equators. To care for our globe, the effective use of our energy should be promoted. Energy sustainability should also be promoted through improved energy efficiency. Sustainable energy system can be defined as a cost-efficient, reliable, and environmentally friendly energy system that effectively utilizes natural resources [16]. In addition to cost-efficiency and reliability, environmental impact is a concern in providing heating and cooling for sustainable buildings.

1.4 Green Building

Sustainability in buildings is an important issue because providing heating and cooling for indoor comfort consumes energy. Moreover, it is essential to keep good indoor air quality (IAQ) to provide comfort environment. According to US Environmental Protection Agency (EPA), IAQ refers to “the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants.” To maintain indoor air quality, both space temperature and humidity must be controlled. Other IAQ elements such as air flow quantity and quality are also important to examine. The energy consumption in buildings is growing and is expected to grow further. The share of heating and cooling in total building energy usage varies between 18 and 73% [17] depending on the heating/cooling requirements and efficiency level of system design. Buildings consume energy mainly in space heating and cooling as well as water heating. In average, building energy consumption account for one-third of overall energy consumption [18].

Recently, the concept of green building (or called sustainable buildings) attracts attention from various perspectives. According to Hong Kong Green Building Council (HKGBC), “green building is a practice of reducing the environmental impact of buildings and enhancing the health and well-being of building occupants.” Energy efficiency and renewable energy are core components of green building. Green buildings consume less energy and produce less waste [19]. More and more public and private buildings commit to sustainable built environment and adopt such measure as energy saving and waste reduction. Green buildings generally involve the several key areas, i.e., life-cycle planning, indoor air quality, and efficient use of energy. In the case of HVAC (heating, ventilation, and air-conditioning) system aiming at providing thermal comfort and good indoor air quality, the life-cycle planning including selection, installation, and operations of HVAC equipment with high coefficient of performance (COP).

Different definitions of green building exist. According to the Environmental Protection Agency (EPA) of USA, green building is defined as “the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building’s life cycle from sitting to design, construction, operation, maintenance, renovation, and deconstruction.” In general, green buildings are designed to reduce the overall negative impact on environment by using energy, water, and other resources efficiently. In addition to social and environmental benefits, green buildings also contribute to economic benefits. Such economic benefits include reduce operating cost, improve occupant productivity, optimize life cycle of equipment, and shape markets for green products and services.

Buildings are responsible for a huge share of energy, electricity, and water consumption across the globe. The building sector has the greatest potential to deliver significant cuts in energy consumptions. The goal of green building or sustainable building practices is to reduce the negative environmental impact of buildings throughout the life cycle. The concept of sustainable development can be traced to the era of energy crisis in the 1970s [20]. Started in the USA, the promotion of green building aims at promoting energy efficiency and environmentally friendly construction practices. Green building brings an array of practices to reduce the negative impacts of buildings on the environment. The practices and technologies in green buildings are constantly revolving to meet increasingly demand on environmental quality. Fundamental principles of green buildings include energy efficiency, water efficiency, materials efficiency, indoor environmental quality enhancement, operations and maintenance optimization, and waste reduction.

The essence of green building is an optimization most of the principles in the life cycle of sustainable buildings [21]. Life-cycle assessment (LCA) aims to assess a full range of impacts associated with all stages from design and build, to use and maintenance of sustainable buildings. As shown in Fig. 1.8, there are several key elements in green buildings practices:

- Energy efficiency: Green buildings include efficiency means to generate energy for heating and cooling and measures to reduce energy consumption. Onsite generation of renewable energy through air or water as heat source by using heat pump system can significantly reduce the negative environmental impact of buildings.

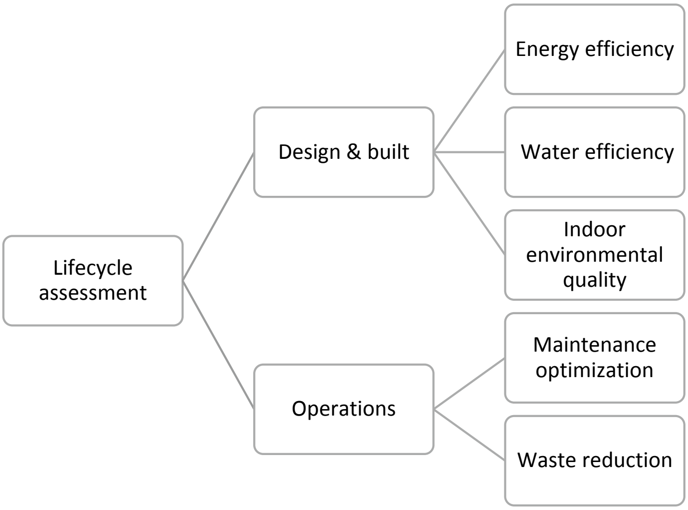


Fig. 1.8 Life-cycle assessment of green building

- Water efficiency: Reducing water consumption and protecting water quality are important. It is desirable to install effective heat pump system with high temperature outlet water to enhance water efficiency and prevent such diseases as Legionnaire completely.
- Indoor environmental quality: The key element of indoor environmental quality is to provide comfort in terms of thermal and humidity quality. Using heat pump system for heating, cooling and dehumidification can control indoor climate to provide comfortable thermal and humidity levels for occupants.
- Operations and maintenance optimization: High quality green buildings should be operated responsibly and maintained properly. Proper operations and maintenance (O&M) are important to retain the green criteria.
- Waste reduction: Green building should seek effective ways to reduce waste of energy and water during the operations. For example, waste heat should be recycle for heating.

Green building uses less resources, reduces wastes, and maximizes occupant health and well-being of the globe. There are various organizations promote sustainability in building design, construction, and operations. Furthermore, green building assessment systems also available to provide third-party verification of green buildings. Examples include Leadership in Energy and Environment Design (LEED) from the US Green Building Council and Building Environmental Assessment Method (BEAM) in Hong Kong. The aims are to provide standards to evaluate existing and new buildings for environment improvement across the life cycle of the buildings.

References

1. Hannon MJ (2015) Raising the temperature of the UK heat pump market: learning lessons from Finland. Energy Policy 85:369–372
2. Kuang YH, Wang RA (2006) Performance of a multi-functional direct-expansion solar assisted heat pump system. Sol Energy 80(7):795–803
3. Hepbasil A, Kalinci Y (2009) A review on heat pump water heating systems. Renew Sustain Rev 16(6/7):1211–1229
4. Alanne K, Saari A (2006) Distributed energy generation and sustainable development. Renew Sustain Energy Rev 10(6):539–558
5. Hepbasli A (2008) A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renew Sustain Energy Rev 12(3):593–661
6. Hasan AA, Goswami DY, Vijayaraghavan S (2002) First and second law analysis of a new power and refrigeration thermodynamic cycle using solar heat source. Sol Energy 7(5):385–393
7. ASHARE Handbook (2017) Fundamental, 2.2
8. Sumeru K, Nasution H, Ani FN (2012) A review on two-phase ejector as expansion valve in vapor compression refrigeration cycle. Renew Sustain Energy Rev 16(7):4927–4937
9. Kumar VP, Baskaran A, Subaramanian KM (2016) A performance study of vapor compression refrigerant system using ZrO_2 Nano particle with R134a and R152a. Int J Sci Res Publ 6(12):2250–3153
10. Brundtland H (1987) Our common future. Oxford University Press, Oxford
11. Sarbu I (2014) A review on substitution of strategy of non-ecological refrigerants from vapour compression-based refrigeration, air-conditioning and heat pump systems. Int J Refrig 46:123–141

12. Zeng C, Deng X, Dong J, Hu P (2016) Urbanization and sustainability: comparison of the processes in "BIC" Countries. Sustainability 8(400):1–18
13. Arrow K et al (2015) Economic growth, carrying capacity, and the environment. Science 268:520–521
14. Wu JG (2014) Urban ecology and sustainability: the state of the science and future directions. Urban Planning 125:209–221
15. Loiseau E, Saikkub L, Antikainenb R, Drostec N, Hansjürgens B, Pitkänenb K, Leskinenb P, Kuikmand P, Thomsene M (2016) Green economy and related concepts: an overview. J Cleaner Prod 139(15):361–371
16. Hepbasli A (2001) A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renew Sustain Energy Rev 12:593–611
17. Urge-Vorsatz D, Cabza LF, Serrano S, Barreneche C, Perichenko K (2015) Heating and cooling energy trends and drivers in buildings. Renew Sustain Energy Rev 41:85–98
18. Zhao B, Qi L, Yang T (2017) Simulation and analysis of the energy consumption for public buildings in different climate regions of China. Procedia Eng 205:2940–2947
19. Abraham TG, Navada SG, Kini SG, Gupta N (2016) Energy conservation measures for an office building in warm and humid climate. India J Sci Technol 9(44):1–7
20. Carson R (1962) Silent spring. Houghton Mifflin, Boston
21. Zuo J, Zhao ZY (2014) Green building research–current status and future agenda: a review. Renew Sustain Energy Rev 30:271–281

Chapter 2
Sustainable Energy

Nomenclature

Seasonal energy efficiency ratio

SEER	Seasonal energy efficiency ratio
Q	Reference annual cooling demand
QE	Annual electricity consumption

Subscript

c	Cooling
h	Heating

Nomenclature: Fanger's comfort equation

I_{ci}	Thermal resistance of clothing
M	Rate of metabolic rate production
P_w	Water vapor pressure
t_{mrt}	Mean radiant temperature
t_a	Air temperature
V_a	Relative air velocity

Y. H. V. Lun and S. L. D. Tung, *Heat Pumps for Sustainable Heating and Cooling*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-31387-6_2

Nomenclature: Heating and Cooling Capacity

C_p	Specific heat at constant pressure, expressed in joules per kilogram and kelvin
E_{bal}	Energy balance
E_{in}	Energy into a system
E_{out}	Energy out of a system
$\dot{m}$	Mass flow rate
Q_C	Cooling capacity, expressed in watts
Q_H	Heating capacity, expressed in watts
Q_{HR}	Heat recovery capacity, express in watts
q	Volume flow rate, expressed in cubic meters per second
r	Density, expressed in kilograms per cubic meter
Δt	Difference between inlet and outlet temperatures

Nomenclature: Coefficient of Performance (COP)

COP_C	COP of cooling
COP_H	COP of heating
COP_{HC}	COP of heating and cooling
Q_{cd}	Capacity of condenser (for heating)
Q_{ev}	Capacity of evaporator (for cooling)
Q_{hrc}	Capacity of heat recovery of condenser (for heating)
W_{input}	Total input power
$h1$	Enthalpy in front of the compressor
$h2$	Enthalpy behind the compressor
$h3$	Enthalpy at the injection valve

2.1 Heating and Cooling Load

Heating and cooling account for the biggest energy consumption in European cities [1]. According to the framework of the Smart Cities and Communities Initiative of the European Union, cities are expected to develop innovative measures to substantially reduce greenhouse gas emission through improvement in energy efficiency. The first Smart Cities call was launched in 2012 to support demonstration of innovative solutions for heating and cooling for buildings. The heating and cooling strategy aims at deploying energy renewable source through improvement in energy efficiency.

The degree of efficiency of a heat pump is evaluated by its coefficient of performance (COP). COP of a heat pump is the ratio of its capacity to its power input. According to British Standard [2], heat pump is defined as "encased assembly or assemblies designed as a unit, using a vapor compression cycle driven by an electric compressor to provide delivery of heat." Heat pump can have means for cooling, heating, circulating, cleaning, and dehumidifying the air. Outputs of heat pump include cooling capacity, heating capacity, and heat recovery capacity.

When sizing a heat pump, it is essential to determine the required cooling and heating capacity. Heating and cooling load calculations depend on such factors as building location, indoor/outdoor design conditions, orientation, and building construction [3]. Loading components consists of heating load and cooling load:

- The peak heating load refers to the amount of heat lost to the outdoor environment at design conditions to maintain occupant comfort. The total estimated heat loss is the sum of the sensible heat loss through conduction, infiltration, and ventilation loads.
- The peak cooling loads refer to the amount of heat gained from the outdoor environment at design conditions to maintain occupant comfort. Cooling loads include both sensible and latent heat gains from conduction, infiltration, ventilation, and radiation.

Some safety factors are applied in calculating the heating and cooling loads. Safety factors include building components and ductwork conditions. Building components refers to the heat gain/loss through windows, walls, and roof. Ductwork conditions refer to the insulation and tightness levels of air ducts. Sizing heat pumps begins by determining the heating and cooling loads. In designing a heat pump system, heat source and heat sink are important to examine. According to [4], heat source is defined as the place from which heat is taken and heat sink is defined as the place from which heat is transferred and then delivered.

To design a heat pump system, it is important to have the "right sizing" based on accurate heating and cooling loading calculation. Adjustments include safety factors and other considerations are usually included in overall system design. Combining several adjustments may compound the inaccuracy of the results. The results of loading calculation affect the equipment selection and the duct/pipe design. An oversized system increases installation costs, wastes energy, and involves higher overall operating costs. The load refers to the amount of heating/cooling energy required to keep the building comfortable. There are three types of loads, i.e., design load, extreme load, and part load:

- Design load: The design cooling load is how much sensible heat and latent heat need to be removed at the summer design levels. The design heating load is how much heating need to be provided at the winter design levels.
- Extreme load: Extreme load refers to the heating and cooling loads at extreme weather conditions. As extreme temperatures occur for about 1% of the time on average, this load carries limited weight when calculating the size of heat pump and does not have a measurable impact on the overall performance of a heat pump system.
- Part load: For most of the time, the outdoor temperatures will be higher than the design temperature in winter and lower than the design temperature in summer. Hence, the heat pump system usually operates under part-load conditions.

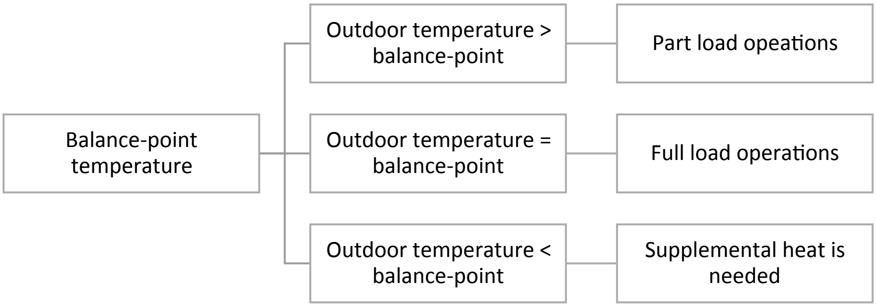


Fig. 2.1 Balance point temperature and heating equipment utilization

The balance point temperature is an important concept in sizing heat pump for heating. According to Li and Chen [5], the balance point temperature is defined as "the value of the outdoor temperature, where, for a specified indoor condition, the total heat loss is equal to indoor heat gains." Hence, the balance point temperature is at which the heat gains from heat sinks are equal to the heat losses. The balance point temperature is the base temperature to calculate heating load and energy demand to heat a building.

The balance point temperature is a key parameter for heat pump system design. The heat pump supplies 100% of the heat at or above the balance point temperature. The supplemental heat is used when the outdoor temperature is below the balance point temperature. Figure 2.1 illustrates the relationship between the balance point temperature and the utilization of equipment. The balance point temperature and the size of heat pump are negatively correlated. The lower the balance point temperature (for heating), the bigger the size of the heat pump. Hence, if the setting of the balance point temperature is too low, an oversized heat pump system exists. For temperatures below the balance point, supplemental heat is needed.

Seasonal fluctuation exists as demand for heating is high in winter while demand for cooling is high in summer. The seasonal efficiency of the system can be rated by the seasonal energy efficiency ratio (SEER). According to EN 14825 [6], the $\mathrm{SEER_h}$ equals reference annual heating demand (Q_h) divided by the annual electricity consumption on heating ($\mathrm{QE_h}$):

$$\mathrm{SEER_h} = Q_\mathrm{h}/\mathrm{QE_h} \tag{2.1}$$

On the other hand, the $\mathrm{SEER_c}$ equals reference annual cooling demand (Q_c) divided by the annual electricity consumption on cooling ($\mathrm{QE_c}$):

$$\mathrm{SEER_c} = Q_\mathrm{c}/\mathrm{QE_c} \tag{2.2}$$

2.2 Thermal Comfort

The demand for heating and cooling is driven by provision of indoor thermal comfort for occupants. However, there is no absolute standard for thermal comfort. According to ANSI/ASHARE Standard 55 [7], thermal comfort is defined as "the condition of mind that express satisfaction with the thermal environment." As defined by Hensen [8], thermal comfort is "condition of mind which express satisfaction with the thermal environment." There are different opinions on thermal comfort as satisfaction to the environment is a complex subjective response. There are different factors affecting thermal comfort. These factors are generally classified as physical variables and personal variables:

- Four physical variables include air temperature, air velocity, relative humidity, and mean radiant temperature.
- Two personal variables include clothing insulation and activity level (i.e., metabolic rate).

Based on these six variables, Fanger's comfort equation is the most commonly adopted equation to examine thermal comfort [9]. Fanger's [10] comfort equations formulate comfort as a function of several variables:

$$f(M, I_{\text{ci}}, V_{\text{a}}, t_{\text{mrt}}, t_{\text{a}}, P_{\text{w}}) = 0 \tag{2.3}$$

where M is rate of metabolic rate production,
I_{ci} is thermal resistance of clothing.
V_{a} is relative air velocity.
t_{a} is air temperature.
t_{mrt} is mean radiant temperature.
P_{w} is water vapor pressure.

There are two different approaches for the definition of thermal comfort [11]: relational approach and adaptive approach. Relational approach (e.g., Fanger's comfort equation) uses empirical data for model development while adaptive approach uses field studies to investigate the acceptability of thermal environment. Thermal comfort standard is also established for design, operations, and evaluation of buildings [12]. There are existing standards for thermal comfort (e.g., ASHARE 55) and indoor environmental criteria (e.g., EN 15251). ASHARE 55 is a thermal comfort standard specifying the combinations of factors affecting thermally comfortable environmental conditions of occupants of green buildings, and EN 15251 aims to examine parameters for design and assessment of energy performance of building addressing thermal environment and indoor air quality.

Developing codes and standards are important for thermal comfort and indoor air quality. Energy conservation and adaptation to climate change is also desirable to include in building codes and standards [13]. Hence, there are various studies on the association between thermal comfort and energy efficiency. Studies on energy saving for thermal comfort include Mui and Chan [14] investigated the association

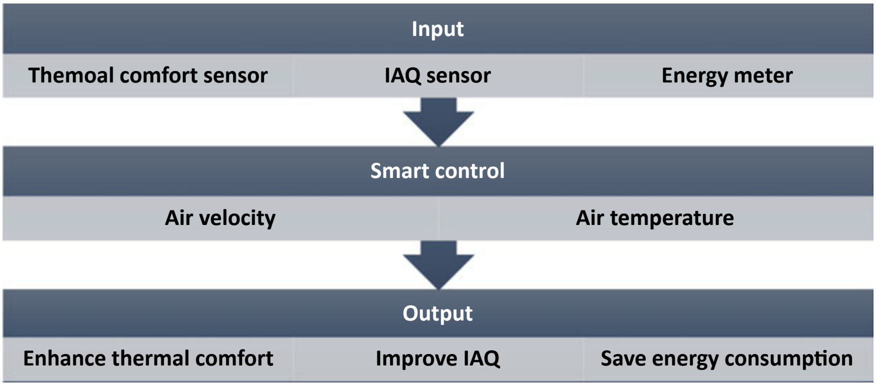


Fig. 2.2 Enabling smart air-conditioning by sensor technologies

between indoor comfort temperature and outdoor air temperature, and Schiavon and Melikov [15] examined the saving of cooling energy by elevated air flow to offset the impact of increased air temperature on thermal comfort.

To monitor energy consumption, power meter for measuring energy usage is integrated with control system to monitor energy consumption. Indoor air quality (IAQ) affects human comfort. Recently, sensors are commonly utilized to provide information to control air temperature, humidity, air velocity, and radiant temperature. Other devices are also available to monitor IAQ. Examples include chemical sensors to detect CO2 and volatile organic compounds (VOCs), electronic nose (e-nose) to detect gas emission, and particles counter to measure the number of particles (i.e., PM2.5 level). To perform smart control on capacity management to meet human comfort and save energy, detection technology using sensor is an important input [16]. As shown in Fig. 2.2, sensor technologies enable the use of various sensors and detectors to achieve smart operations of thermal comfort and IAO systems.

2.3 Heating and Cooling Capacity

Load is demand for energy (in kWh). It refers to the amount of heating or cooling building needs while capacity refers to the amount of heating or cooling a heat pump provides. Load calculation and capacity calculation are equally important in studying heat pump. Capacity is a measurable physical quantity that characterizes the air side and water side flow rate. According to EN14511-3:2013 [17], cooling capacity (Q_c), heating capacity (Q_H), and heat recovery capacity (Q_{HR}) for steady-state operations (with no phase change) can be determined using the following equations:

$$Q_C = q \times r \times C_p \times \Delta t \tag{2.4}$$

$$Q_{\mathrm{H}} = q \times r \times C_{\mathrm{p}} \times \Delta t \tag{2.5}$$

$$Q_{\mathrm{HR}} = q \times r \times C_{\mathrm{p}} \times \Delta t \tag{2.6}$$

Notes: The mass flow rate ($\dot{m}$) can be determined directly instead of the term ($q \times r$) where q is the volume flow rate expressed in m^3/s and r is the density expressed in kg/m^3.

When phase change is involved, the enthalpy change (Δh) can be directly measured instead of the term ($C_p \times \Delta t$) where C_p is specific heat and Δt is the difference between inlet and out temperature.

In water chilling and water heating, capacity is the product of the water mass flow rate ($\dot{m}$) and specific heat (C_p) and the temperature difference between entering and leaving the heat exchanger. Capacity can be measured in gross capacity and net capacity [18]. In a water-to-water heat pump, net heating/cooling capacity can be defined as the capacity of the standard heating/cooling condenser/evaporator is available for useful heating/cooling of the thermal load.

The calculation of heating capacity (Q_H) is based on the water temperature, water flow rate, and water properties at the entering and leaving conditions. It is calculated using only the sensible heat transfer:

$$Q_{\mathrm{H}} = \dot{m} \times C_{\mathrm{p}} \times \Delta t \tag{2.7}$$

In the case of net recovery heating capacity (Q_{HR}), the calculation is based on below equation:

$$Q_{\mathrm{HR}} = \dot{m} \times C_{\mathrm{p}} \times \Delta t \tag{2.8}$$

Net cooling capacity (Q_C): The capacity of the evaporator available for cooling of the thermal load external to the water chilling package. It is calculated using only the sensible heat transfer,

$$Q_{\mathrm{C}} = \dot{m} \times C_{\mathrm{p}} \times \Delta t \tag{2.9}$$

The following steps are generally used for capacity calculation:

- Know the capacity formula, i.e., $\dot{m} \times C_p \times \Delta t$,
- Find the difference in temperature (i.e., Δt),
- Identify the appropriate measuring units, and
- Know the specific heat (i.e., C_p) refers to the energy needed, i.e., the specific heat of water is 4.18 kJ/kg while the specific heat of air is 1.01 kJ/kg.

The capacity of the heat pump is the mass flow rate ($\dot{m}$) × specific heat (C_p) × temperature change (Δt). Examples of capacity calculation of water-to-water heat pump and air-to-water heat pump are shown in Tables 2.1 and 2.2, respectively.

Table 2.1 Parameters of water-to-water heat pump

Chilled water inlet temperature (°C)	12
Chilled water outlet temperature (°C)	7
Water flow rate (l/s)	5.67
Cooling capacity	118.5 kW i.e., 5.67 × 4.18 × (12 − 7)
Hot water inlet temperature (°C)	60
Hot water outlet temperature (°C)	65
Water flow rate (l/s)	9.91
Heat capacity	207.1 kW, 9.91 × 4.18 × (65 − 60)

Table 2.2 Parameters of air-to-water heat pump

Hot water inlet temperature (°C)	60
Hot water outlet temperature (°C)	65
Water flow rate (l/s)	9.32
Heat capacity	194.8 kW, 9.32 × 4.18 × (65 − 60)

In evaluating the heating and cooling capacity, energy balance is also important to examine. An energy balance (E_{bal}) evaluates all the measured energy flow into and out of a control volume. Energy into the system (E_{in}) refers to gross cooling capacity generated from evaporator plus power (i.e., total compressor work and auxiliary devices transferring energy into the refrigerant). Energy out of the system (E_{out}) refers to gross capacity from condenser (including heating and heat recovery). In case there is a nonzero difference between energy flow in and energy flow out, the system is not at steady state.

According to AHRI 550/590 (2015 [18]), general energy equation is expressed as a percentage:

$$E_{bal} = [E_{in} - E_{out}]/\text{avg}(E_{in}, E_{out}) \times 100\% \quad (2.10)$$

$$E_{bal} = 2[(E_{in} - E_{out})/(E_{in} + E_{out})] \times 100\% \quad (2.11)$$

where E_{bal} is energy balance, E_{in} is energy into a system, and E_{out} is energy out of a system.

2.4 Capacity Control

ASHARE [19] defines the COP as the benefit of the cycle divided by the required energy input to operate the cycle:

$$\text{COP} = [\text{Useful refrigerating effect}]/[\text{Net energy supplied from external sources}]$$

Total input power refers to the combined power input of all components of the heat pump. Heat pump uses a vapor compression cycle driven by an electric compressor to provide heating, cooling, dehumidifying, circulating, and cleaning air. Heat pump can serve as air conditioner to satisfy the thermal comfort requirements of occupants. Heat pump can provide water heating and air processing. Source of power input of heat pump is electricity which driven compressor and fan for circulating air. The compressor is the component at the heart of a refrigerant circuit in the vapor compression cycle. Heat pumps generally use compressors including rotary vane, scroll, or screw compressors.

Rotary vane compressors consist of a cylindrical casing with a rotor and two openings, one suction and one discharge. It can apply in a wider range of applications up to 50 kW. Key features of rotary compressors include:

- Low cost and compact dimensions,
- Good choice for low capacity,
- Lower noise, and
- High efficiency on average.

Scroll compressor: Scroll compressor uses two scrolls, one fixed and the other moving, coupled to the motor. A scroll compressor uses two interleaving scrolls to pump, compress, or pressurize fluids (i.e., liquids and gases). Scroll compressors are widely used in heat pump applications with capacity ranges from 2 kW to more than 50 kW. Key features of scroll compressors include:

- smaller dimensions and lower weight,
- high efficiency at the design compression ratio, but efficiency decreases at different working conditions,
- low noise operations, and
- reduced vibrations.

Screw compressor: Screw compressors are based on a mechanism made up of two intermeshing rotors. The fluids (i.e., gases) are drawn in through the inlet port to fill the volume between two lobes when the rotors revolve. Screw compressors originally were made with symmetrical rotor cavity profiles. Modern versions use asymmetrical rotors in which convex lobes (male rotor) mesh with concave cavities (female rotor). Key features of screw compressors include:

- Use in larger industrial applications,
- Requirement of high-precision control techniques,
- Require lubrication, and
- Provide step or continuous modulation of capacity.

The operating condition of the heat pump system differs greatly throughout the year. The demand for heating and cooling also varies from time to time. Heat pump with constant speed compressors can provide indoor comfort for occupants during the peak load period. During the off-peak period, the full load operation is not only incurring high energy consumption, but also reducing the thermal comfort. The function of capacity control is generally available for large heat pump. Large heat pump uses screw compressor that can control capacity with either continuous or step modulation. With improved heat pump technology, small-sized heat pump system can also operate variable speed to control operating capacity [20]. The availability of variable speed control of compressor is a useful method to regulate the capacity of heat pump for energy saving [21].

2.5 Coefficient of Performance

There are different measurements for efficiency ratings. Coefficient of performance (COP) is the most popular indicator for energy system. Another common measurement includes energy-efficient ratio (EER). EER refers to the heat pump's British thermal units (BTU) rating over its wattage. For example, the rating of a 10,000-BTU unit consuming 1200 W energy power is 8.3 (10,000 BTU/1200 W). The higher the rating, the more efficient the air heat pump unit is. However, a higher rating is usually accompanied by a higher price.

According to AHRI 550/590 [18], coefficient of performance (COP) is ratio of output capacity to the total input power at any given set of rating condition. For vapor compression system, the net energy supplied is usually in the form of work (W_{input}) in total input power. Hence, COP is

$$\text{COP} = Q/W_{\text{input}} \tag{2.12}$$

COP can be classified into cooling coefficient of performance (COP_C) and heating coefficient of performance (COP_H). In addition, there are simultaneous cooling and heating operations which consists of simultaneous heating and cooling coefficient of performance (COP_HC) and heat recovery coefficient of performance (COP_HR).

Cooling coefficient of performance (COP_C) is a ratio of net cooling capacity to the total input power at any given set of rating conditions:

$$\text{COP}_\text{C} = Q_{\text{ev}}/W_{\text{input}} \tag{2.13}$$

Figure 2.3 illustrates a heat pump with DX cooling coil (evaporator) for cooling. For a 10 hp (horsepower) heat pump:

- Cooling capacity (Q_{ev}) is 33 kW
- Total input power (W_{input}) includes compressor input power (8.1 kW) and fan motor input power (2.2 kW)

$$\text{COP}_\text{C} = 33\,\text{kW}/(8.1\,\text{kW} + 2.2\,\text{kW}) = 3.2$$

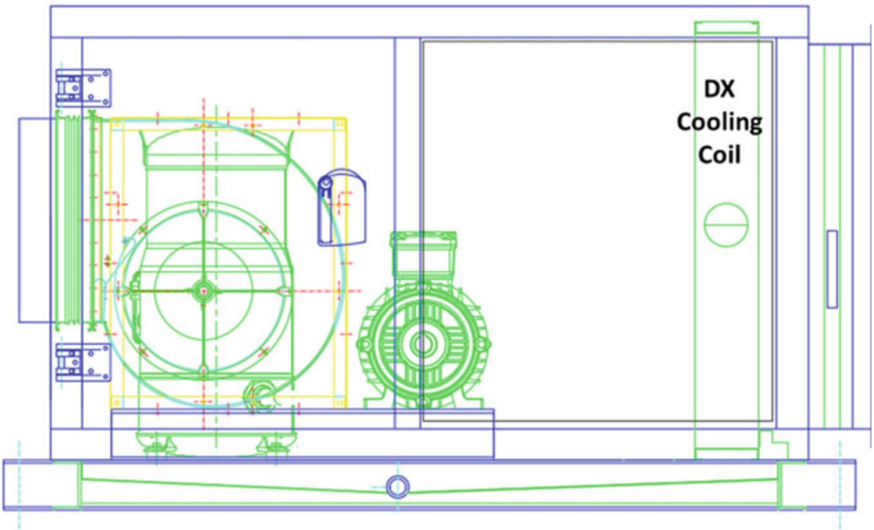


Fig. 2.3 Heat pump for space cooling

Heating coefficient of performance (COP_H) is a ratio of net heating capacity to the total input power at any given set of rating conditions:

$$COP_H = Q_{cd}/W_{input} \tag{2.14}$$

Figure 2.4 illustrates an air-to-water heat pump with hot water heat exchanger for water heating. For a 10 hp (horsepower) heat pump:

– Heating capacity (Q_{cd}) is 27.8 kW
– Total input power (W_{input}) includes compressor input power (4.85 kW) and fan motor input power (0.8 kW)

$$COP_H = 27.8\,kW/(4.85\,kW + 0.8\,kW) = 4.92$$

Simultaneous heating and cooling coefficient of performance (COP_{HC}) is applied when the heat pump is generating both heating and cooling during operations. COP_{HC} is a ratio of net heating capacity plus the net cooling capacity to the total input power at any given set of rating conditions:

$$COP_{HC} = (Q_{cd} + Q_{ev})/W_{input} \tag{2.15}$$

Figure 2.5 illustrates a water-to-water heat pump to generate both chilled water and hot water simultaneous. For a 10 hp (horsepower) heat pump:

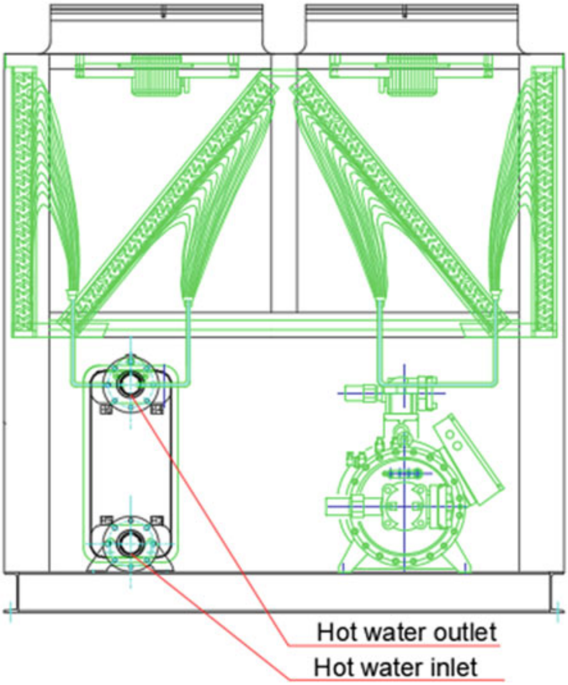


Fig. 2.4 Air-to-water heat pump for water heating

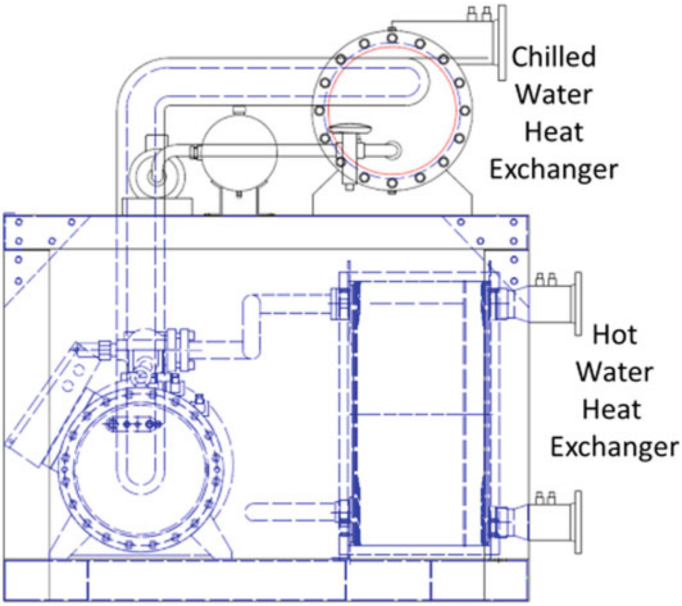


Fig. 2.5 Water-to-water heat pump generating both chilled water and hot water

– Heating capacity (Q_{cd}) is 30.4 kW.
– Cooling capacity (Q_{ev}) is 20.1 kW.
– Total input power (W_{input}) is compressor input power (10.3 kW).

$$COP_{HC} = 30.4\,kW + 20.1\,kW/10.3\,kW = 4.9$$

Heat recovery coefficient of performance (COP_{HR}) applies to heat pump units that are operating in a manner that use either all or only a portion of heat generated during cooling operations for space or water heating. COP_{HR} is a ratio of net recovery heating capacity plus the net cooling capacity to the total input power at any given set of rating conditions:

$$COP_{HR} = (Q_{ev} + Q_{hrc})/W_{input} \tag{2.16}$$

Figure 2.6 illustrates a heat pump with cooling coil for cooling and generate recovery heat to reheating coil for space heating and hot water heat exchanger for water heating. For a 10 hp (horsepower) heat pump:

– Cooling capacity (Q_{ev}) is 33 kW
– Recovery heating capacity for space and water heating (Q_{hrc}) is 41
– Total input power (W_{input}) includes compressor input power (8.1 kW) and fan motor input power (2.2 KW)

$$COP_{HR} = (33\,kW + 41\,kW)/(8.1\,kW + 2.2\,kW) = 7.18$$

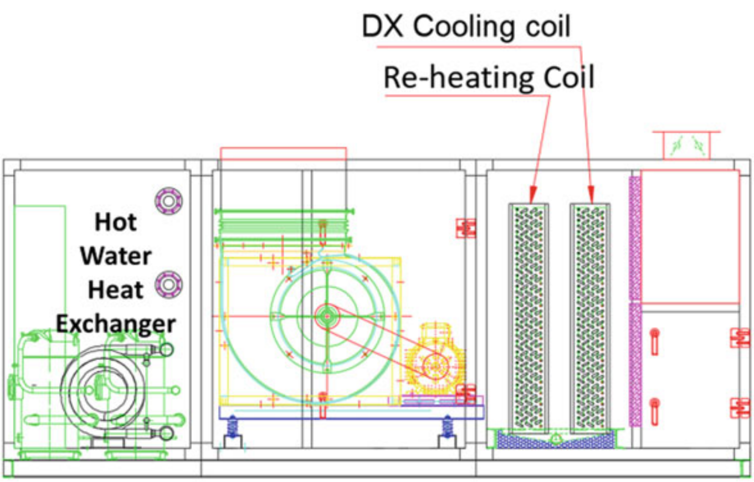


Fig. 2.6 Heat pump with DX cooling coil, reheating coil and hot water heat exchanger

COP is generally the ratio of energy output to power input. There are many different categories of heat pump operations, including single function and multiple functions. Above equations illustrate various ways to calculate COP of heat pump with examples. There are serval factors to be considered in evaluating the COP:

- For single function heat pump for cooling or heating, the COP of cooling is generally lower than heating.
- When using heat pumps for cooling, it is possible to provide dehumidification function at the same time by cooling the temperature below dew point. Latent heat can be generated and recovered for space and/or water heating.
- As heat pumps transfer energy from renewable sources, it is desirable to use the heat pumps to provide heating and cooling simultaneously.
- The COP of heat pump used to heat water is better when the outlet hot water temperature is lower. For high temperature heat pumps with outlet temperature above 60 °C, the COP is lower and correction factors should be added when comparing their performance with low temperature heat pumps.
- If fans are included, energy consumption on fan motor power is included. Fans can be used for ventilation to enhance the overall air quality or provide free cooling when the outdoor ambient condition is suitable.

Bonin [22] presented a method based on the property of refrigerant to calculate the coefficient of performance. Instead of using the ratio of output capacity to total power input, the COP_{PH} is calculated according to the PH (i.e., pressure and enthalpy) diagram for each refrigerant:

$$COP_{PH} = (h_2 - h_3)/(h_2 - h_1) \tag{2.17}$$

Figure 2.7 illustrates the PH diagram of a refrigerant. The ideal cycle is described with the following phases:

- Compress the refrigerant by the compressor (from point 1 to point 2).

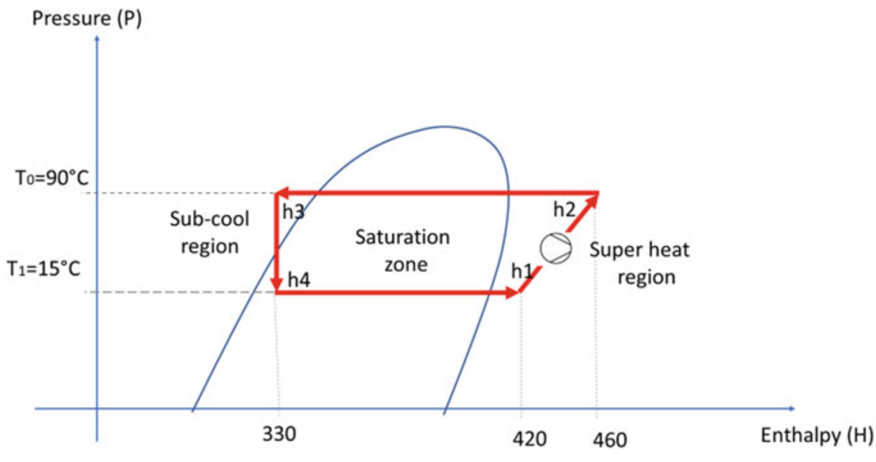


Fig. 2.7 PH diagram of a refrigerant

- Transfer the condensation heat to the condenser (from point 2 to point 3).
- Decompress the refrigerant without the release of energy (from point 3 to point 4).
- Take up the vaporization heat from the environment in the evaporator (from point 4 to point 1).

Based on above equation, the coefficient of performance is calculated as follows:

$$\begin{aligned} COP_{PH} &= (h_2 - h_3)/(h_2 - h_1) \\ &= (460\,kJ/kg - 330\,kJ/kg)/(460\,kJ/kg - 420\,kJ/kg) \\ &= 130\,kJ/kg/40\,kJ/kg \\ &= 3.25 \end{aligned}$$

There are different ways to determine COP of heat pumps. Nevertheless, the most commonly used method is to calculate the output-to-input ratio (i.e., output capacity to total power input). Although COP is an energy efficiency indicator to illustrate the efficiency of a heat pump, there are many variables to affect the COP. Such variables include outdoor operating condition, inlet and outlet air/water temperature, equipment configuration integrated with ventilation, or other air quality control system. When using COP as an indicator to compare the performance of heat pumps, it is essential to have standard rating condition.

Key factors affecting COP of heat pump include outdoor air temperature and outlet water temperature. In case of heat generation, the increase in evaporating temperature shall increase total heat output, thus leading to a higher COP. Hence, the COP of heat pump is lower when operating in lower ambient temperature [23]. It indicates that seasonal difference and regional difference exist. From the seasonal perspective, the COP of heat pump is lower in winter. From the regional perspective, the COP of heat pump is lower in cold region. Figure 2.8 illustrates the relationship between COP

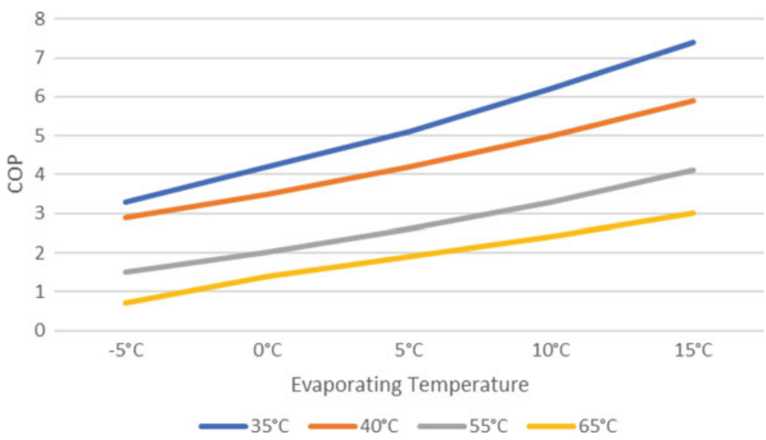


Fig. 2.8 Relationship between COP and temperature

and hot water outlet temperature. When the outlet hot water temperature increases from 35 to 60 °C, the COP reduces. The higher the hot water outlet temperature, the lower the COP of heat pump. Assume all other things being equal; the COP of heat pump is negatively associated with outlet water temperature.

References

1. European Commission (2016) Overview of support activities and projects of European Union and energy efficiency and renewable energy in the heating and cooling. European Union
2. British Standard (BS EN 14522-1) (2013) Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling. BSI Standards Publication
3. Burdick A (2011) Strategy guideline: accurate heating and cooling load calculations. U.S. Department of Energy (Building Technologies Program)
4. Robin R (2010) Getting warmer: a field trial of heat pumps. The Energy Saving Trust
5. Li Y, Cheng Z (2003) A balance-point method for assessing the effect of natural ventilation on indoor particle concentrations. Atmos Environ 37:4277–4285
6. En 14825 (2016) Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and rating at part load conditions and calculation of seasonal perform. British Standard
7. ANSI/ASHARE Standard 55 (2014) Thermal environment conditions for human occupancy
8. Hensen JLM (1990) Literature review on thermal comfort in transient condition. Build Environ 25(4):309–316
9. Ekici C (2013) A review of thermal comfort and method of using Fanger's PMV equation. In: 5th International symposium on measurement, analysis and modelling of human functions. Vancouver, Canada
10. Fanger PO (1970) Thermal comfort, analysis and application in environmental engineering. Danish Technical Press, Copenhagen
11. Noel D, Rene T, Donatien N (2010) Thermal comfort: a review paper. Renew Sustain Energy Rev 14:2626–2640
12. Dear RJ (2002) Thermal comfort in naturally ventilated buildings: revisions to ASHARE Standard 55. Energy Build 34(6):549–561
13. Kwok A, Rakovich NB (2010) Addressing climate change in comfort standards. Build Environ 45:18–22
14. Mui K, Chan W (2003) Adaptive comfort temperature model of air-conditioned building in Hong Kong. Build Environ 38:837–852
15. Schiavon S, Melikov AK (2008) Energy saving and improved comfort by increased air movement. Energy Build 40:1954–1960
16. Cheng CC, Lee D (2016) Enabling smart air conditioning by sensor development: a review. Sensors 16(12):2028. https://doi.org/10.3390/s16122028
17. British Standard (BS EN 14522-3) (2013) Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling. BSI Standards Publication
18. AHRI (550/590) (2015) Standard for performance rating of water-chilling and heat pump water-heating packages using the vapor compressor cycle. Air Conditioning Heating and Refrigeration Institute
19. ASHARE Handbook (2017) Fundamentals 2.3
20. Shao S, Shi W, Li X, Ma J (2004) A new inverter heat pump operated all year round with domestic hot water. Energy Convers Manag 45:2255–2268

21. Shao S, Shi W, Li X, Cheng H (2004) Performance representation of variable-speed compressor for invert air conditioners based on experimental data. Int J Refrig 27(8):805–815
22. Bonin J (2016) Heat pump planning handbook. Routledge, London
23. Zogou O, Stamatelos A (1998) Effect of climatic conditions on the design optimization of heat pump systems for space heating and cooling. Energy Conserv Manage 39(7):609–622

Chapter 3
Sustainability in Heating and Cooling

Nomenclature

C	Energy consumption (kWh)
D	Thermal demand (kWh)
η	Efficiency
SC	Specific consumption (kWh/m^3)
V	Volume (m^3)

Subscript

A	Air
AT	Air transport
CG	Cool generation
HG	Heat generation
W	Water
WT	Water transport

3.1 Sustainable Initiative

Due to the widely use of heating and cooling system for indoor thermal comfort, the share of energy for heating and cooling in total energy consumption increases gradually. It is essential to promote sustainability in heating and cooling to use energy-efficient system for heating and cooling in residential, commercial, and industrial buildings. Becasue of economic benefits resulting from high coefficient of performance (COP), heat pump systems become desirable devices for heating and

Y. H. V. Lun and S. L. D. Tung, *Heat Pumps for Sustainable Heating and Cooling*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-31387-6_3

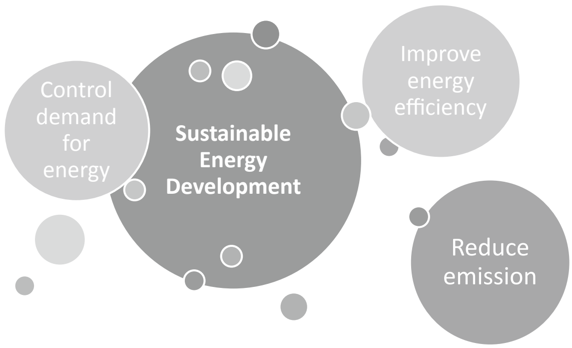


Fig. 3.1 Key elements of sustainable energy development

cooling purposes [1]. Heat pump technology enables the use of air, water, or other renewable energy sources to generate required heating and/or cooling with electrical power input. The COP is a key indicator for energy efficiency. The COP and energy efficiency are associated positively. Sustainable energy development involves three major areas, i.e., energy saving on demand side, efficiency improvement, and replacement of energy sources by various source of renewable energy [2].

In designing heat pump system for indoor comfort, it is desirable to integrate the concepts of sustainable energy development (as shown in Fig. 3.1). Using advanced heat pump technologies, the areas of sustainable energy development can be addressed:

- Demand for energy: The system design should reduce the demand for energy whenever possible. The technique of free cooling is an example for energy saving. Free cooling is an economical method to use door air as a free cooling source. When the ambient air temperature reaches a certain temperature level, the ventilation system increases the fresh air flow rate through the free cooling system, which reduces the power consumption.
- Energy efficiency: In heat pump system design, energy improvement can be done in various ways. Researchers are working hard on efficiency improvement. Key area is fully utilizing the energy to avoid heat rejection and reduce waste heat. Examples include use heat pump to generate both cooling and heating simultaneously for space cooling and water heating or use recovery heat from air cooling/dehumidification for space reheat and water heating.
- Greenhouse emission: Greenhouse gas absorbs and emits radiant energy within the thermal infrared range causing greenhouse effect by trapping heat and making the planet warmer. Key sources of greenhouse gas include burning fossil fuels and using gas boiler heating. Heat pumps offer a promising opportunity to help achieve deep decarbonization of building sector. Using heat pump can expect emission reductions over its life of between 50 and 70% compared to conventional gas alternatives [3].

Sustainable energy can be achieved through improved energy efficiency with high COP. According to UN's Brundtland Commission (term in 1987), sustainability is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." Sustainable energy concerns about finding efficient and renewable source of energy to meet the needs of present and future generations. Sustainable energy is not only naturally replenished, but also causes no harm to the environment. In the case of using heat pump for cooling and heating with high COP, heat pump technology enables the use of renewable aerothermal or hydrothermal as source to generate heat and/or cool energy at a useful temperature level to comfort buildings.

3.2 Building Performance

Using heat pump to generate heating and cooling is energy efficient as heat pump technology allows the use of renewable energy as heat source and requires less input power to perform the functions of heating and cooling. Buildings in general consume more than one-third of global total energy, and therefore, there is a strive to achieve higher energy efficiency in buildings. For instance, there are studies on energy saving on temperature set point. Results suggest that raising setpoint temperature (SPT) contributes to reduction in energy consumption.

According to Yang et al. [4], the following studies conducted on change of SPT in office buildings:

Researcher(s)	Measure	Results
Chow and Lam [5]	Raise SPT from 21.5 to 25.5 °C in summer	Cooling energy reduced by 25%
Zmeureanu and Doramajian [6]	Raise SPT from 24.6 to 25.2 °C from 9:00 to 15:00 and up to 27 °C from 15:00 to 18:00	Chilled water consumption reduced by 34–40%
Sekhar [7]	Raise SPT from 23 to 26 °C	Cooling energy reduced by 13%
Nicol and Roaf [8]	Change from 26 °C SPT to variable indoor design temperature ($T_C = 17 + 0.38T_O$)[a]	Energy saving of 20–25%
Mui and Chan [9]	Change SPT from 24 °C to adaptive comfort temperature ($T_C = 18.303 + 0.158T_O$)[a]	Total percentage of energy saving is about 7%
Roussac [10]	Static (raise SPT 1 °C higher) and dynamic (adjust SPT in response to ambient conditions)	Electricity consumption reduced by 6% (static) and 6.3% (dynamic)

[a]where T_C is comfort temperature and T_O is outdoor temperature

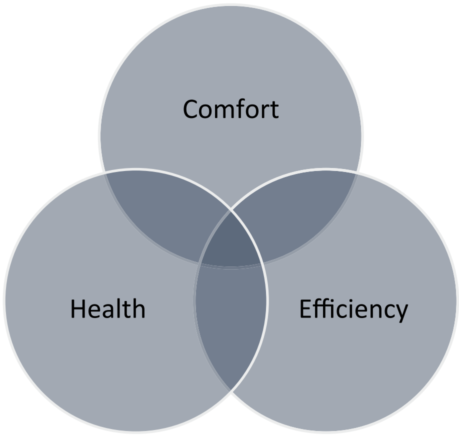


Fig. 3.2 Three dimensions of building performance

Although energy efficiency is the priority for green buildings, there are other key components to examine. As shown in Fig. 3.2, building performance consists of three dimensions, i.e., health, comfort, and efficiency [11]:

- Efficiency: Building performance often associated with energy efficiency. In general, building performance makes up of positive and negative effects on performance. Negative effects involve discomforts or health risks. Airtight building leads to lower energy consumption and makes for higher energy efficiency. However, insufficient ventilation results in excessive carbon dioxide and accumulation of pollutants.
- Health: Building also brings out health challenges including obesity and asthma, leading to sick building syndrome with common disease caused improper designed and ventilated buildings. On the other hand, building can promote health positively by improving indoor air quality, providing better lighting, and selecting environmental materials.
- Comfort: From the perspective of building performance, components of comfort include thermal comfort and visual comfort. Factors affecting thermal comfort are air temperature, air humidity, and air flow. On the other hand, visual comfort consists of lighting, outside view, and exterior shading.

Building performance involves not only energy efficiency but also indoor environmental quality. A holistic approach comprising "energy efficiency—thermal comfort—indoor air quality" is essential to examine building performance [12]. Indoor environmental quality extends indoor air quality (IAQ), indoor thermal comfort, visual comfort, and other factors (e.g., acoustical quality) affecting the quality of indoor environmental. As shown in Fig. 3.3, it is essential to use an integrated approach to take measures during the design, installation, and operations stages to ensure the quality of indoor environment.

Fig. 3.3 Integrated approach of indoor environmental quality assurance

- Measures during design stage include:
  - Use effective ventilation system,
  - Provide enough fresh air,
  - Apply negative/positive pressure appropriately, and
  - Use efficient air filter.
- Measures during installation stage include:
  - Supply and install equipment according to the specification,
  - Keep equipment/materials packed and stored appropriately,
  - Cover duct opening, and
  - Perform effective housekeeping.
- Measures during operations stage include:
  - Keep air vents clear,
  - Report any leaking immediately,
  - Perform proper maintenance and conduct repairing when needed, and
  - Dispose all wastes appropriately.

3.3 Sustainability Challenges

The energy performance is a key concern for sustainable development. According to the European Commission, heating and cooling in buildings account for almost half of the energy consumption in the regions of European Union (EU). In response to the sustainability challenges, the EU has issued the 2030 climate and energy framework with the following targets for 2030: (1) at least 30% share for renewable energy and (2) at least 30% improvement in energy efficiency

EU also provides several suggestions for energy saving:

- Reduction in the energy consumed by heating and cooling in buildings can be achieved through the adoption of advanced materials in renovating buildings to prevent heat losses and heat gains.
- Energy consumption can be reduced by providing better data for analysis and advanced control system for the management of energy use.

- Energy can be saved by upgrading heating and cooling equipment to the most efficient level.
- Renewable heating and cooling technologies can cut the use of fossil fuels. In industry, energy for heating and cooling can be saved with energy-efficient technologies.

In addition, recent studies on heat pump technology indicate that there are ways for further improvement in heat pump technologies [13]. Examples include: (1) phase change by cooling air down to dew point in heat exchanger for dehumidification and (2) recover latent heat from dew point dehumidification process for space and water heating. The EU [14] also published "Best Available Technologies for the heating and cooling market in the European Union." Heat pump is identified as one of the technologies for heating and cooling. Due to the capability of producing useful energy with higher energy efficiency, EU selected heat pump as best available technologies for heating and cooling for the following applications:

- Heat pump for district heating and cooling
- Heat pump for industry
- Heat pump for service and residential buildings
- Heat pump for heating and cooling in agriculture.

There is a study on "Heat Roadmap Europe" to examine the use of heat pumps in district heating and cooling systems [15]. The energy efficiency of heat pump is much higher than electric heater. The heat pump system is incorporating waste or free energy for transformation to higher temperature. The advantage is higher efficiency. However, there are several parameters affecting the performance of the heat pump systems. Important parameters include the type of heat pump and the selection of components, and the designed temperature.

Furthermore, the ambient conditions play a significant role in heat pump performance. According to a study conducted by Zhang et al. [16], the COP varies across the seasons. Figure 3.4 illustrates the positive relationship between COP and ambient temperature. The COP of heat pump is 4.817 at $T_O = 25$ °C where T_O is outdoor ambient temperature. The COP decreases when T_O reduced. COP in winter is 2.61

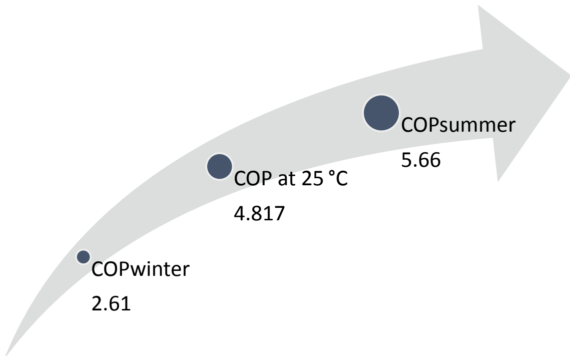


Fig. 3.4 Relationship between COP and ambient conditions

(at $T_O = 0$ °C). On the other hand, the COP increases when T_O raised. COP in summer is 5.66 (at $T_O = 35$ °C).

To enhance the overall energy efficiency of heat pump system, following strategies can be adopted:

- Variable speed drives for fans and compressors: Compressor and fan capacities can be reduced to save energy by using variable speed drives to control their speed. Operating at varying loads by using variable speed, both peak and off-peak energy costs can be obtained.
- Dedicated outdoor air system: The dedicated outdoor air system uses a separate air handler to process the fresh air from outdoor instead of directly delivering to indoor space. It is particularly effective in buildings with multiple spaces with different ventilation requirements. It allows the separation of the latent load from the sensible load to provide accurate humidity control and save energy.
- Supply air system control: Free cooling can be used for supply air when the outdoor ambient condition is suitable for thermal comfort. Free cooling is an economical method of using external air as supply air.
- Demand control ventilation: Demand control ventilation is an adjustment on ventilation equipment based on the occupant demand. This is a modulation method to regulate the fresh air flow rate according to data from sensors or time schedules.

3.4 Efficiency of HVAC Subsystem

In the framework of the EU's Smart Cities Initiative, cities are expected to develop innovative measures to substantially reduce energy consumption and greenhouse gas emissions through improvement on energy efficiency. Energy efficiency indicator become hot topic to explore in the building services industry. Heat pump systems provide an alternative solution to recover heat from different sources for usage in various green building applications. Some recent research efforts have improved the energy efficiency of heat pump remarkably. Furthermore, the cutting-edge compressor technology provides potential to reduce energy consumptions of heat pump systems by as high as 80% [17]. Using heat pumps in HVAC systems can improve overall energy efficiency substantially. Heat pumps in HVAC system perform the functions of ventilation, cooling, and heating through air transport via air ducts and water transport via water pipes. Ventilation can also be done through air transport. As shown in Fig. 3.5, HVAC (heating, ventilation, and air-conditioning) systems include four subsystems to provide heating, cooling, and ventilation services. The four subsystems are heat generation, cool generation, air transport, and water transport.

Accurate forecasting of energy consumption in a building is an important tool to achieve the objectives of reducing energy demand and improving energy efficiency [18]. To examine the energy efficiency indicator, Lombard et al. [19] propose four equations to determine the energy efficiency of the four subsystems:

Fig. 3.5 Subsystems and services of HVAC

The efficiency (η) of cool generation (CG) is defined as the ratio of the sum of thermal energy demands (D) on cool generators (cool generation real demand) to the energy consumption (C) of cool generation and heat rejection equipment:

$$\eta_{CG} = D_{CG}/C_{CG} \tag{3.1}$$

The efficient (η) of heat generation (HG) is defined as the ratio of the sum of thermal energy demands (D) on heat generators (heat generation real demand) to the sum of their energy consumption (C):

$$\eta_{HG} = D_{HG}/C_{HG} \tag{3.2}$$

The efficiency of water transport (WT) can be enhanced by minimizing the distribution losses (both thermal energy and fluid leakage) and reducing the energy use of pumps and accessories. Hence, the specific consumption (SC) in terms of energy use per unit of water volume (V_W) is the best indicator to examine transport efficiency.

$$SC_{WT} = C_{WT}/V_W \left[\text{in kWh/m}^3\right] \tag{3.3}$$

Similarly, the energy efficiency indicator for air transport (AT) is the specific consumption (SC), energy consumption of fan motor per unit of air volume (V_A).

$$SC_{AT} = C_{AT}/V_A \left[\text{kWh/m}^3\right] \tag{3.4}$$

The energy consumption (C) of the four systems may be obtained by summing up the four subsystems:

$$C = [D_{HG}/\eta_{HG} + D_{CG}/\eta_{CG}] + [SC_{AT} \times V_A] + [SC_{WT} \times V_W] \tag{3.5}$$

The energy consumption (C) is a key energy efficiency indicator. The lower the value of C, the higher the energy efficiency. There are several advantages of using the subsystem approach to evaluate energy efficiency:

- It clearly separates the energy use for generation (cooling and heating) from transportation (air and water)

- It differentiates cool generation and heat generation
- It provides rich information about system performance for further evaluation and identifies ways for further improvement.

3.5 Generation of Cooling and Heating

Traditional systems use separate equipment for heat generation and cool generation. Examples are chiller to generate chilled water for cooling, boiler to generate hot water heating, and electric heater for space heating. With advanced heat pump technology, it is possible to apply heat pump for system optimization [20]. Heat pump systems offer economical alternatives of recovering heat from air and/or water for use in various applications [17]. As shown in Fig. 3.6, water-to-water heat pumps and air-to-water heat pumps are alternatives for cool generation and heat generation. When both demand for chilled water and demand for hot water exist, water-to-water heat pump is desirable to use evaporator to generate chilled water for cooling and condenser to generate hot water for heating. To cope with seasonal fluctuation in demand for cooling and heating, air-to-water heat pump can be applied to generate chilled water for cooling in summer or hot water for heating in winter.

There are options to select when using the heat pump systems. Although types of heat pumps can be classified by several parameters, the most commonly used classification is based on the heat source and distribution means. As shown in Fig. 3.7, the basic types of heat pumps are air-to-water heat pump, water-to-water heat pump, and air-to-air heat pump. Air-to-air heat pump uses air as the source for heat absorption or heat rejection and air is utilized to distribute useful energy via heating coil or cooling coil. Air-to-water heat pump uses air as the source for heat absorption or heat rejection and water is utilized to distribute useful energy via water heat exchanger. Water to air heat pump uses water system as the source for heat absorption or heat rejection and air is utilized to distribute useful energy via heating coil or cooling coil. Water-to-water heat pump uses water system as the source for heat absorption or heat rejection and water is utilized to distribute useful energy via water heat exchanger.

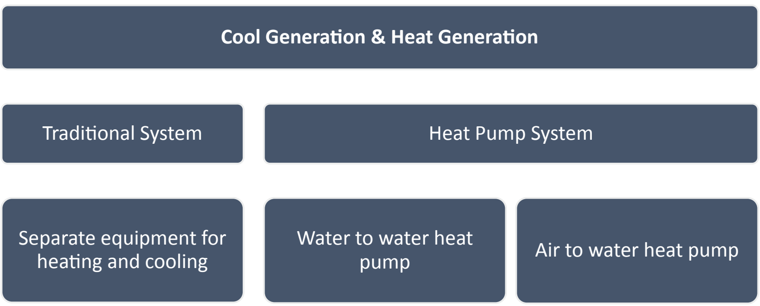


Fig. 3.6 Options to provide cooling and heating

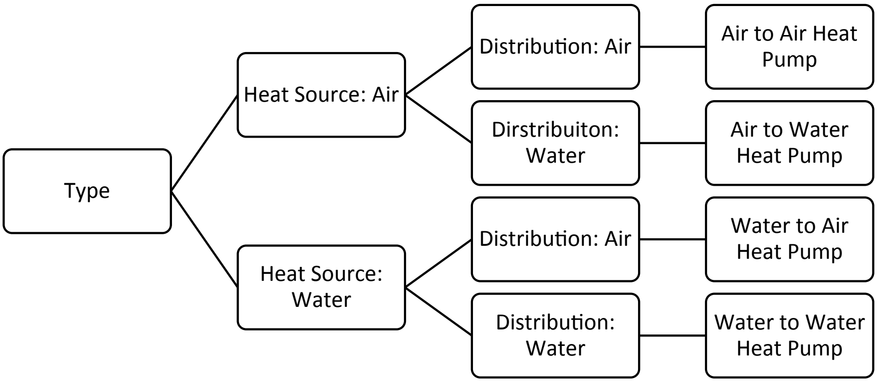


Fig. 3.7 Types of heat pumps

3.6 Water Source Heat Pump

The main difference between the types of heat pump is the sources and the means of distribution or dispose. Heat source of water source heat pump is water. Water-to-water heat pump is the most energy-efficient HVAC system. Water-to-water heat pump is capable to provide both cooling and heating providing the most benefit of delivering useful energy. Water source heat pump systems can provide indoor comfort climate in a wide range of building types. The water source heat pump recover energy through a system of pipes. Heat pumps are connected to a common water loop for heat reject and heat absorb.

Typical benefits of using the water-to-water heat pump systems include cost-effective, low noise operations, reliable performance, and energy recovery. As the water-to water-heat pump generates both heating and cooling, balance of energy in both hot side and cold side is an issue. As shown in Fig. 3.8, the water-to-water heat pump consists of a source side water-to-refrigerant heat exchanger (i.e., evaporator) and a load side refrigerant-to-water (condenser) heat exchanger.

In water-to-water heat pump operations, refrigerant-to-water heat exchangers are connected to hot water for heat generation and chilled water for cool generation. Figure 3.9 illustrates the water-to-water heat pump connects with both hot water pipes and chilled water pipes. The source side is typically connected to chilled water system for cool generation and the load side connected to the hot water system for heat generation. Two pairs of water pipes are connected. The first pair is hot water in and hot water out for heating and the second pair is chilled water in and chilled water out for cooling.

The water-to-water heat pump consists of two heat exchangers (i.e., evaporator and condenser). The evaporator generates chilled water which connected to chilled water system. On the other hand, the condenser generates hot water which connected to hot water system. As hot water is for mainly domestic use (e.g., bathing, food preparation, washing clothes, and dished), the type of heat exchanger is usually

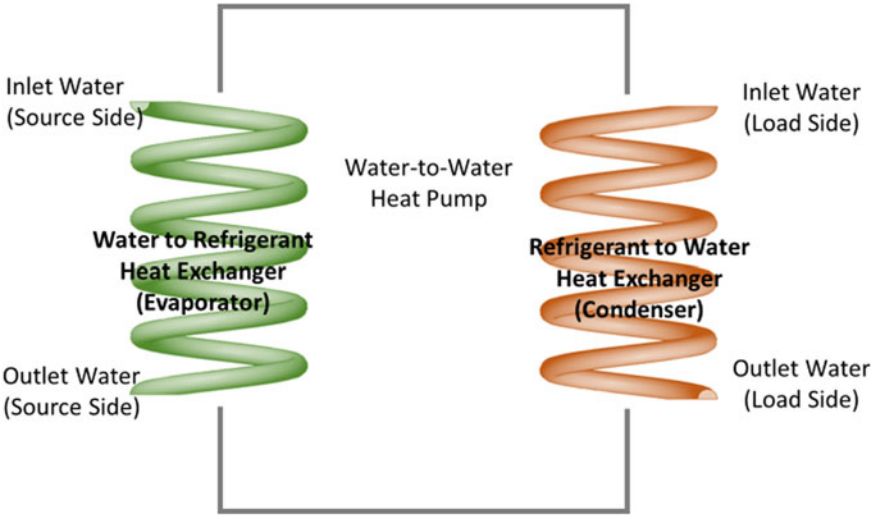
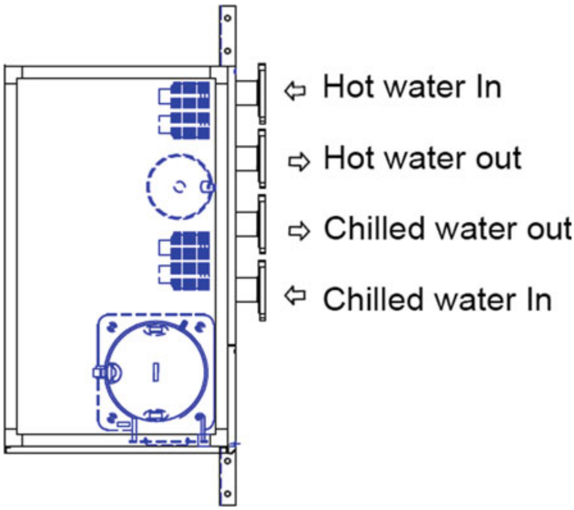


Fig. 3.8 Source side and load side of water-to-water heat pump

Fig. 3.9 Water-to-water heat pump with two water heat exchangers



double wall. Figure 3.10 illustrates a typical application of water-to-water heat pump system. Chilled water inlet temperature is 13 °C and outlet temperature is 8 °C with temperature difference of 5 °C (i.e., $\Delta t = 5$). The outlet temperature of hot water can be varied depending on the system design. Typical hot water inlet temperature is 60 °C and outlet temperature is 65 °C with temperature difference of 5 °C (i.e., $\Delta t = 5$). A water-to water-heat exchanger can be added to connect to the hot water storage tank.

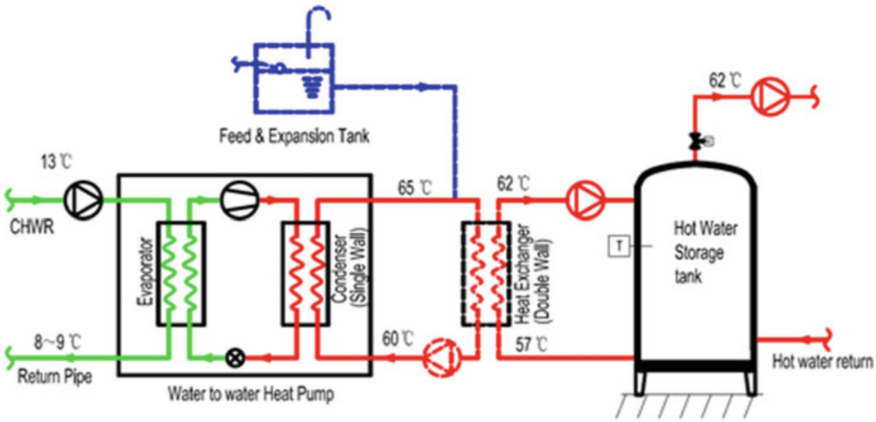


Fig. 3.10 Application of water-to water-heat pump

3.7 Air Source Heat Pump

Air source heat pump is an option to provide heating and cooling for buildings. Air source heat pump absorbs heat from outside air and discharged the heat at higher temperature to air or water. In general, there are two main types of air source heat pumps. The first type is air-to-air heat pump absorbing heat from outside air and transferring the heat directly to indoor space via fan system. The air-to-air heat pump can operate reversely by rejecting heat to outside air to cool indoor air via fan system. The other type is air-to-water heat pump to connect the cooling and heating system. The heat pump can reject heat to outside air to generate chilled water for cooling in summer and absorb heat from outside air to generate hot water for heating in winter.

Figure 3.11 illustrates a typical air-to-water heat pump with one pair of water pipes for inlet water and outlet water. The air side heat source can perform heat rejection for cooling generation and heat absorption for heating generation. Depending on the configuration, there are several operating modes for air-to-water heat pumps:

- Cooling only to generate chilled water
- Heating only to generate hot water
- Reverse cycle option to generate chilled water for cooling in summer and generate hot water for heating in winter.

The operations of air source heat pump can perform heat recovery. Heat recovery generally refers to waste heat recovery and utilization. For instance, cooling coil of the heat pump can cool air to below dew point for dehumidification and generate latent heat. The latent heat recovered from coiling coil can be recovered as heat source for space reheat or water heating.

Heat pump operations with heat recovery function can be an example of adoption of the principle of 3R, i.e., reduce, reuse, and recycle [21]:

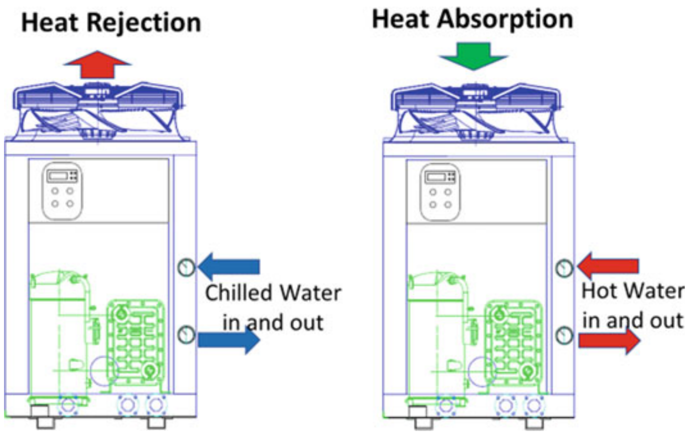


Fig. 3.11 Air-to-water heat pump

- Reduce: The first step is to prevent the generation of waste by reducing at source. The use of heat pump can significantly reduce electricity use.
- Reuse: The waste heat should be recovered and reused. In heat pump operations, latent heat generated from cooling coil can be recovered and utilized for space reheat or water heating.
- Recycle: Recycling is taking a product at the end of its useful life and turning it into a usable product. The heat pump system is a useful recycle process to transfer energy from return air stream to supply air steam.

In general, heat pumps operations use a smaller amount of electricity than traditional heating and cooling system. Standard air source heat pump can extract useful heat at any temperature above absolute zero. Advanced air source heat pump designed specially for very cold climate which can extract useful heat from low ambient air temperature [22]. Air source has become popular due to several factors. First, air source heat pumps use air as primary air sources. Next, air source heat pump can provide cooling in summer and heating in winter. Besides, it is not necessary to provide fuel storage. Furthermore, it is easy to install as most of the air source heat pumps are packaged units.

However, there are limitations in using heat pumps. The efficiency of heat pumps drops as outdoor temperature falls. Supplementary or backup heat may be required to provide indoor comfort when the outdoor temperature is extremely low. Besides, heat pump system may temporarily switch to reverse operation to defrost the coils. It is essential to take it into account when sizing the heat pump system. Furthermore, heat pumps system takes longer time to respond to the change in demand. It may not fully meet the quick response demand for indoor comfort. All these factors need to be considered when designing the heat pump system.

References

1. Demir H, Mobedi M, Ulku S (2008) A review on adsorption heat pump: problem and solutions. Renew Sustain Energy Rev 12:2381–2403
2. Lund H (2007) Renewable energy strategies for sustainable development. Energy 32:912–919
3. Brockway AM, Delforge P (2018) Emission reduction potential from electric heat pumps in California homes. Electricity J 31(9):44–53
4. Yang L, Yan H, Lam JC (2014) Thermal comfort and building energy consumption implications: a review. Appl Energy 115:164–173
5. Chow TT, Lam JC (1992) Thermal comfort and energy conservation in commercial buildings in Hong Kong. Architectural Sci Rev 35:67–72
6. Zmeureanu R, Doramajian A (1992) A thermal acceptable temperature drifts can reduce the energy consumption for cooling in office buildings. Build Environ 28:469–481
7. Sekhar SC (1995) Higher space temperatures and better thermal comfort—a tropical analysis. Energy Build 23:169–174
8. Nicol F, Roaf S (1996) Pioneering new indoor temperature standards: the Pakistan project. Energy Build 23:169–174
9. Mui KWH, Chang WTD (2003) Adaptive comfort temperature model of air-conditioned building in Hong Kong. Build Environ 38(6):837–852
10. Roussac ACS (2011) A preliminary evaluation of two strategies for raising indoor air temperature setpoints in office buildings. Architectural Sci Rev 54:148–156
11. Jain AK (2018) Health, comfort, efficiency: three dimension of building performance. Cooling India 2018:1–6
12. Dascalaki EG, Sermpetzoglou VG (2011) Energy performance and indoor environmental quality in Hellenic schools. Energy Build 43(2–3):718–727
13. Zou D, Ma X, Liu X, Zheng P, Cai B, Huang J, Guo J, Liu M (2017) Experimental research of an air-source heat pump water heater using water-PCM for heat storage. Appl Energy 206:784–792
14. Garica NP, Vatopoulos K, Riekkola AK, Lopez AP, Olsen L (2012) Best available technologies for the heating and cooling market in the European Union. JRC Scientific and Policy Reports, European Commission
15. David A, Mathiesen BV, Averfalk H, Werner S, Lund H (2017) Heat roadmap Europe: large-scale electric heat pumps in district heating systems. Energy 10(578):1–18
16. Zhang J, Wang RZ, Wu JY (2007) System optimization and experimental research on air source heat pump water heater. Appl Therm Eng 27:1029–1035
17. Chua KJ, Chou SK, Yang WM (2010) Advances in heat pump systems: a review. Appl Energy 87(12):3611–3624
18. Bakar NNA, Hassan MY, Abdullah H, Rahman HA, Abdullah MP, Hussin F, Bandi M (2015) Energy efficiency index as an indicator for measuring building energy performance: a review. Renew Sustain Energy 44:1–11
19. Lombard LP, Ortiz J, Maestre IR, Coronel JF (2012) Constructing HVAC energy efficiency indicators. Energy Build 47:619–629
20. Zhang J, Wang RZ, Wu JY (2007) System optimization and experimental research on air source heat pump water heater. Appl Therm Eng 27(5/6):1029–1035
21. Samilha B (2013) The importance of the 3R principle of municipal solid waste management for achieving sustainable development. Mediterr J Soc Sci 4(3):129–135
22. Li Y, Chen G, Tang L, Liu L (2011) Analysis on performance of a novel frost-free air-source heat pump system. Build Environ 46(10):2052–2059

Part II
Heating and Cooling

Chapter 4
Air Handling Unit

Nomenclature

F	Flow rate
H	Humidity
O	Output
T	Temperature

Subscript

cc	Cooling coil
ea	Exhaust air
fa	Fresh air
hc	Heating coil
ma	Mixing air
ra	Return air
oa	Outdoor air
sa	Supply air

4.1 AHU and Indoor Air Quality

Ventilation of buildings is accomplished by circulating fresh air from outdoor through the building and exhausting indoor air. Ventilation is important in indoor air quality. Researchers also conduct studies to examine the association between ventilation and health of occupants [1]. There are various standards to determine acceptable ventilation flow rate. Examples include l/s per person, air change per hour (ACH), or

Y. H. V. Lun and S. L. D. Tung, *Heat Pumps for Sustainable Heating and Cooling*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-31387-6_4

CO_2 concentration level in ppm (parts per million). Ventilation requirement in terms of fresh air flow rate is directly related to energy consumption. Hence, it is essential to optimize the fresh air flow rate and energy consumption.

Increased ventilation can improve indoor air quality which negatively affects sick building syndrome (SBS) symptoms. Fanger [2] proposed principles of HVAC operations:

- There is a strong economic incentive to enhance ventilation and improve air quality as better air quality results in higher productivity.
- The most effective way to improve indoor air quality is to avoid indoor air pollution through ventilation. Other means (e.g., air filter) can also be implemented to enhance indoor air quality.
- Maintain a moderately indoor air temperature and humidity decrease the required level of ventilation.
- The concept of "personalize air" should be applied by a providing small amount of clean air to serve at zone where it is consumed.
- Customized individual thermal control should be provided to meet personal differences in thermal preference.

While thermal comfort and ventilation are important, the increase in energy cost due to higher ventilation requirements need to address. Energy is required to process fresh air intakes from outdoor. There are numerous studies on the relationship between indoor temperature and energy savings for air handling. Examples include Kuisak and Li [3] recommended to minimize cooling outputs to reduce energy consumption and Fong et al. [4] investigated supply air temperature setpoint optimization for energy saving. Air handling unit (AHU) is one of the most important equipments in HVAC (heating, ventilation, and air-conditioning) particularly in large-scale buildings for providing both heating and cooling for multiple zones. There are two common types of AHU systems, i.e., constant air volume system (CAV) and variable air volume system (VAV). The CAV system supplies constant air flow to a conditioned zone under all conditions. The VAV system modulates the air flow rate according to the variation of building loads. In the VAV system, the supply fan is equipped with a variable frequency drive (VFD) to adjust air flow when the load condition changes.

4.2 Key Components of AHU

AHU operations not only significantly impact supply air temperature and humidity levels, but also the energy consumed for heating, cooling, and ventilation. AHU operations greatly affect building energy use, thermal comfort, and health of occupants. In addition, to control building ventilation intake, AHUs connect primary heating and cooling plants with building zones [5]. To perform ventilation functions, various dampers are provided to connect to air ducts including return air duct, exhaust air duct, fresh air duct, and supply air duct [6].

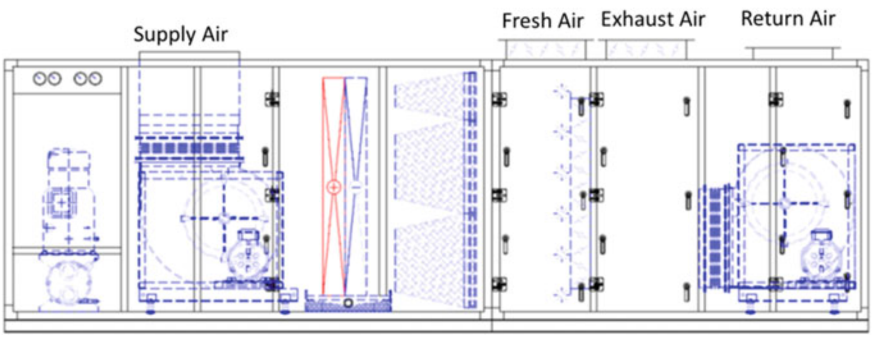


Fig. 4.1 AHU operations

The main categories of heat pump systems are water–water, water–air, and air–air. Air distribution system is usually used in the system as air temperature and humidity are controlled by supply air to the conditioned spaces [7]. AHU aims to remove energy from or add energy to airstreams before supplying to conditioned spaces [8]. AHU also distributes processed air to various conditioned spaces in a zone or zones. Key components of AHU include fans, heating/cooling coils, and dampers. DX (direct-expansion) AHU includes refrigerant circuits with components of compressor and expansion valve. Figure 4.1 illustrates the AHU operations with ventilation system with the return air flow in the AHU, part of the returned air exhaust to outdoor and certain amount of fresh air flow into the system. The mixed air is then passed through the air filter. Processed air is then supplied to indoor air after passing through the heating and cooling coils perform the heating to provide occupants with indoor thermal comfort.

In addition to air distribution, the key function of AHU is air-conditioning. The two main types of central air-conditioning systems are water type and direct expansion (DX) type of central air-conditioning plant. In water type, the air-conditioning system is integrated with chilled water and hot water system. In DX type, the air is cooled or heated directly by the refrigerant in the cooling coil and heating coil of the AHU. Since the air is cooled/heated directly by the refrigerant, the cooling/heating efficiency of DX plant is higher for small and medium plant. For large plant, chilled water system has higher efficiency.

There are three main categories of heat pump systems, i.e., water–water, water–air, and air–air. In HVAC system, air temperature and humidity are controlled by supply air to the conditioned spaces [7]. AHU aims to provide cooling or heating to airstreams before supplying to conditioned spaces [8]. AHU also distributes processed air to various conditioned spaces in a zone or zones. Key components of AHU include fans, heating/cooling coils, and dampers.

4.3 Operating Modes

AHU generally includes heating coil and cooling coil for heating and cooling in order to keep indoor room temperature at the pre-setpoint for thermal comfort. AHU also performs the function of ventilation to delivery supply air to indoor room to ensure air quality. There are various AHU operating modes. The four typical modes are DX (direct expansion) heating, economizer cooling, DX cooling, and DX cooling with ventilation [9]. Figure 4.2 illustrates the air distribution system of AHU. When return air flow from indoor room to the AHU, a certain among of air is exhaust to outdoor. Then fresh air from outdoor is mixed with the returned air. The mixed air passes through air filter. The air is then processed via cooling/dehumidification coil and heating coil before supply to the indoor room.

Mode 1: DX heating consists of the operations of heating coil and supply air. In DX heating mode, the heating coil is controlled to maintain the supply air temperature at the setpoint. The output of heating coil (O_{hc}) is the function of mixing air (ma) temperature (T) and flow rate (F) of supply air (sa):

$$O_{hc} = f(T_{ma}, F_{sa}) \tag{4.1}$$

Mode 2: Economizer cooling is desirable when the outdoor air is comfortable for free cooling. This is free cooling because economizer cooling uses 100% outdoor air to meeting the indoor cooling requirement. In the operations of economizer cooling, both heating coil and cooling coil are not operated. In this operating mode, the economizer system adjusts the outdoor damper and return air damper to modulate air flow to match cooling capacity against cooling load requirement.

Mode 3: DX cooling consists of the operations of cooling coil and supply air. In DX cooling mode, the cooling coil is controlled to maintain the supply air temperature at the setpoint. The output of cooling coil (O_{cc}) is the function of mixing air (ma) temperature (T), humidity (H) of return air (ra), and flow rate (F) of supply air (sa):

$$O_{cc} = f(T_{ma}, F_{sa}, H_{ra}) \tag{4.2}$$

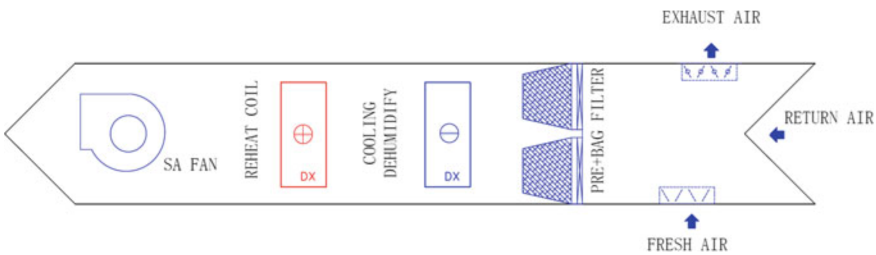


Fig. 4.2 AHU ventilation system

Mode 4: DX cooling with ventilation (fresh air intake and exhaust air discharge) consists of the operations of cooling coil and supply air. In DX cooling mode, the cooling coil is controlled to maintain the supply air temperature at the setpoint. At the same time, the fresh air damper is controlled to provide the amount of outdoor air at the pre-set fresh flow rate. The exhaust air is discharged via exhaust air duct to maintain air flow balance. The output of cooling coil (O_{cc}) is the function of temperature (T) mixing air (ma), flow rate (F) of supply air (sa), and humidity (H) of return air (ra) and outdoor air (oa):

$$O_{cc}(\text{with fresh air intake}) = f(T_{ma}, F_{sa}, H_{ra}, H_{oa}) \tag{4.3}$$

In controlling the indoor humidity level, there are various methods for dehumidification. The most common method in heat pump system is dew point cooling which removes moisture from air by cooling the air temperature below the dew point. During the cooling and dehumidification process, the dry bulb temperature, the wet bulb temperature, and the dew point temperature of air reduce. The sensible heat and the latent heat of the air also reduce to lower the enthalpy of the air.

4.4 Cooling and Heat Rejection

The functions of AHU include air mixing, air filtering, heating, cooling, dehumidification, or humidification. Air supply to a building is also performed by AHU. The ventilation system includes the operations of supply air (sa), return air (ra), exhaust air (ea), and fresh air (fa). The system starts with supply air delivery.

The supply air (sa) flow rate (F) is:

$$F_{sa} = F_{ra} - F_{ea} + F_{fa} \tag{4.4}$$

As shown in Fig. 4.3, dampers are used to regulate the flow of fresh air (fa) and exhaust air (ea) in and out of the AHU. The air manipulation of AHU is through return air (ra) as inlet and supply air (sa) as outlet. The mixed air (i.e., ra − ea + fa) is filtered via air filter and perform cooling or heating before distributing to the indoor space.

The coiling coil of AHU performs dehumidification by cooling the air down to the dew point. The latent heat generated from the dehumidification can be recovered for air reheat. Excess heat is rejected via remote condenser. Remote condensers can perform heat rejection by top discharge or side discharge depending on the configuration. Figure 4.4 illustrates the two common types of remote condensers. Remote condenser connects with the AHU via refrigerant pipes (i.e., liquid pipe and suction pipe).

The remote heat exchanger can act as remote condenser to perform heat rejection to outdoor air or remote evaporator for heat absorption from outdoor air. In vapor compression cycle, remote condenser is generally used for rejecting excess heat

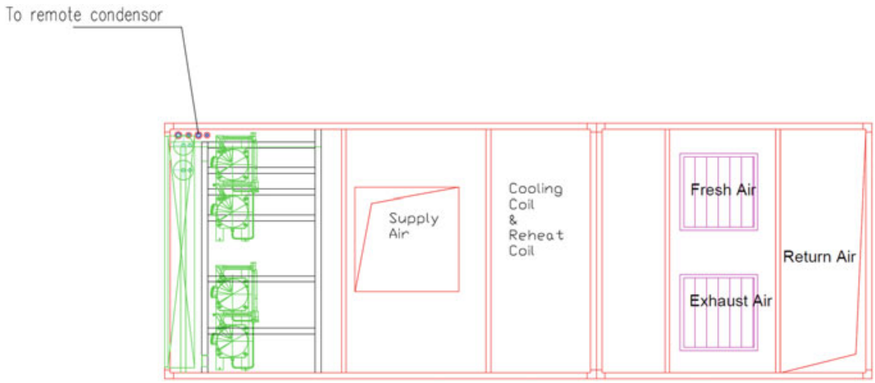


Fig. 4.3 Air dampers of AHU

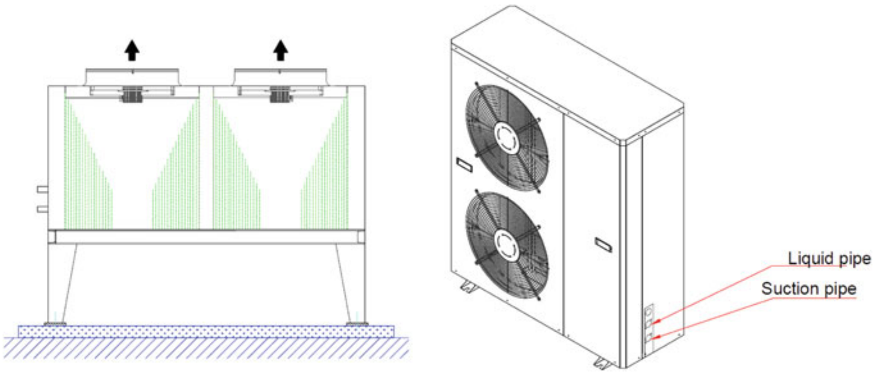


Fig. 4.4 Remote heat exchanger

generated. The total heat of rejection of remote condenser is the sum of the cooling capacity of the compressor(s) and the power input to the compressor(s). The power consumption of the remote heat exchanger is fan power. The higher the ambient temperature, the higher the temperature of air-cooled condenser. High condenser temperature decreases cooling capacity of the refrigeration cycle. These two effects decrease the performance of the air-conditioning system as increasing the condenser temperature increases the pressure ratio across the compressor(s) leading to higher power consumption [10].

4.5 Dehumidification

HVAC systems, which included space cooling and dehumidification, space heating, and ventilation, account for nearly 40% of the total energy consumption in commercial building sector [11]. When designing, installing, and operating a HVAC system, it is essential to use an integrated approach to ensure all stages of operations are considered to maximize heat recovery and minimize heat rejection.

Figure 4.5 illustrates a heat pump as AHU system. Air distribution includes return air from indoor, exhaust air to outdoor, and fresh air from outdoor. Air filter is provided to purify air before supply the mixing air to cooling/heating coils and processed air to indoor room. DX cooling coil and reheat coil are installed to provide cooling and dehumidification. In the process of dehumidification with heat pump, the cooling coil acts as the evaporator and the heating coil acts as a condenser. The pre-processed air first flows through the cooling coil where it is dehumidified below dew point, then the air flows through a heating coil where it is heated up to the set point of supply air [12].

In using the DX cooling coil for dehumidification, latent heat is recovered from cooling and dehumidification for DX heating coil to provide space reheat. When the heat generated from the dehumidification is larger than that required to heat the supply air [13], heat rejection device is necessary to reject the surplus heat. To minimize the heat rejection, a hot water coil can be installed to utilize the recovered heat for water heating for domestic use.

In addition to using DX cooling coil for dehumidification, desiccant dehumidification is another common method. Desiccant materials attract moisture from air. Desiccant air-conditioning system can be classified into two categories: (1) solid desiccant system which consists of fixed bed type and rotary wheel type and (2) liquid desiccant system. The first patent on rotary desiccant air-conditioning cycle was introduced in the 1950s [14]. Studies on rotary desiccant were conducted since the

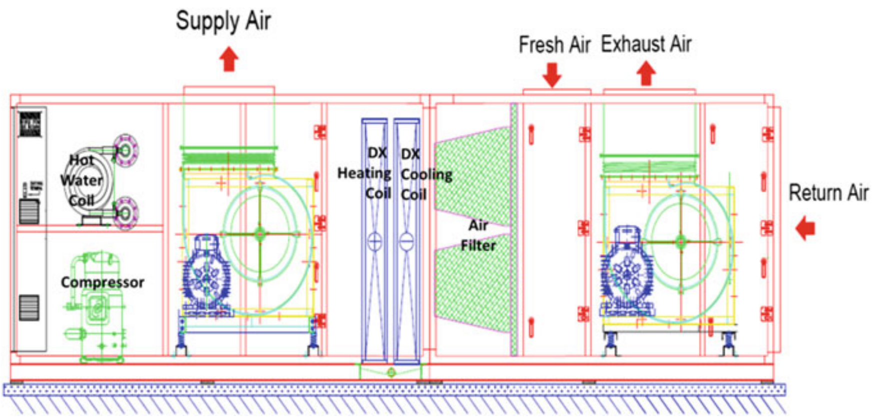


Fig. 4.5 Heat pump as AHU

1960s [15–17]. The rotary desiccant air-conditioning system, with the advantages of less subject to corrosion and can work continuously, has been widely used.

The operating principle of rotary desiccant dehumidifier consists of process air side and regeneration air side. The process air is dried by the desiccant, and the regeneration air is humidified at the same time. According to La [18], there are different type of system configurations for the operations of desiccant rotary wheel including ventilation cycle and recirculation cycle:

- Ventilation cycle [14] with process air side from ambient air to supply air, and regeneration air side from return air to exhaust air.
- Recirculation cycle [19] with process air side from return air to supply air, and regeneration air side from ambient air to exhaust air.

Figure 4.6 illustrates an example of the inlet and outlet of process air and regeneration air of desiccant rotary wheel. In the process air side, the return air passes

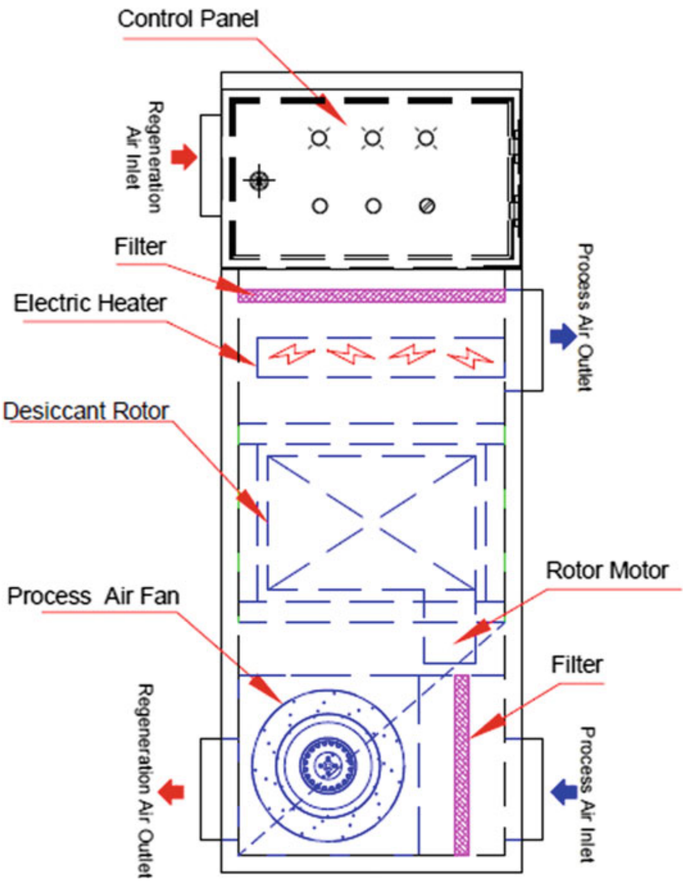


Fig. 4.6 Operations of rotary desiccant dehumidifier

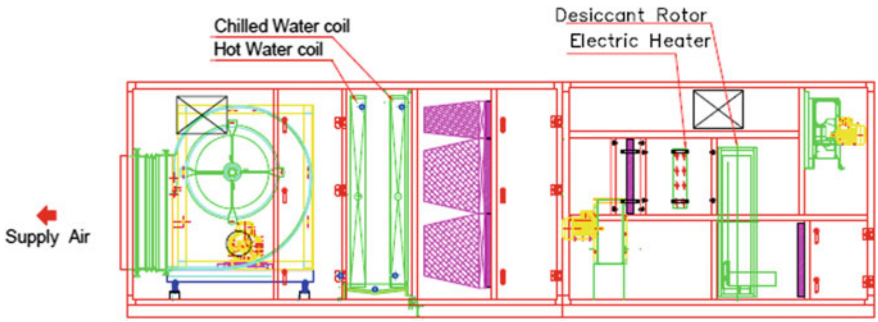


Fig. 4.7 Hybrid AHU integrated desiccant rotor

through air filter and process air fan, air is then dried by the desiccant rotor due to the absorption effect of the desiccant material. Air filter is including in the process air side to ensure air is clean before supply to the indoor room. In the regeneration air side, the ambient air passes through the air filter, electric heater, and desiccant rotor, the moist air is then exhausted to the outdoor. Air filter is included in the regeneration air side system to ensure outdoor air is clean before passing through the desiccant rotary wheel.

There are many investigations on hybrid desiccant air-conditioning system including integration of rotary desiccant dehumidification with AHU [20]. Figure 4.7 illustrates an AHU system with desiccant rotor. The mixed air is first dehumidified by the rotary desiccant dehumidification system to the required humidity level. The chilled water coil for sensible cooling and the hot water coil for sensible heating are installed in the AHU. This hybrid system can be applied to buildings with requirement on very low humidity level. There are several advantages of using the hybrid system. First, the absorption capacity of desiccant is high with the capability to perform dehumidification to a very low humidity level. Another advantage of the hybrid system is to use high COP equipment for sensible heating and cooling. Separate equipment to treat the latent load and the sensible load can increase the overall COP when the required relative humidity level is lower than 40%.

In addition to dehumidification, the hybrid AHU provides the function of air handling. As shown in Fig. 4.8, the AHU with dampers to connect fresh air (fa), exhaust air (ea), and return air (ra). After the air mixing and handling, the processed supply air (sa) is disturbed to the indoor. There are two stages of air handing. Stage 1 aims to handle latent load to remove moisture and stage 2 aims to handle sensible load to supply air at set point temperature.

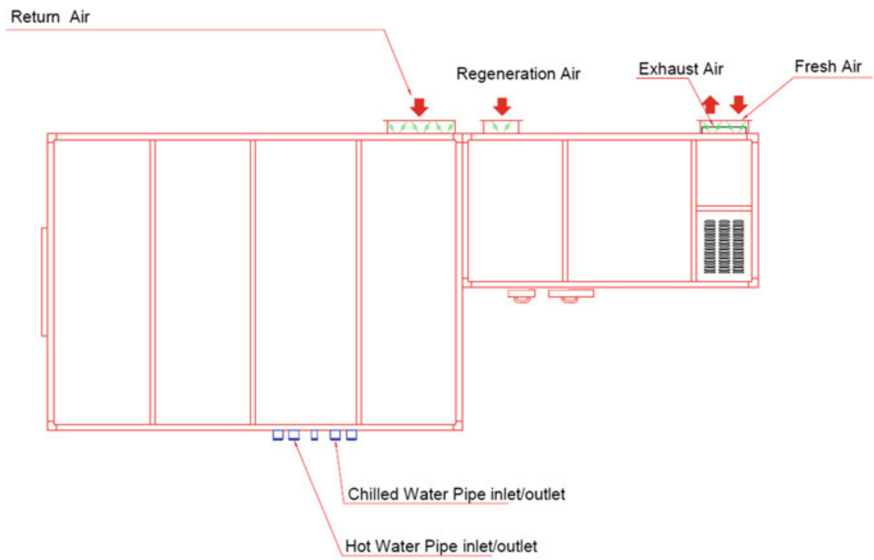


Fig. 4.8 Schematic of air flow and water pipe connection

4.6 Case Study—Cold Vault

The AHU is designed for cooling and dehumidification system in the cold vault of a heritage conservation and resource center. The design procedure includes calculation of cooling loads and selection of equipment type of the AHU. The design indoor air temperature is 4 ± 1 °C and the relative humidity is 35 ± 5%. Table 4.1 shows the cooling load calculation includes zone (i.e., envelope, lighting, and occupant) and ventilation loads. The zone and ventilation load can be further categorized as sensible load and latent load.

The design of the cooling and dehumidification system is based on the load calculation. Since the indoor design air temperature and humidity are set at a relatively low level, the sensible load and latent load are handled separately. An independent coil (cooling coil 3 with cooling capacity of 60.03 kW) is used for zone sensible cooling. The use of two independent systems for indoor air handling is more energy efficient.

Figure 4.9 provides a schematic of the cooling and dehumidification system for the cold vault. The two independent systems are:

- Zone sensible cooling: An independent air circulation system (i.e., return air from cold vault and supply air to cold vault) is used for sensible cooling. Cooling coil 3 is used for zone sensible cooling.
- Cooling and dehumidification system: The outdoor air passes through cooling coil 1 for preliminary cooling and dehumidification. Then desiccant rotor 1 handles the rest of the moisture. The indoor air returns to desiccant rotor 2 and mixing with

Table 4.1 Cooling load calculation

Envelope	Dimension: Width (m)	Dimension: Height (m)	U-value (W/m²/k)	Indoor temp. (°C)	Outdoor/Adjacent space temp. (°C)	Total load (kW)	
External wall	15	5.4	2.9	4	35	7.28	
Internal wall	49	5.4	2.9	4	35	23.79	
Ceiling	240	m²	2.9	4	22	12.53	
Floor	240	m²	2.9	4	22	12.53	
Item	Area		Lighting power density (W/m²)			Total load (kW)	
Lighting	240	m²	15			3.60	
Item	Nos. of occupants		Human sensible load (W)		Human latent load (W)	Total load (kW)	
Human	4		75		55	0.52	
Item	Fresh air flow (m³/s)	Indoor temp. (°C)	Indoor RH (%)	Outdoor temp. (°C)	Indoor RH (%)	Sensible load (kW)	Latent load (kW)
Ventilation	0.04	4	35	35	80	1.52	3.39
Zone load				Ventilation load			
Sensible load (kW)		Latent load (kW)		Sensible load (kW)		Latent load (kW)	
60.03		0.22		1.52		3.39	

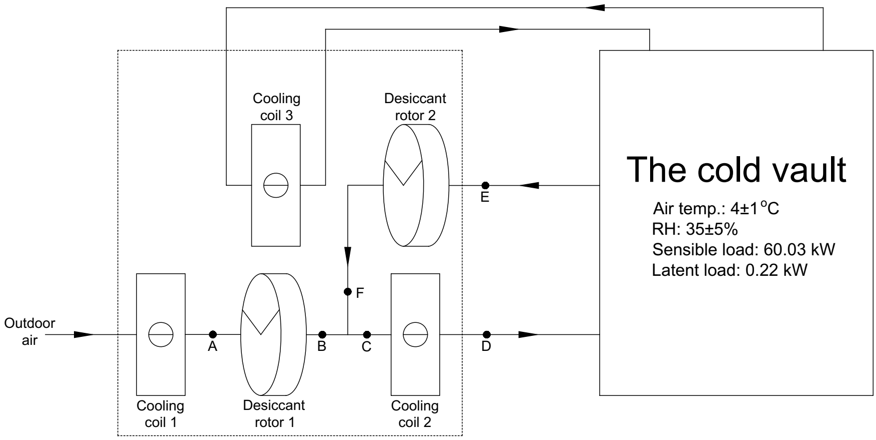


Fig. 4.9 Schematic of cooling and dehumidification system

the processed air from desiccant rotor 1. The mixed air passes through cooling coil 2 for cooling and then supply to the indoor cold vault.

Figure 4.10 and Table 4.2 show the air handling process and the air conditions at different points:

– The outdoor air goes through cooling coil 1 to remove a part of moisture load and cooling load in the outdoor air (i.e., from outdoor air to point A).

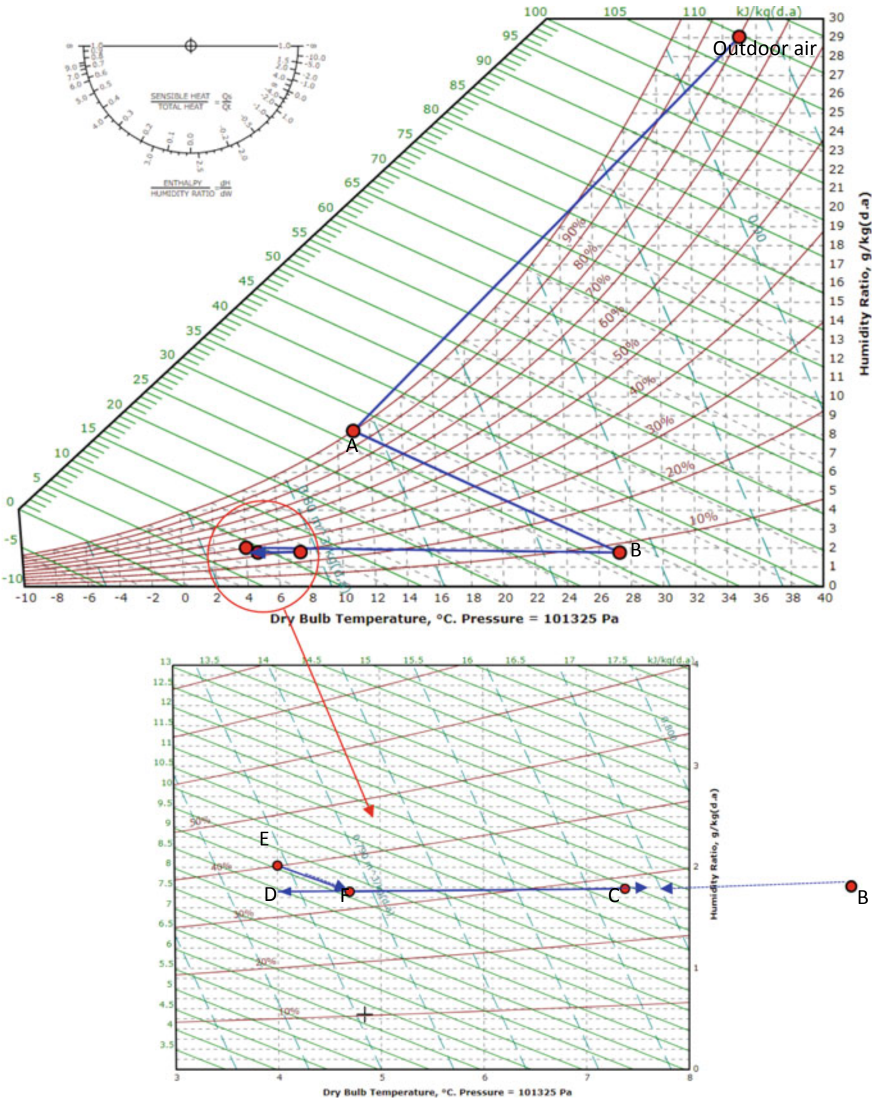


Fig. 4.10 Air conditions at different points in psychrometric chart

Table 4.2 Summary of air conditions at different points and cooling coil load

Air handling points	Outdoor air	A	B	F	E	C	D
Dry bulb temp. (°C)	35	11	27.29	4.72	4	7.38	4
Relative humidity (%)	80	100	7.85	33.31	40.1	28.13	35
Moisture content (kg water)/(kg dry air)	0.02946	0.00831	0.00178	0.00178	0.00204	0.00178	0.00178
Enthalpy (kJ/kg dry air)	110.767	32.001	32.001	9.151	9.151	11.895	8.498
Volumetric flow rate (m^3/s)	0.04	0.04	0.04	0.3	0.3	0.34	0.34
Cooling load for coil 1 (A → B) (kW)						3.61	
Cooling load for coil 2 (C → D) (kW)						1.31	

- Due to the limited moisture removal capacity of cooling coil, the dew point temperature of air point A is 11 °C.
- After cooling coil 1, the moisture content in the air is still above the required level. The rest moisture needs to be handled by desiccant rotor 1. Through desiccant rotor 1, the moisture content in the air is lower to indoor air design moisture content (i.e., from point A to point B), and the enthalpy between point A and point B is the same.
- The desiccant rotor 2 is used to remove occupant latent load in the cold vault (i.e., from point E to point F). Therefore, the moisture content in the air after desiccant rotor 2 is equal to indoor air design moisture content, and the enthalpy between point E and point F is at the same level.
- Through the dehumidification system, the processed air from outdoor air (point B) is mixed with return air (point F) and becomes the air mixture (point C).
- By the two desiccant rotors, latent load is turned into sensible cooling load, which is handled by cooling coil 2 (from point C to point D).
- Thus, the air temperature of the air (point D) is lower to 4 °C which meets indoor air design temperature.

References

1. Wargocki P, Djukanovic R (2005) Simulations of the potential revenue from investment in improved indoor air quality in an office building. ASHARE Trans 111:669–711
2. Fanger PO (2000) Indoor air quality in the 21st century: search for excellence. Indoor Air 10:68–73
3. Kusiak A, Li M (2010) Cooling output optimization of an air handling unit. Appl Energy 87:901–909
4. Fong KF, Hanby VI, Chow TT (2006) HVAC system optimization for energy management by evolution programming. Energy Build 38(3):220–231
5. Li S, Wen J (2010) Development and validation of a dynamic air handling unit model. In: ASHARE 2010 winter conference
6. Yu Y, Woradechjumroen D, Yu D (2014) A review of fault detection and diagnosis methodologies on air handling units. Energy Build 82:550–562
7. McQuiston FC, Parker JD, Spilter JD (2005) Heating, ventilation, and air conditioning: analysis and Design. Wiley, New York
8. Khaled M, Ramadam M (2016) Heating fresh air by hot exhaust air of HVAC systems. Case Stud Therm Eng 8:398–402
9. Zhao Y, Wen J, Wang S (2015) Diagnostic Bayesian networks for diagnosing air handling units' faults. Appl Therm Eng 90:145–157
10. Hajidavalloo E, Eghtedari H (2010) Performance improvement of air-cooled refrigeration system by using evaporatively cooled air condenser. Int J Refrig 33:982–988
11. DOE, Energy efficiency and renewable energy, energy efficiency trends in residential and commercial building, Building Energy Data Book (US Department of Energy)
12. Mazzei P, Minichiella F, Palma D (2005) HVAC dehumidification systems for thermal comfort: a critical review. Appl Therm Eng 25:677–707
13. Zhang LZ (2006) Energy performance of independent air dehumidification system with energy recovery measures. Energy 31:1228–1242
14. Pennington NA (1955) Humidity changer for air conditioning. USA Patent No. 2,700,537
15. Dunkle RV (1965) A method of solar air conditioning. Mech Chem Eng Trans Inst Eng 73:73–78
16. Maclaine-cross IL (1985) High performance adiabatic desiccant open-cooling cycle. J Sol Energy Eng 107(1):102–104
17. Shelpuk B (1993) The technical challenges for solid desiccant cooling. Heat Recovery Syst CHP 13(4):321–328
18. La D, Dai YJ, Li Y, Wang RZ, Ge TS (2010) Technical development of rotary desiccant dehumidification and air conditioning: a review. Renew Sustain Energy Rev 14:130–147
19. Waugaman DG, Kinin A, Kettleborough CF (1993) A review of desiccant cooling system. J Energy Res Technol 115(1):1–8
20. Dhar PI, Singh SK (2001) Studies on solid desiccant-based hybrid air-conditioning systems. Appl Therm Eng 21(2):119–134

Chapter 5
Total Energy Heat Pump

Nomenclature

A	Area
COP	Coefficient of performance
C_p	Specific heat
dp	Total pressure
$\dot{E}$	Energy rate
h_1	Specific enthalpy at stage 1
h_2	Specific enthalpy at stage 2
h_3	Specific enthalpy at stage 3
h_4	Specific enthalpy at stage 4
Δh $(h_2 - h_1)$	Enthalpy difference stage 2 and stage 1
HR	Heat rejection
$\dot{m}$	Mass flow rate
η	Efficiency
q	Air volume delivered
Q	Output capacity
$\dot{Q}$	Heat transfer rate
U	Overall heat transfer coefficient
W	Power input (W)
$\dot{W}$	Power
$\dot{W}_i$	Compression indicated power

Subscript

comp	Compressor
cond	Condenser
dest	Destroy (or destruction)

Y. H. V. Lun and S. L. D. Tung, *Heat Pumps for Sustainable Heating and Cooling*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-31387-6_5

fan	Fan
eva	Evaporator
ht	Heat exchanger
in	Inlet (or input)
out	Outlet (or output)
r	Refrigerant
w	Water

5.1 Heat Rejection and Heat Absorption

The application of heat pump system in buildings has gained popularity and is a competitive solution compared with traditional heating and cooling systems [1]. Heat pump generates heat by transporting heat from cool outdoors into indoors for heating. Despite the name, heat pumps do a lot more than heating. Heat pump can be air-conditioning units that generating cooling in summer to provide thermal comfort for occupants. In addition to generate air cooling and air heating, heat pumps can provide chilled water for chiller and hot water for water systems. Heat pump can also perform dehumidification and integrated with various HVAC (heating, ventilation, and air-conditioning) equipments. Classification of heat pump generally based on heat source and delivery means [2]. Air-to-air heat pump uses air as both the heat source and the delivery mean to building. Air-to-water heat pump utilizes air as heat source to generate chilled water for cooling or heat water for heating.

Air source heat pump system is the most commonly installed heat pumps. Recently, the advanced technology has improved the performance of heat pump and makes air source heat pump viable for colder regions. However, an auxiliary heating system may be needed as backup if outdoor ambient temperatures drop below the design capacity level. Air source backup heating can utilize low cost equipment including electric heating or gas furnace. Air source heat pump consists of two parts, i.e., an air handler and a heat pump (with compressor, expansion valve, evaporator and condenser). A refrigerant circulates between evaporator and consender through piping to absorb and release heat as it moves back and forth.

Extensive works have been conducted in testing an array of new refrigerant mixtures to improve energy efficiency and operations of heat pump [3]. Examples include Comakli et al. [4] examined R404A, Liu et al. [5] investigated R407C, and Han et al. [6] studied R410A. According to Chen [7] found that compressors use R410A runs cooler. It means that heat pump systems use R410A consumes less energy with the same level of output which comparing with other refrigerant. R410A also absorbs and releases heat more efficiently with potential to reduce heat exchange size.

Heat pump is a large device moving heat from one place to another. In heating mode, air source heat pump absorbs heat from the outdoor and releases heating in forms of hot air and/or hot water to provide indoor thermal comfort. As shown in Fig. 5.1, air coil of air-to-water heat pump performs heat absorption and generates hot water for heating to provide indoor comfort climate.

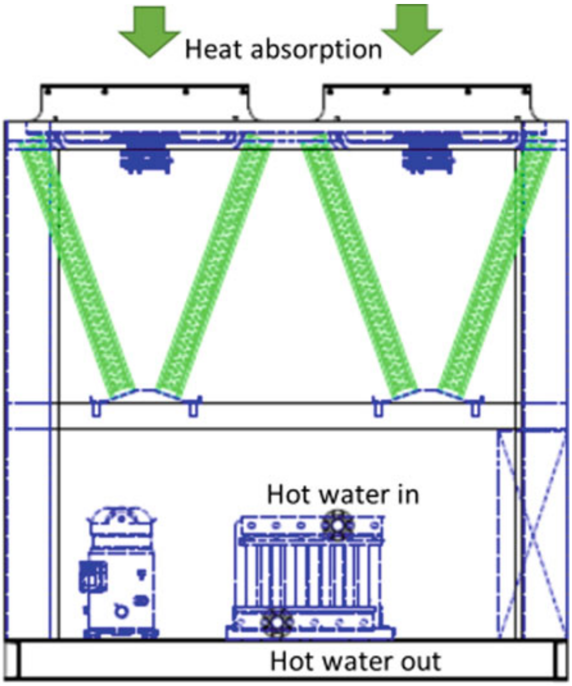


Fig. 5.1 Air-to-water heat pump for heating

In cooing mode, air source heat pump rejects heat to the outdoor and releases cooling to provide indoor thermal comfort. As shown in Fig. 5.2, air coil of air-to-water heat pump performs heat rejection when the air-to-water heat pump generating chilled water for cooling. Air source heat pumps can perform cooling function by generating chilled water to provide comfortable indoor environment. Waste heat from cooling system is rejected via air coil. Waste heat can be recovered in some heat pump systems for space heating or water heating.

Heat rejection (HR) is the total amount of heat energy (Q) transferred from the cool side to the hot side, plus the power input of compressor (W_{comp}) of the system. The calculation of the capacity of the air-cooled condenser is based on the total heat of rejection of the refrigeration system:

$$\text{HR} = Q + W_{\text{comp}} \tag{5.1}$$

5.2 Power Input and Performance

Key components of air source heat pump consist of compressor, expansion valve, fan, evaporator, and condenser. In the operations of air-to-water heat pump, the heat source is air. To operate the heat pump for heat generation or cool generation,

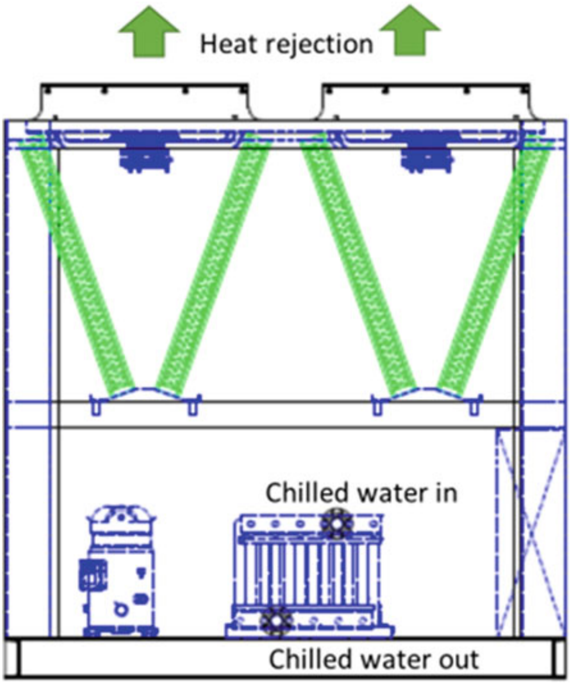


Fig. 5.2 Air-to-water heat pump for cooling

power input (W) is required for compressor (comp) and fan (fan). The total power consumption of air-to-water heat pump is:

$$W = W_{\text{comp}} + W_{\text{fan}} \tag{5.2}$$

According to Lu et al. [8], the efficiency of fan (η_{fan}) is beaded on total pressure (dp), air volume delivered by fan (q_{fan}), and power used by fan (W_{fan}):

$$\eta_{\text{fan}} = \text{dp} \times q_{\text{fan}} / W_{\text{fan}} \tag{5.3}$$

$$W_{\text{fan}} = \text{dp} \times q_{\text{fan}} / \eta_{\text{fan}} \tag{5.4}$$

In heating mode, heat pump water heating systems generate hot water for space and water heating with high COP. While air water heat pump uses air as heat source, water source heat pump uses water as heat source. The heat pump absorbs heat at lower temperature and transfers it via heat exchanger at higher temperature. The energy consumed to drive the heat pump system is relatively small proportion (approximately 30%) of the transferred energy [9]. Water source heat pumps can utilize closed-loop pipes and heat exchangers for heat exchange. This process removes or absorbs heat for heating or cooling. The difference between water-to-water heat pump and air-to-water heat pump is that the heat source is water instead of air. Figure 5.3 illustrates

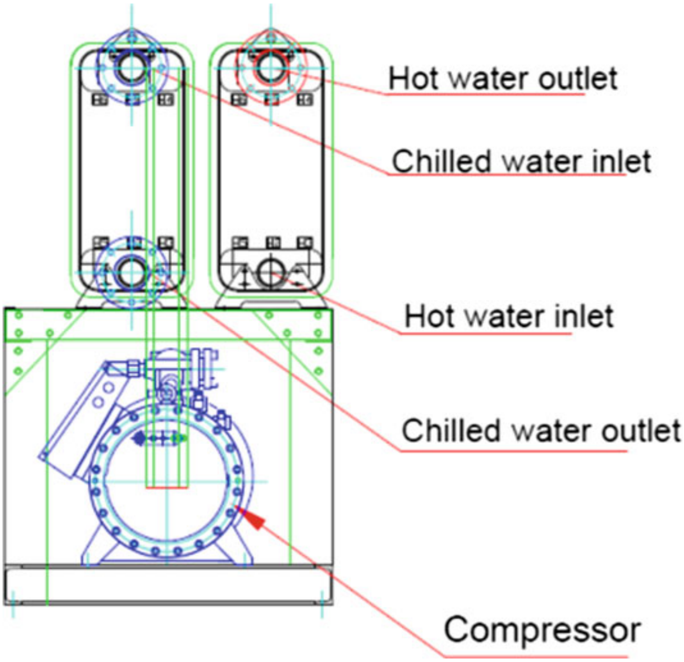


Fig. 5.3 Water-to-water heat pump

a water-to-water heat pump to provide both cooling and heating. The chilled water heat exchanger generates chilled water for cooling and the hot water heat exchanger generates hot water for heating at the same time.

Heat exchanger is a key component of heat pump. The number of transfer unit (NTU) model is one of the main methods of modeling a heat exchanger. The NTU model approach is developed from the water-cooled condenser and can be transferred to other heat exchangers including intercooler, economizers, and evaporator using their configuration and properties of working fluids (i.e., air, refrigerant, and water).

The NTU model is a useful method to calculate heat transfer rate of water (w) heat exchanger (ht). According to Bertsch and Groll [10], the variables to determine the NTU are the overall heat transfer coefficient (U), area of heat exchanger (A), specific heat capacity (C_p), and mass flow rate ($\dot{m}$):

$$\mathrm{NTU}_{\mathrm{ht}} = UA_{\mathrm{ht}}/C_{\mathrm{p_w}}\dot{m}_{\mathrm{w}} \quad (5.5)$$

While NTU is useful to examine heat exchanger, there are other studies focus on the investigation of overall performance. To examine the overall coefficient of performance (COP) of the heat pump, Hajidavalloo and Eghtedari [11] developed the following equations to examine the overall performance based on output (W) and power input (Q):

$$\mathrm{COP} = Q/W \tag{5.6}$$

5.3 Energy and Exergy

Energy and Exergy are fundamental to determine the quantity and quality of the system performance. The first law of thermodynamics states that energy cannot be created nor destroyed but it can be change from one form to anohter form. Energy analysis illustrates the energy balance at inlet and outlet of the system. However, energy analysis does not examine wastes due to thermodynamics losesses. To deal with system inefficiencies, exergy analysis examines the qualities of energies flow througy the system. Based on the second law of thermodyamics, exergy analysis aims to identify energy loss to examine system degradation. Energy analysis and exergy analysis are important in investigating vapor compression refrigeration system. Energy analysis aims to examine heat flow, capacity, and power consumption. Exergy is a measure of the maximum useful work that can be done by a system interacting with ambient at constant pressure and constant temperature. Exergy analysis is essential when conducting energy analysis [12]. According to Hepbasil and Kalinci [13], the mass balance equation of a heat pump system can be expressed as mass flow ($\dot{m}$) on input (in) and mass flow ($\dot{m}$) of output (out):

$$\sum \dot{m}_{\mathrm{in}} = \dot{m}_{\mathrm{out}} \tag{5.7}$$

The energy ($\dot{E}$) and exergy ($\dot{\mathrm{E}}\mathrm{X}$) balance can be expressed at the total energy inputs equal to the total energy outputs and total exergy inputs equal to the total exergy outputs, respectively,

$$\sum \dot{E}_{\mathrm{in}} = \sum \dot{E}_{\mathrm{out}} \tag{5.8}$$

$$\sum \dot{E}X_{\mathrm{in}} = \sum \dot{E}X_{\mathrm{out}} \tag{5.9}$$

The refrigerant cycle conducts a heat transfer process from a low temperature source to a higher temperature source [14]. As shown in Fig. 5.4, the process consists of four stages:

- Stage 1: The refrigerant fluid enters the compressor as saturated steam, as a result of mechanical compression process; the compressor increases the temperature and pressure of the refrigerant as superheated gas.
- Stage 2: The fluid enters the condenser to exchange heat and reduce the temperature of the fluid. The fluid becomes saturated liquid properties at the exit of condenser.
- Stage 3: The refrigerant passes through the expansion valve to lower its pressure through the steady-state process in which the enthalpy level remains constant.

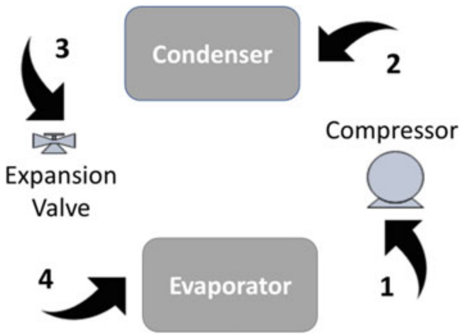


Fig. 5.4 Vapor compression refrigeration system

- Stage 4: The fluid enters the evaporator to extract heat from the cooled space and repeat the cycle.

The heat transfer rate of the evaporator ($\dot{Q}_{eva}$) and the condenser ($\dot{Q}_{cond}$) is based on the mass flow rate ($\dot{m}$) and the difference of specific enthalpy (h) between the inlet and outlet, and can be expressed the following equations, respectively:

$$\dot{Q}_{eva} = \dot{m}(h_1 - h_4) \tag{5.10}$$

$$\dot{Q}_{cond} = \dot{m}(h_3 - h_2) \tag{5.11}$$

According to Li et al. [15], the compression indicated power ($\dot{W}_i$) is the product of total input electrical power to compressor (W_{comp}) and efficiency of compressor (η_{comp}) in terms of enthalpy change ($\Delta h = h_2 - h_1$) of the refrigerant (r) from the inlet (i.e., stage 1) and outlet (stage 2) of the compressor is:

$$\dot{W}_i = W_{comp} \times \eta_{comp} = \dot{m}_r \Delta h \tag{5.12}$$

5.4 Combine Air Source and Water Source Heat Pump

With advanced technology, heat pump is capable to provide many functions. The basic functions of heat pump are heating and cooling. There are different types of heat pump systems available to perform heating and cooling for indoor thermal comfort. Heat pumps for fundamental heating and cooling can be grouped into several categories [16]:

- Heating only heat pump providing space heating and/or water heating via hot water system
- Cooling only heat pump providing space cooling via chilled water system

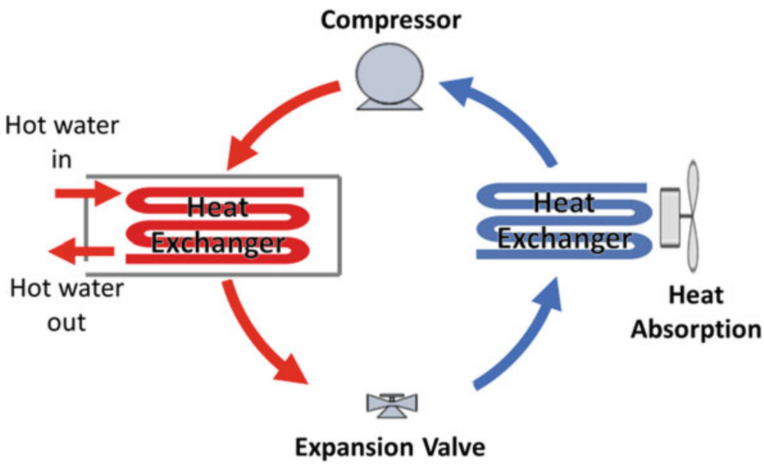


Fig. 5.5 Air-to-water heat pump heating operations

– Heating and cooling heat pump providing both heating and cooling at the same time.

Figure 5.5 illustrates the refrigeration system of heat pump with heating only operations with the components of compressor, expansion valve, refrigerant-to-water heat exchanger, refrigerant-to-air heat exchanger, and a blower. Air-to-water heat pump absorbs heat from outside cold air to generate hot water. Water pipes are connected to the heat pump to transport hot water to the hot water system. Hot water can be used for various commercial and industrial applications. Heat pump system can also operate reversely to generate chilled water for space cooling and reject heat to outside. As shown in Fig. 5.6, air-to-water heat pump air source heat pump rejects heat to the outdoor and generates cooling in forms of chilled water to provide indoor thermal comfort.

While air-to-water heat pump uses outdoor air as heat source to generate heating or cooling, water-to-water heat pump is important to generate both heating and cooling simultaneously for sustainable buildings. Using air-to-water heat pump and water-to-water heat pump is environmentally friendly as both air and water are renewable energy. Figure 5.7 illustrates the refrigeration cycle of water-to-water heat pump with two heat exchangers to supply chilled water and hot water, respectively.

Water-to-water heat pump is a heat recovery system to generate both chilled water and hot water concurrently. The refrigerant of refrigent-to-water heat exchanger at chilled water (as evaporator) side absorbs heat energy to provide chilled water for cooling and the system heat energy is recovered by the heat exchanger at hot water side (as heat recovery condenser) to provide hot water for heating. However, the water to water may not be applied to systems that do not have balanced demand for cooling and heating. Furthermore, there is seasonal fluctuation in demand for cooling and heating fluctuates. Although the heat pump has evolved to become a

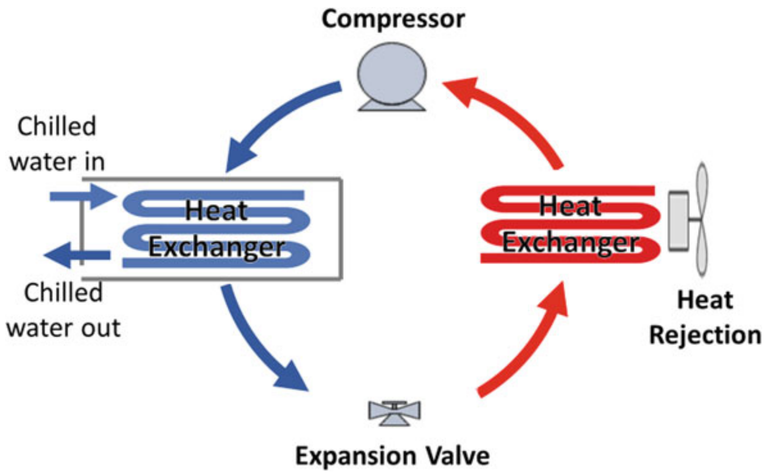


Fig. 5.6 Air-to-water heat pump cooling operations

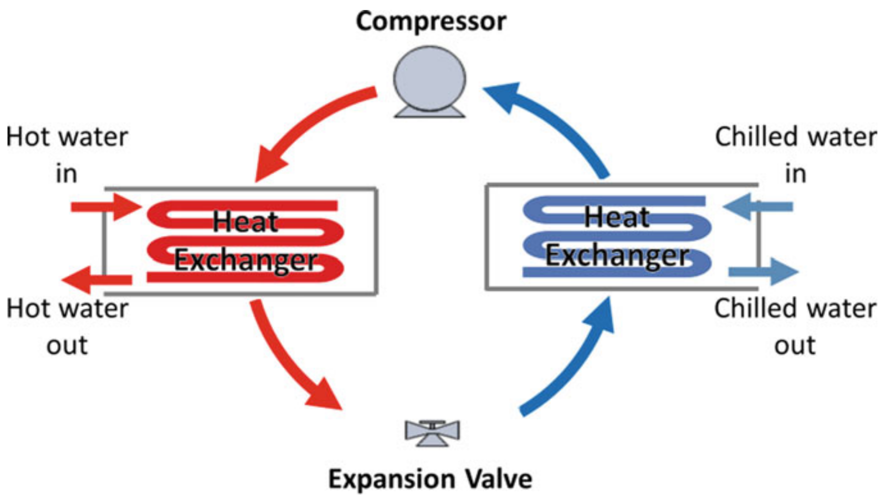


Fig. 5.7 Water-to-water heat pump

mature technology over the past decade, it is not applied as widely because of the constraint in heat pump usage [16].

With the recent heat pump technology, total energy heat pump is available to serve chilled water and hot water plant and is capable to produce chilled water and hot water to meet fluctuating cooling and heating demand. Wang et al. [17] investigated the coupled heat hump system to couple air source heat pump and water source heat pump together for cold region. The usage of the novel total energy heat pump is enhanced with application in both winter and summer. The total energy heat pump is

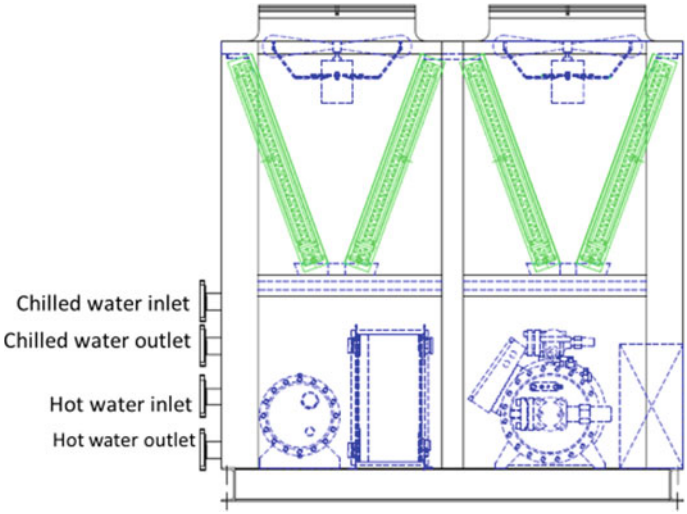


Fig. 5.8 Total energy heat pump providing both cooling and heating

a combination of air source and water source heat pump. As shown in Fig. 5.8, total energy heat pump is capable to produce chilled water and hot water to serve both the cooling and heating demand simultaneously for the air-conditioning system and hot water system. Typical total energy heat pump is designed to cool chilled water with $\Delta t = 5$ (from inlet water at 12 °C to outlet water at 7 °C). Depending on the demand requirements, the total energy heat pump is capable of heat hot water up to 90 °C.

The total energy heat pump consists of various operating modes to meet the demand for heating and cooling:

- Heating mode to produce hot water when there is no demand for cooling. As shown in Fig. 5.9, air coil is served as evaporator to absorb heat from ambient and transfer to hot water heat exchanger via refrigerant cycle.
- Cooling mode to produce chilled water when there is no demand for heating. As shown in Fig. 5.10, air coil is served as condenser to reject heat to ambient and transfer to chilled water heat exchanger via refrigerant cycle.
- Water-to-water heat pump mode to provide both hot water and chilled water simultaneously according to the demand for heating and cooling. This is the most energy efficiency mode to fully utilize all recovery heat.

Heat pump technology is the only known process that recirculates environmental and waste heat back into a heat process to provide energy efficient in heating and cooling [18]. In the operations of heat pump system, energy balance is important. According to Li [15], the simple mass balance equation can be expressed in the rate form as:

$$\dot{m}_{\text{in}} = \dot{m}_{\text{out}} \tag{5.12}$$

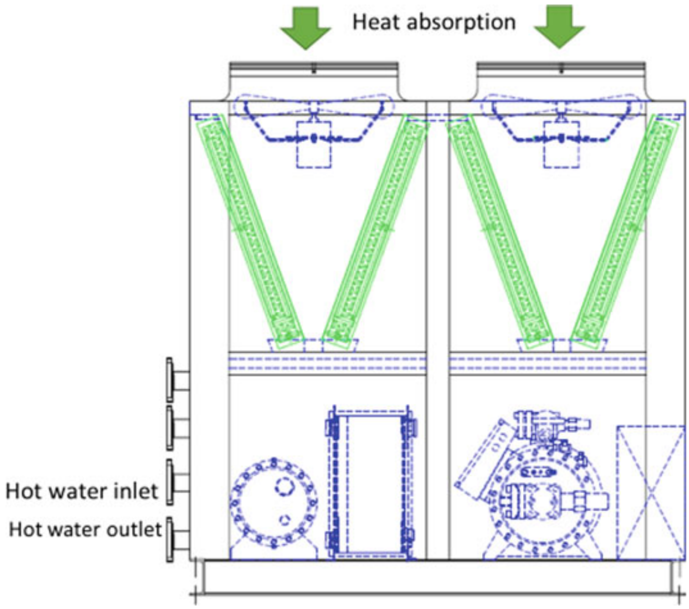


Fig. 5.9 Total energy heat pump operating heating mode

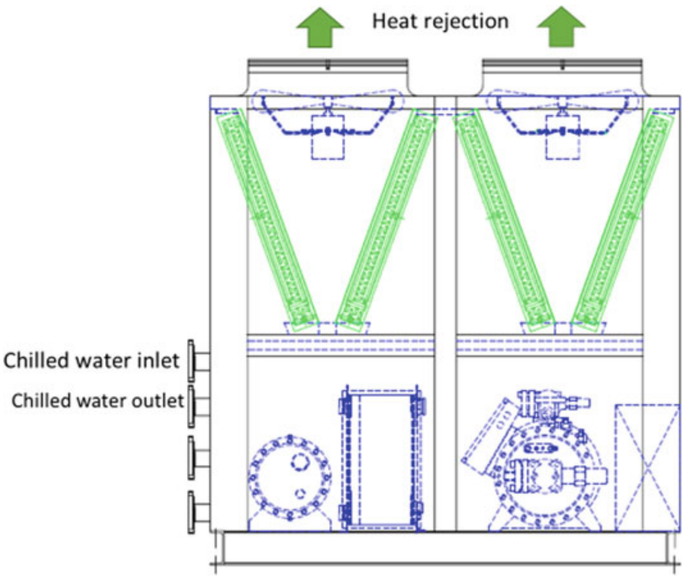


Fig. 5.10 Total energy heat pump operating cooling mode

where

$\dot{m}_{\text{in}}$ is the mass flow rate of inlet (input)

$\dot{m}_{\text{out}}$ is the mass flow rate out outlet (output).

The energy balance equation can be expressed as:

$$\dot{Q}_{\text{cond}} = \dot{Q}_{\text{eva}} + W_{\text{in}} \quad (5.13)$$

where

$\dot{Q}_{\text{cond}}$ is heat transfer rate of condenser

$\dot{Q}_{\text{eav}}$ is heat transfer rate of evaporator

$\dot{W}_{\text{in}}$ is indicated power of compressor.

Equation 5.13 is the energy balance equation illustrating that the heat transfer rate of condenser is proportional to the heat transfer rate of evaporator. Multiple refrigerant circuits can be utilized to manage the imbalance of demand for cooling and heating:

- High cooling and low heating demand: The energy absorbed from chilled water side is partially recovered by the heat exchanger and transfer to hot water side. At the same time, the surplus hat energy is rejected to the outdoor via the condenser.
- Low cooling and high heating demand: The energy absorbed from chilled water side is fully recovered by the heat exchanger and transfer to hot water side. At the same time, the air heat exchanger absorbs heat energy from outdoor air to provide an extra heat source to meet the heat load.

5.5 Case Study—Hotel

The system is targeted to supply chilled water in summer and hot water in winter for the PAU to serve the corridors of 16 floors of the hotel, and hot water for all guest rooms. The demand can be fluctuated as the demand of hot water is high during winter, and demand of chilled water is huge during summer. Under such circumstance, the advantages of using total energy heat pump include:

- Maximize saving when using heating and cooling mode to produce hot water and chilled water simultaneously,
- Flexible in operations to shift one or more circuits from heat recovery water-to-water operations to cooling only mode in summer or heating only mode in winter,
- Enable shifting between operating mode automatically via built-in control system, and
- Save initial investment cost to install total energy heat pump instead of air-to-water and water-to-water heat pump separately.

It is essential to determine the demand of cooling and heating for the total energy heat pump system in the initial stage. The loading calculation is listed as follows:

- Cooling load calculation: Chilled water loading for PAU (primary air handling unit) is 48 kW per unit. Cooling load of fully opened fan coil is 6 kW per unit. With the operations of 2 units of PAU and 16 units of fan coil, the total cooling load is 192 kW (i.e., 48 kW $\times$ 2 + 6 kW $\times$ 16).
- Heating load calculation:
  - Total heating loading for each PAU is 44 kW per unit. With the operations of 2 units of PAU, the heating load for the 2 units of PAU is 88 kW.
  - The calculation of hot water heating capacity is based on 90% of 336 rooms with 1.5 guests per room (GPR). Other assumptions: water consumption per guest (Q) = 80 L; diversity (DF) = 0.8; city water temp (CWT) = 15 °C; hot water temp (HWT) = 65 °C; shower outlet temp (SWT) = 40 °C; peak hour consumption is 20% of total water consumption:
    Total water consumption (Q_t) =
    $336 \times 90\% \times \text{GPR} \times Q \times \text{DF} = 29{,}030$ L
    Hot water consumption (Q_{ch}) =
    $Q_{\text{t}} \times (\text{SWT} - \text{CWT})/(\text{HWT} - \text{CWT}) = 14{,}515$ L
    Energy required in kW =
    $[Q_{\text{ch}} \times 4.18 \times (\text{HWT} - \text{CWT})] \times 0.2/3600 = 169$ kW
- The total demand load is:

  Cooling load: 48 kW $\times$ 2 + 6 kW $\times$ 16 = 192 kW
  Heating load: 44 kW $\times$ 2 + 169 kW = 213 kW.

The system design is 1 unit on-duty and 1 unit for standby. The total energy heat pump is a combination of air source heat pump and water source heat pump. The heat pump is capable to produce chilled water and hot water to meet the cooling and heating demand simultaneously. The operations can also be shifted to an air-cooled chiller unit and a hot water heat pump. The total energy heat pump is designed to cool chilled water from 12 to 7 °C and to heat hot water up to 65 °C simultaneously. Each unit consists of two circuits which can be operated independently. The capacity of each unit is:

Operating mode	Capacity (kW)	Power input (kW)	Chilled water (inlet/outlet)	Hot water (inlet/outlet)
HA: Heating only (air-to-water)	250	116	N/A	60 °C/65 °C
CA: Cooling only (air-to-water)	213	77	12 °C/7 °C	N/A
WW: Heating (water-to-water)	267	106	12 °C/7 °C	60 °C/65 °C
WW: Cooling (water-to-water)	161			

The heat pump system can operate under various operating modes. Operating modes of the total energy heat pump include:

- Heating mode: The heat pump operates as air source heat pump to provide hot water when there is no demand for cooling.
- Heat recovery mode: The heat pump operates as water-to-water heat pump to provide chilled water and uncontrolled hot water simultaneously
- Cooling mode: The heat pump operates as air-cooled package chilled when there is no demand for heating
- High cooling and low heating mode: The energy absorbed from chilled water side is partially recovered by the heat exchanger and transfers to hot water side; the surplus heat energy is rejected to the ambient air via air condenser.
- Low cooling and high heating mode: The energy absorbed from chilled water side is fully recovered by the heat exchanger and transfers to hot water side, and at the same time, the air heat exchanger absorbs heat energy from outdoor air to provide extra heat energy to meet the total heat load.

References

1. Adhikari RS, Aste N, Manfre M, Marini D (2012) Energy saving through variable speed compressors heat pump systems. Energy Procedia 14:1337–1342
2. Calm JM (1987) Heat pumps in the USA. Int J Refrig 10:190–196
3. Rajapaksha L (2007) Influence of special attributes of zeotropic refrigerant mixtures on design and operation of vapour compression refrigeration and heat pump system. Energy Convers Manag 48(2):539–545
4. Comkali K, Simsek F, Comakli O, Sahin B (2009) Determination of optimum working conditions R22 and R404A refrigerant mixtures in heat pumps using Taguchi method. Appl Energy 86(11):2451–5458
5. Liu Z, Li X, Wang H, Pang H (2008) Performance comparisons of air source heat pump with R407C and R22 under forsting and defrosting. Energy Convers Manag 49(2):232–239
6. Han DH, Lee KJ, Kim YH (2003) Experiments on the characteristics of evaporation of R410A in brazed plate heat exchangers with different geometric configurations. Appl Therm Eng 23(10):1209–1225
7. Chen WA (2008) A comparative study on the performance and environmental characteristics of R410A and R22 residential air conditioners. Appl Therm Eng 28(1):1–7
8. Lu L, Cai W, Xie L, Li S, Soh YC (2005) HVAC system optimization: in-building section. Energy Build 37:11–22
9. Lbrahim O, Fardoun F, Younes R, Louahlia-Gualous H (2014) Air source heat pump water heater: dynamic modelling, optimal energy management and mini-tubes condensers. Energy 64:1102–1116
10. Bertsch S, Groll EA (2008) Two stage air-source heat pump for residential heating and cooling applications in northern U.S. climates. Int J Refrig 31:1282–1292
11. Hajidavalloo E, Eghtedari H (2010) Performance improvement of air-cooled refrigeration system by using evaporatively cooled air condenser. Int J Refrig 33:982–988
12. Ozgener O (2005) Experimental performance analysis of a solar assisted ground-source heat pump green hose heating system. Energy Build 27:101–110
13. Hepbasil A, Kalinci Y (2009) A review of heat pump water heating systems. Renew Sustain Energy Rev 13(6/7):1211–1229

14. Guillermo EVO, Ochoa SLC, Milled de Jesus PN (2018) Application of a genetic algorithm to optimize the energy performance of a vapor compression refrigerant system. Contemp Eng Sci 11(25):1245–1254
15. Li YW, Wang RZ, Wu JY, Xu YX (2007) Experimental performance analysis of a direct expansion solar assisted heat pump water heater. Appl Therm Eng 27:2858–2868
16. Chua KJ, Chou SK, Yang WM (2010) Advances in heat pump reviews: a review. Appl Energy 87:3611–3624
17. Wang W, Ma Z, Yang Y, Xu S, Yang Z (2005) Field test investigation of a double stage coupled heat pumps heating system for cold regions. Int J Refrig 28(5):672–679
18. Laue HJ (2006) Heat Pump. Renew Energy 3C:605–626

Chapter 6
Innovation in Heat and Cooling

Nomenclature

h	Enthalpy
$\dot{m}$	Mass flow rate
ρ	Density
D	Demand for energy (heating/cooling)
Q	Volume flow rate
w	Humidity ratio

Subscript

c	Cooling (total)
h	Heating
l	Latent cooling
ls	Latent and sensible cooling
tot	Total

6.1 Efficiency Improvement

The rapid growth of energy consumption in built environment leading to the development of energy efficiency strategies. The application of heat pump system seems to be a competitive solution to improve energy efficiency. Key components of heat pump are compressors and heat exchangers. The design of heat pump, with vapor compression refrigeration system, is to satisfy the maximum load. However, the system works at part load for most of its life [1]. Studies to explore the improvement

Y. H. V. Lun and S. L. D. Tung, *Heat Pumps for Sustainable Heating and Cooling*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-31387-6_6

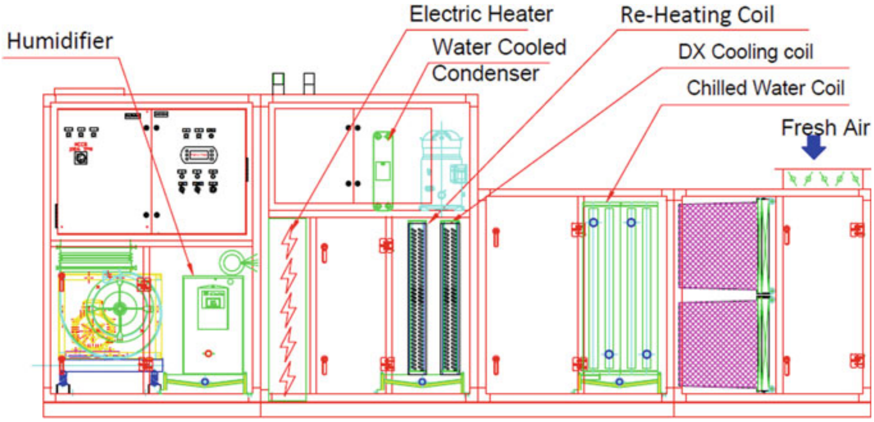


Fig. 6.1 Heat pump PAU unit

of refrigeration compressor show that the compressor speed variation is one of the most efficient techniques as capacity control methods in full-load and part-load conditions [2]. Another useful method is step-control to regulate the output capacity of compressors. The use of variable speed compressor or step-control system is useful to reduce the energy consumption because the heat pump system operates at its part load most of the time.

The cooling load and heating load vary during seasonal fluctuation. The HVAC system handles constant indoor airflow volume with variable inlet temperature and humidity level depending on outdoor weather condition [3]. The design and sizing of primary air handing unit (PAU) depend on user's requirement. Variable-speed compressors with inverter are useful for capacity control. Figure 6.1 illustrates a PAU for data center with precision control on temperature and humidity level. PAU is air handling unit that handles fresh air from outside air. Hence, the temperature and humidity level of inlet air varies according to the outside ambient air.

The heat pump PAU is an innovative heat pump with multiple-stages operations. The stages of air handling include:

- Pre-filter: Washable metal mesh filter to create a baffling effect when the outside air passing through to provide better filtration of airborne particulates.
- Bag filter: Bag filter (or pocket filter) with significantly higher dust holding capacity is used as second filter stage to provide complete filtration solutions to protect the AHU and provide clean air to occupants.
- Chilled water coil: After air filtration, ambient air passes through chilled water coil for sensible cooling.
- DX cooling coil: The processed air then passes through the DX cooling coil to cool down to dew point for dehumidification up to required humidity level.
- DX Reheating coil: Latent heat generated from DX cooling coil is recovered for reheating air up to required temperature level.

– Water-cooled condenser: Excess heat from dehumidification is rejected via water cooled condenser.
– Electric heater: Electric heat as backup when the heat generated from the DX reheating coil is insufficient to heat-up temperature to required temperature level.
– Humidifier: When outside humidity level is below required setpoint, humidifier provides humidification function.

The design of the heat pump system aims to minimize energy consumption and maximize indoor air quality. Precision control system is implemented to ensure constant temperature and constant humidity level. The innovative heat pump system includes improvements in new features to create value for efficiency operations:

– Air filtration: The system provides both washable pre-filter and high-efficiency bag filter for air clean. The fresh air passes through air filters before air handling to keep the equipment and air clean.
– Chilled water for cooling: The chilled water coil is utilized to provide sensible cooling for fresh air. The PAU aims to handle fresh air without inflow of return air to the PAU. Chilled water is capable to provide sensible cooling for fresh air when there is no demand for dehumidification.
– DX cooling coil and heating coil: The dehumidification of the fresh air is handled by the DX cooling coil by cooling the air down to dew point. The latent heat is recovered for the reheat coil to reheat the air up to the setpoint. The heat recovery system uses waste heat for air reheat. The system performs heat rejection to the chilled water cooler when excess heat is recovered. When there is huge demand for cooling and the capacity of the chilled water coil is inadequate to cope with the demand, the DX cooling can provide both latent cooling and sensible cooling.
– Heating: When there is demand for dehumidification, the DX cooling coil of the heat pump system is capable to generate latent heat. The latent heat can be recovered to provide waste heat for the DX reheat coil for air heating. When there is no demand for dehumidification, the system operates reverse cycle to absorb heat from the chilled water cooler to generate heat for space heating. Electric heater serves as a backup equipment for space heating.
– Humidity control: Humidity control consists of dehumidification and humidification. The DX system is capable to provide dehumidification to reduce the humidity level. When the humidity level of ambient is too low, the humidifier of the heat pump system can perform the humidification function.

The heat pump consists of innovative element to handle fresh air from outdoor. Innovation is the process of translating invention into product that creates value for users. Innovation involves deliberate application of initiative in deriving greater value. It also includes production process by which new ideas are generated and converted into useful product. Furthermore, the innovative product must be replicable at an economical cost and must satisfy a specific need. The heat pump PAU unit is an innovative product aims at efficiency improvement.

First, the variable speed heat pump system uses variable speed fan and compressor operations with greater energy-saving potentials [4–6]. Refrigeration capacity control of variable speed system can continuously match the compressor refrigeration capacity to the load. The capacity and COP of the heat pump system can be enhanced by using variable speed compressor [7]. Compressor operating power can also be obtained by power meter (or current/voltage transducer) to monitor the power consumption [8].

Second, the heat pump uses multiple heat exchangers including chilled water coil, DX cooling coil, and DX reheating coil. The chilled water coil is added for sensible cooling in addition to DX coil to optimize the energy consumption [9]. When there is demand for dehumidification, the DX cooling coil operates to cool the air below dew point. Latent heat generated is recovered for air reheat. Excess latent heat is rejected to chilled water cooler. When there is no demand for dehumidification and no latent heat can be generated, the heat pump system shall absorb heat from the chilled water cooler to generate heat via the DX reheating coil.

Finally, the system aims to provide an energy efficiency constant temperature and humidity control. The system requires a control system to regulate the operations of compressor, fan, and other components. An integrated direct digital control (DDC) provides an approach to improve the energy efficiency [10]. DDC is the use of digital device in conjunction with sensors an actuator to provide system control. DDC is a combination of both hardware and software. The controller is programmable controller with program features include operating schedules, set-points, control logic, timers, and alarms. The DDC consists of analog and digital inputs/outputs. Digital inputs/outputs are dry contacts from a control device to start and stop equipment. Analog inputs/outputs are a voltage or current measurement from a variable sensor (temperature, humidity, velocity, or pressure) sensing device.

6.2 Heat Recovery System

A direct expansion (DX) coil heat pump system can provide either heating with heat absorption via remote condenser or cooling with heat rejection via remote condenser. An DX-based dehumidification system with additional coil is useful to improve the indoor thermal comfort [11]. The system performs cooling and dehumidification to cool the air down to the dew point [12]. A DX air dehumidification system is an efficient way for air handling in hot and humid regions [13].

Figure 6.2 illustrates an enhanced DX system with heat recovery for efficiency improvement. The heat pump system aims to perform both air handling and water heating. When demand for cooling and dehumidification exists, the DX cooling coil performs dew point cooling and generates latent heat. The latent is recovered for space reheat via DX heating coil, and water heating via water heat exchanger.

For air handling, the inlet air passes through the DX cooling coil. The cooling process consists of both sensible cooling and latent cooling. According to Fig. 6.3, the demand for sensible cooling (D_s) is from point A to point B and the demand for total cooling (D_{tot}) is from point A to point C. The total demand for cooling include

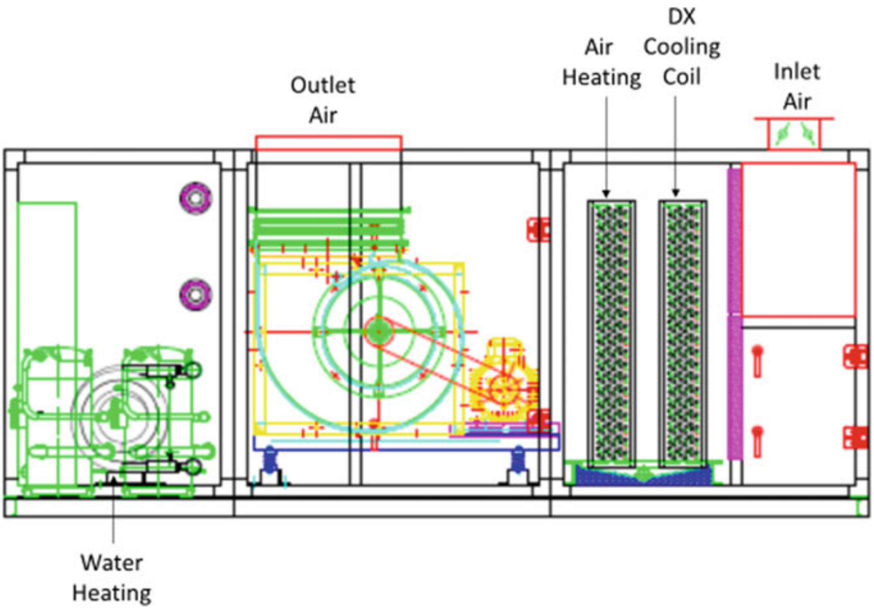


Fig. 6.2 Heat recovery system

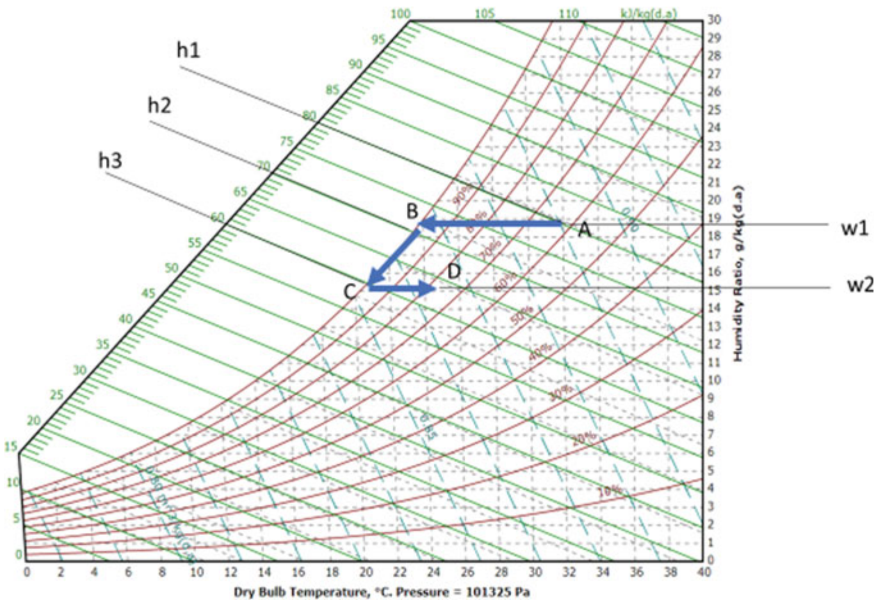


Fig. 6.3 Sensible cooling and latent cooling

sensible cooling and latent cooling. The total moisture removed through dew-point dehumidification is $(w_1 - w_2)$.

The cooling demand required is:

$$D_s = \dot{m} \times (h_2 - h_1) \tag{6.1}$$

$$D_{tot} = \dot{m} \times (h_3 - h_1) \tag{6.2}$$

where D_s is the demand for sensible cooling, D_{tot} is the demand for total cooling, and $\dot{m}$ is the mass flow rate.

During the dehumidification process, latent heat can be recovered. The latent is recovered for air reheat up to the temperature setpoint for distribution to indoor air supply air duct. The excess latent heat is utilized for water heating for domestic water usage. The advantage of the heat recovery system is to reuse low-grade waste heat [14]. On the one hand, the heat recovery system reuse waste heat to contribute to remove undesired by-product of the cooling and heating system. On the other hand, the heat recovery system improves the overall system efficiency.

6.3 Air-to-Air Heat Exchanger

Studies on heat pump system for green building are focused on the topics of indoor air quality, thermal comfort, energy saving, and environmental protection [15]. The installation of air-to-air heat exchanger in heat pump system is capable to address all these topics. Air-to-air heat exchanger aims to perform energy recovery from exhaust air before discharging to outdoor. There are experimental and theoretical investigations on air-to-air heat exchanger for energy recovery [16]. The energy recovery system is particularly useful in tropical regions where inlet fresh air at high ambient temperature could be pre-cooled by room temperature exhaust air stream before entering to the heat pump [17].

Heat exchanger is equipment used for transferring energy from one medium to another. When the medium passes through the two sides of the heat exchanger is air, the heat exchanger is called air-to-air heat exchanger. The benefit of using air-to-air heat exchanger for energy recovery is that hot or cold air can be transported through a cross-sectional area with no additional power input to the system except for the fan power to drive the air streams [18]. Figure 6.4 illustrates the air side 1 and air side 2 of an air-to-air heat exchanger. Table 6.1 illustrates an example of energy balance of the air-to-air heat exchanger. The air-to-air heat exchanger is capable to recover energy from exhaust air for sensible cooling.

The use of air-to-air heat exchanger for cooling and heating is the most energy efficiency. Figure 6.5 illustrates an example of air-to-air heat exchanger to handle sensible loads. According to Fig. 6.6, the inlet air temperature is 32 °C and the relative humidity is 80%. After the inlet air passes through the air filter, the sensible

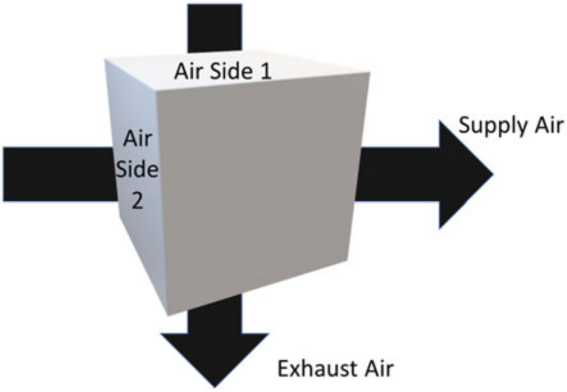


Fig. 6.4 Air side of air-to-air heat exchanger

Table 6.1 Energy balance of air-to-air heat exchanger

	Air side 1		Air side 2	
	Inlet	Outlet	Inlet	Outlet
Air flow rate (m^3/s)	3.8	3.8	3.8	3.8
Temperature (°C) (DB/WB)	12.5/11.94	24.05/16.36	30.6/25.0	22.3/21.94
Relative humidity (%)	97	45.4	63.9	97
Enthalpy (kJ/kg)	33.938	45.739	76.068	64.270
Velocity	2.5	2.5	2.5	2.5
Heat transfer (kW)	55		55	

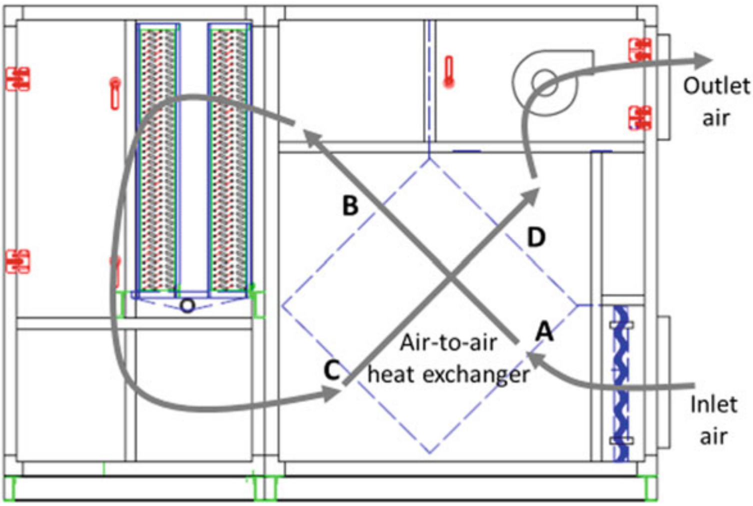


Fig. 6.5 Air-to-air heat exchanger for energy recovery

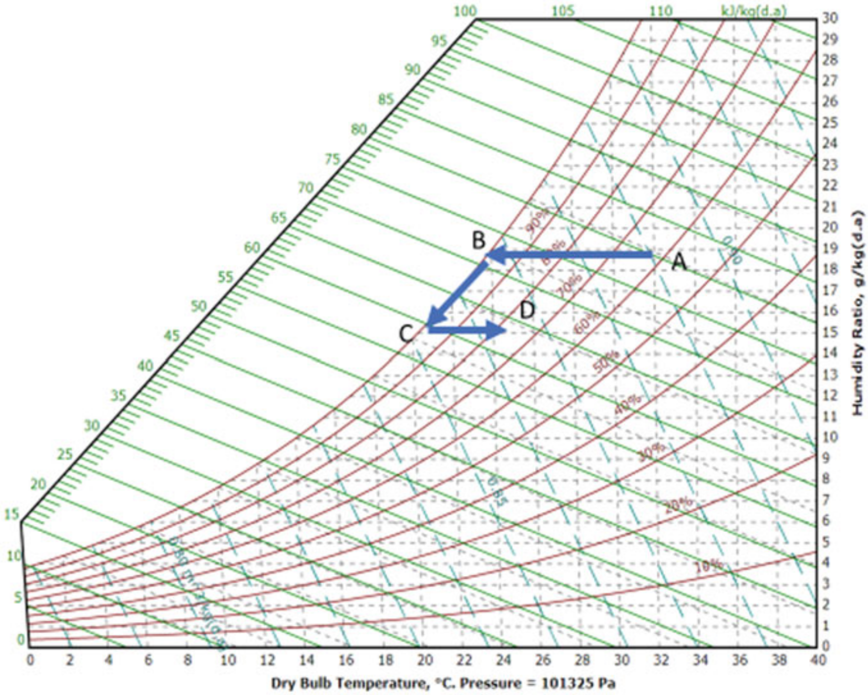


Fig. 6.6 Psychometric chart of cooling and heating recovery system

cooling is performed by the air-to-air heat exchanger to cool the air from point A to point B (i.e., from dry-bulb temperate 32 to 24 °C with the same humidity ratio). The processed air then passes through the DX cooling coils for dehumidification. The humidity ratio drops from point B (19 g/kg) to point C (15 g/kg). The air-to-air heat exchanger then performs air sensible heating to raises the temperature from point C (dry-bulb temperature 21 °C) to point D (dry-bulb temperature 24 °C).

The operations of the heat pump system include:

- D_s, i.e., sensible cooling from point A to point B by air-to-air heat exchanger for energy recovery,
- D_l, i.e., dehumidification from point B to point C via DX cooling coil, and
- D_h, i.e., sensible heating from point C to point D before exhaust to outdoor.

The energy recovery system uses air-to-air heat exchanger to perform the sensible cooling for energy saving. The DX cooling coil of the heat pump handles the dehumidification instead of total demand.

6.4 Multiple-Stage Cooling Heat Pump

Heat pump is a highly attractive energy conversion device as an effective and efficient means to reduce overall energy consumption. Nowadays, heat pumps are used for space heating and cooling and hot water production. There is a diverse demand for heating and cooling at different temperature levels [19]. The applications are common in food refrigeration industry or storage for special products.

The basic heat pump system consists of a single-stage compressor, a condenser, an expansion valve, and an evaporator. In addition to energy recovery system, multistage cooling cycles have developed for improving performance. Multistage cooling cycle aims to cope with large temperature differences between source and sink [20]. Multiple-stage cooling cycles gather and deliver heat at multiple temperature level using multiple evaporators. There are configurations that use only one compressor with two or more evaporators operating at different temperature levels.

Figure 6.7 illustrates an example of innovative multistage cooling cycles heat pump with air-to-air heat exchanger. The design of this heat pump aims to address several challenges. First, the indoor environment is a cold room to storage special product with temperature at 0 °C. Second, fresh air is required in the air circulation system. Third, the cold room is located at hot and humid region with high temperature and high humidity level. The heat pump system also aims at energy efficiency.

As shown in Table 6.2, the operating cycles of the multistage cooling cycles heat pump with air-to air-heat exchanger consist of four stages:

- Stage 1 (air-to-air heat exchanger): The return air flow rate of this system is 1000 l/s. Part of the return air (flow rate: 220 l/s) passes through the air-to-air heat exchanger and part of return air (flow rate: 780 l/s) transports to the air mixing section. Part

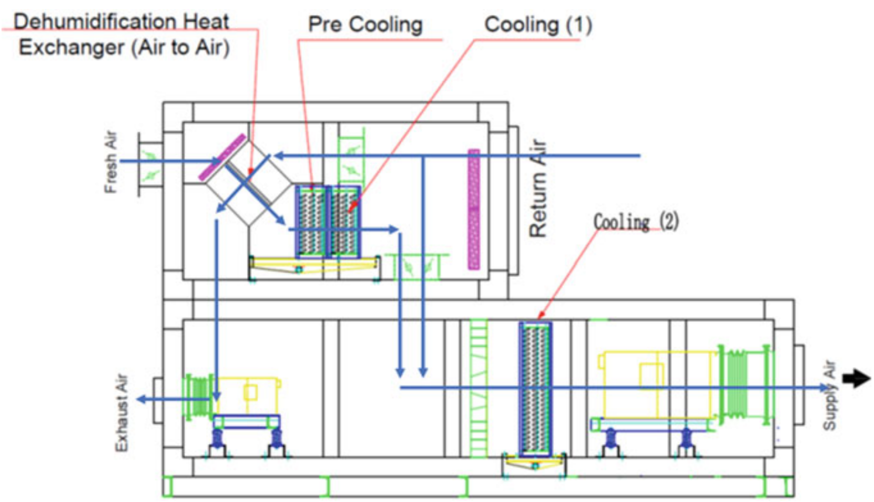


Fig. 6.7 Multistage cooling cycles heat pump with air-to-air heat exchanger

Table 6.2 Stages of operating cycles

Stage	Air flow rate (l/s)	Inlet temperature	Outlet temperature	Operating capacity
1	220	36.1 °C DB 36.1 °C WB	14.2 °C DB 13.9 °C WB	Air-to-Air Heat Exchanger
2	220	36.1 °C DB 36.1 °C WB	8 °C DB 7.5 °C WB	7.7 kW
3	220	8 °C DB 7.5 °C WB	0 °C DB −0.16 °C WB	2.4 kW
4	1000	0 °C DB −0.16 °C WB	−5.5 °C DB −5.5 °C WB	7.8 kW

Notes Supply air = 1000 l/s; Return air = 1000 l/s; Exhaust air = 220 l/s; Fresh air = 220 l/s

of the return air (flow rate: 220 l/s) passes through side 1 of the air-to-air heat exchanger before exhaust to outside, and the fresh air (flow rate: 220 l/s) passes through side 2 of the air-to-air heat exchanger. The air-to-air heat exchanger serves as energy recovery from return air for dehumidification purpose.

- Stage 2 (DX cooling coil): Fresh air (flow rate: 220 l/s) passes through the pre-cooling coil to cool down the fresh air and removes most of the water content.
- Stage 3 (DX cooling coil): Fresh air (flow rate: 220 l/s) passes through the cooling coil to further cool down the fresh air and removes water content down to required level.
- Stage 4 (DX cooling coil): Fresh air mixed with return air in the mixing. The mixed air (flow rate: 1000 l/s) passes through the final cooling coil and supply the air at setpoint to the designated area.

There are several advantages of this multistages cooling heat pump. First, an air-to-air heat exchanger is included in the system for energy recovery. Second, the hot and humid fresh air is handled in Stages 2 and 3 before mixing with return air. Finally, the mixed air is handled in Stage 4. The overall design to maximize the energy saving and optimize the operations of each stage.

6.5 Case Study—Heating and Cooling Recovery System

The heating and cooling recovery system is a heat pump system makes up of a heat exchanger, a cooling coil and a supply fan, and the schematic of which is shown in Fig. 6.8. The air-to-air heat exchanger has two nodes of air. The heat exchanger is on one hand to cool and dehumidify the air at Air node 1, and on the other hand to heat the air at Air node 4. The air-to-air heat exchanger aims to transfer the heat from Air node 1 to Air node 4. The DX cooling coil performs the function of cooling and dehumidifying the air at Air node 2. It should be noted that, due to fan motor efficiency, some heat will be added to the air when flowing through the supply fan.

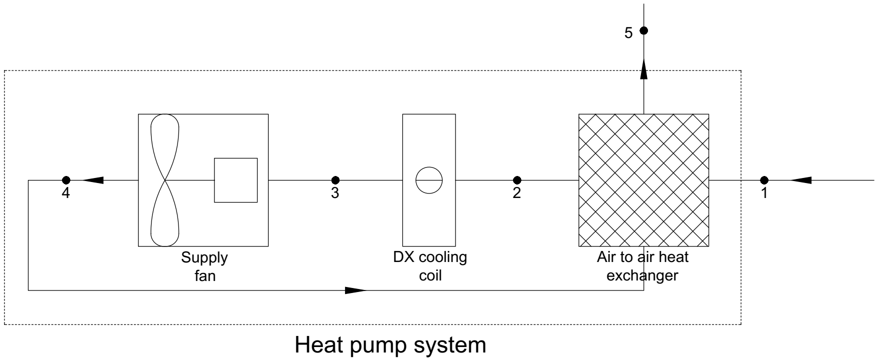


Fig. 6.8 Schematic of the heat pump system

The air states for the air nodes shown are drawn in psychrometric chart. As shown in Fig. 6.9 and Table 6.3, the air process of the heat pump system is specified as below:

- Stage 1, i.e., Air node 1 → Air node 2: cooled and slightly dehumidified by the heat exchanger,
- Stage 2, Air node 2 → Air node 3: cooled and dehumidified by DX cooling coil,

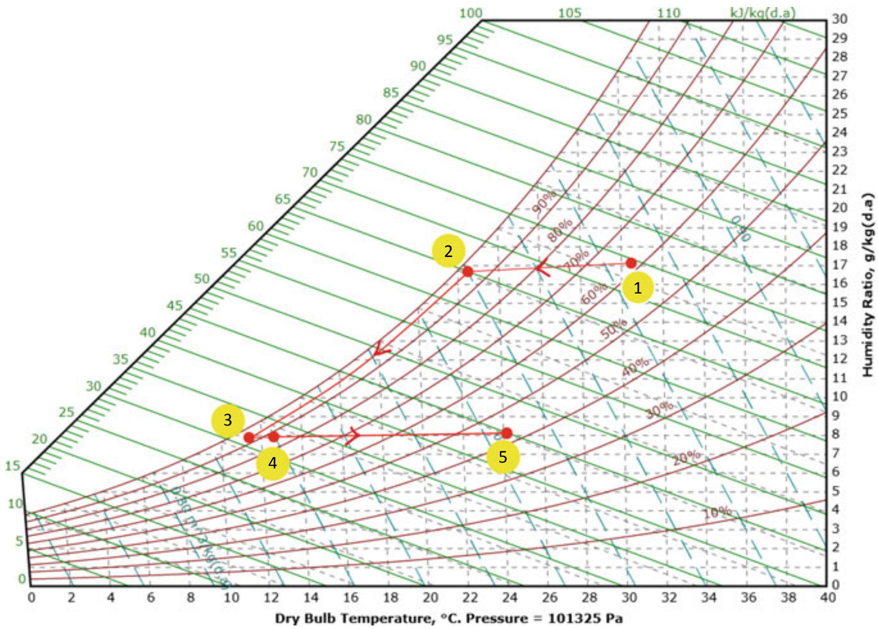


Fig. 6.9 Air states of different air nodes in psychrometric chart

Table 6.3 Air states of the five air nodes

Air node	Dry-bulb temperature, T_{db}	Wet-bulb temperature, T_{wb}	Humidity ratio, w	Enthalpy, h	Air flow rate, Q
	(°C)	(°C)	(kg/kg dry air)	(kJ/kg dry air)	(m^3/s)
1	30.60	25.00	0.01771	76.068	3.8
2	22.30	21.94	0.01645	64.270	3.8
3	12.00	11.73	0.00846	33.427	3.8
4	12.50	11.94	0.00846	33.938	3.8
5	24.05	16.36	0.00846	45.739	3.8

- State 3, Air node 3 → Air node 4: heated by the supply fan due to heat-producing fan motor,
- Stage 4, Air node 4 → Air node 5: heated by the heat exchanger.

Stage 1 aims to use air-to-air heat exchanger for energy recovery. In the first side, the inlet air passes through the one side of the air-to-air heat exchanger. Stage 2 uses DX cooling coil for cooling and dehumidification. The DX cooling coil is connected with other heat pump components including compressor, expansion valve, and remote condenser. The next stage is passing through supply air. The final stage is the outlet air passes through the other side of the air-to-air heat exchanger.

Based on the air states for the five air nodes, moisture load, and cooling load can be calculated from the following equation:

$$\text{Moisture load} = (w_1 - w_2) \times Q \times \rho$$

$$\text{Cooling load} = (h_2 - h_3) \times Q \times \rho$$

where
Q is volume flow rate
ρ is density
w_1 and w_1 is humidity ratio at node 1 and node 2
h_2 and h_3 is enthalpy at node 2 and node 3.

For heat exchanger, heat loss for air side 1 should be identical to heat gain for air side 2, the equation of which is defined as:

$$\text{Heat loss} = (h_1 - h_2) \times Q \times \rho$$

$$\text{Heat gain} = (h_4 - h_5) \times Q \times \rho$$

where
h_1 and h_2 is enthalpy at node 1 and node 2
$h4$ and $h5$ is enthalpy at node 4 and node 5

Table 6.4 Load calculation summary

Load calculation		Value
Moisture load kg/h: 1 → 3		155.03
Cooling load kW: 2 → 3		143.57
Heat transfer for heat exchanger (kW)	Side 1: 1 → 2	54.92
	Side 2: 4 → 5	−54.93

Q is volume flow rate
ρ is density.

The results are summarized in Table 6.4. As seen, calculated values of moisture load and cooling load approximate the designed capacities and energy balance is achieved for the heat exchanger:

References

1. Aprea C, Mastrullo R, Ronno C (2004) Fuzzy control of the compressor speed in a refrigerant plan. Int J Refrig 27:639–648
2. Zubair SM, Bahel V (1989) Compressor capacity modulation schemes. Heating Pip Air Conditioning 1989:135–143
3. Canby CS, Hepbasli A, Gokcen G (2004) Evaluating performance indices of a shopping centre and implementing HVAC control principles to minimize energy usage. Energy Build 36:587–598
4. Ahem O (1991) DDC applications in variable-water systems. ASHARE Trans 97(1):751–758
5. Tillack L, Rishel JB (1998) Proper control of HVAC variable speed pumps. ASHARE J 40(11):41–47
6. Bynum H, Merwin E (1999) Variable flow: a control engineer's perspective. ASHARE J 41(1):26–30
7. Yan G, Jia Q, Bai T (2016) Experimental investigation on vapor injection heat pump with a newly designed twin rotary variable speed compressor for cold regions. Int J Refrig 62:232–241
8. Guo Y, Li G, Cheng H, Hu Y, Shen L, Li H, Hu M, Li J (2017) Development of a virtual variable-speed compressor power sensor for variable speed refrigerant flow air condition system. Int J Refrig 74:73–85
9. Wepfer WJ, Shelton SV (1990) Chilled water loop optimization. ASHARE Trans 96(2):656–661
10. Hartman TB (1995) Global optimization strategies for high-performance control. ASHARE Trans 101(2):679–687
11. Chen W, Chan M, Deng S, Yan H, Weng W (2018) A direct expansion based enhanced dehumidification air conditioning system for improved year-round indoor humidity control in hot and humid climates. Build Environ 139:95–109
12. Chen W, Chan MY, Weng W, Yan H, Deng S (2018) An experimental study on the operational characteristics of a direct expansion based enhanced dehumidification air conditioning system. Appl Energy 225:922–933
13. Liang C, Zhang L, Pei L (2010) Performance analysis of a direct expansion air dehumidification system combined with membrane-based total heat recovery. Energy 35(9):3891–3901
14. Ebrahimi K, Jones GF, Fleischer AS (2014) A review of data centre cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renew Sustain Energy Rev 31:622–638

15. Francisco M, Mario P, Eloy G, Fernando D, Ruth M (2003) Design and experimental study of a mixed energy recovery system heat pipe and indirect evaporative equipment for air conditioning. Energy Build 35:1021–1030
16. Zhang H, Zhuang J (2003) Research development and industrial application of heat pipe technology in China. Appl Therm Eng 23:1067–1083
17. Ong KS, Haider-E-Alahi M (2003) Performance of a R-137a filled thermosyphon. Appl Therm Eng 23:2373–2381
18. Mostafa A, Adb EB, Mousa MM (2007) Heat pipe heat exchanger for heat recovery in air conditioning. Appl Therm Eng 27:795–801
19. IEA (International Energy Agency) (2012) Industrial heat pump. IEA Heat Pump Centre Newsl 30(1):15
20. Dincer I, Kanoglu M (2010) Refrigeration system and application. Wiley, New York

Part III
Green Operations

Chapter 7
Operating Mode

Nomenclature

c	Concentration of pollution
$\bar{c}$	Mean of concentration
C_p	Specific heat
e_c	Concentration ventilation effectiveness
e_t	Thermal ventilation effectiveness
$\dot{m}$	Mass flow rate
Q	Energy load
t	Temperature
Δt	Different in temperature
$\bar{t}$	Mean of temperature

7.1 Heat Pump System

Heat naturally flows from high to low temperature. Heat pumps can flow heat in both directions with reversible operations. Heat pumps use relatively small amount of external energy to transfer heat from a heat source to a heat sink. Accordingly, heat pumps can transfer heat from natural heat sources (such as air and water) or from man-made heat sources (such as chilled water system and cooling tower) to buildings or industrial applications. Hence, heat pumps use renewable energy to generate cooling and heating to provide indoor comfort climate. Innovative heat pumps are introduced to provide comprehensive energy-efficiency air handling and water heating. Built-in control systems are adopted to maximize indoor air quality and minimize energy consumption. Heat pumps can be used for both heating and cooling. Innovative heat pumps combine the functions of air heating/cooling and other functions (e.g., dehumidification and air purification) to enhance indoor air

Y. H. V. Lun and S. L. D. Tung, *Heat Pumps for Sustainable Heating and Cooling*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-31387-6_7

quality. Furthermore, innovative heat pump aims to minimize the use of energy and maximize indoor comfort. Typical methods include fully utilized recovery heat and maximise the usage of existing equipment.

Basically, there are two main types of heat pump: vapor compression heat pump and absorptive heat pump. The great majority of heat pumps are operated under the principle of vapor compression cycle with the main components of compressor, expansion valve, and two heat exchangers (i.e., evaporator and condenser). On the other hand, the absorption heat pump transfers heat from a low-temperature reservoir to a high-temperature reservoir by using thermal energy [1]. Heat sources for heat pumps include air, ground, water, and others. Air-source heat pumps are the most widely used because of their flexibility and their lower installation costs [2]. The main purpose to install heat pumps is to provide indoor comfort climate. Most of the existing air source heat pumps are capable to provide space heating in winter and space cooling in summer. Because of the incentive of using renewable heat source, heat pumps are attracting more interested in the past decade. To this end, inventors work hard to improve the energy performance and functionalities of heat pumps to provide thermal comfort and indoor air quality.

Nowadays, the functions of heat pumps extend to providing energy-efficient indoor climate for users to benefit from excellent indoor quality. Existing multi-functional heat pump consists of the functions of space cooling, space heating, and water heating [3]. The innovative heat pump provides the additional functions of ventilation, air cooling and dew point dehumidification, air heating and water heating. Dehumidification is performed by cooling down the air to dew point to generate latent heat. Then, the latent heat is recovered for space and water heating. If there is no demand for dehumidification, reverse cycle operations can be applied to absorb heat from outdoor air for indoor air and space heating. Combination of functions can also be performed depending on the demand for heating and cooling.

As both energy saving and thermal comfort are important, researchers develop new and innovative ways to improve or replace existing equipment and system [4]. With improved functions and energy efficiency, heat pump installation is a direct alternative to replace existing boiler [5]. To maximize energy efficiency and indoor air climate, there are two options for heat pumps to perform heating for air and water. The first option is dehumidification and heat recovery heating, whereas the second option is reverse cycle heating. According to Chua et al. [6], heat pumps for heating and cooling can be classified into four main categories:

1. Heating only heat pumps provides space heating and water heating.
2. Heating and cooling heat pumps provide both space heating and space cooling.
3. Heat pumps water heaters dedicate to water heating
4. Integrated heat pump system provides space heating and cooling, water heating, heat recovery, and reverse cycle operations.

7.2 Dehumidification Operations

Integrated system is desirable not only because single system with built-in control is cost-effective to initial installation, but also heat pump with heat recovery system is energy saving and environmentally friendly. An option of heat recovery is to reuse recovered heat from dehumidification. This is an energy-efficiency method for heating when there is demand for dehumidification. This method removes moisture from the air by cooling it below dew point. As shown in Fig. 7.1, energy is required to change the phase of a substance. During a phase change, energy can be added or subtracted from a system. The energy is absorbed by the substance in the case of evaporation, whereas heat is released during the condensation processing. According to Datt [7], latent heat of condensation is defined as “the heat released when one mole of substance condenses expressed as kJ/kg.”

The innovative heat pump ues latent heat released from condensation for heating. Components of the heat pump to provide the functions of cooling/dehumidification and heating include fan, cooling heat exchanger, reheating heat exchanger, compressor, and other accessories. Compressors can be considered as “beating hearts” of heat pumps. To achieve a higher COP, one key approach is to reduce the energy consumption of compressors. According to Chua [6], the ranges of compressors are:

- Scroll compressors (unit capacity less than 15 R tons),
- Reciprocating compressors (unit capacity less than 20 R tons),
- Screw compressors (unit capacity between 30 R tons and 200 R tons),
- Centrifugal compressors with capacities up to 3000 R tons.

Relative humidity (i.e., the amount of moisture in the air) is critical in determining indoor comfort. High humidity leaves to stuffy feeling and overly hot, while low humidity causes dry skin and other forms of discomfort. Figure 7.2 illustrates

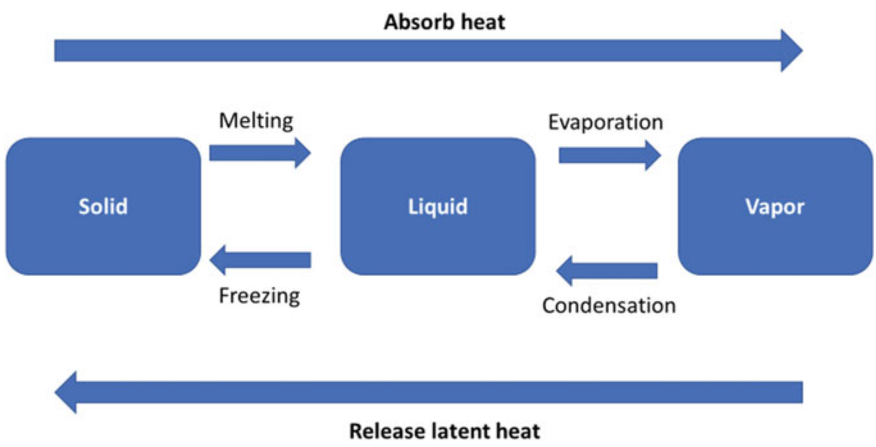


Fig. 7.1 Latent heat released during the condensation process

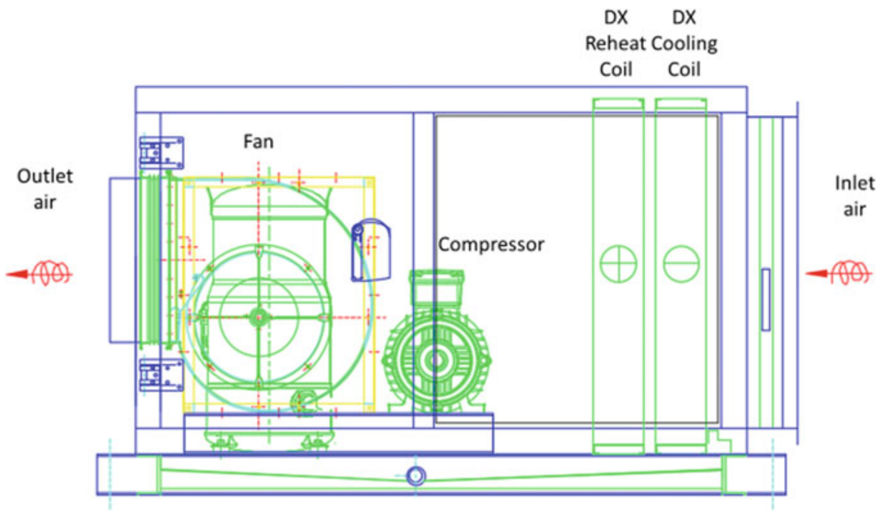


Fig. 7.2 Heat pump with dehumidification function

a heat pump with dehumidification function. The inlet air flows across the cooling coiling for direct-expansion (DX) cooling and dehumidification. The dehumidification process (i.e., condensation) is performed by the DX cooling coil through phase change by cooling air down to dew point. Latent heat can be recovered from the dehumidification process, and the latent heat is recovered for space heating. Excess recovered heat can be used for water heating or rejected to our sources.

Condensation is the process by which water vapor in the air changes to liquid water [8]. Condensation occurs in one of the two ways, i.e., the air is cooled to its dew point or the air becomes saturated. For dehumidification and cooling, the use of vapor-compression system cooling air to below dew point is the most effective technology [9]. During the process of condensation or phase change, latent heat is energy released when water vapor condenses to form liquid droplets. The latent heat is recovered for reheating through the reheating coil. The processed dry and warm air is then supplied to provide comfort indoor climate.

Due to phase change in the DX cooling coil, latent heat can be recovered during the dehumidification process. Recent studies found that heat exchanger performing phase change has higher cooling power, and latent heat can be recovered for useful energy [10]. As shown in Fig. 7.3, the latent heat can be recovered and reused for space heating to provide indoor comfort and water heating for domestic use. To design a heat pump system, it is desirable to evaluate the overall demand for energy to space cooling/heating, and water heating. The best practice to fully utilize the recovered latent heat from dehumidification before rejecting heat to outdoor. In that case, the latent heat can be recovered and reused freely instead of releasing the latent heat as waste heat.

As shown in Fig. 7.4, the remote condenser is installed with the heat pump.

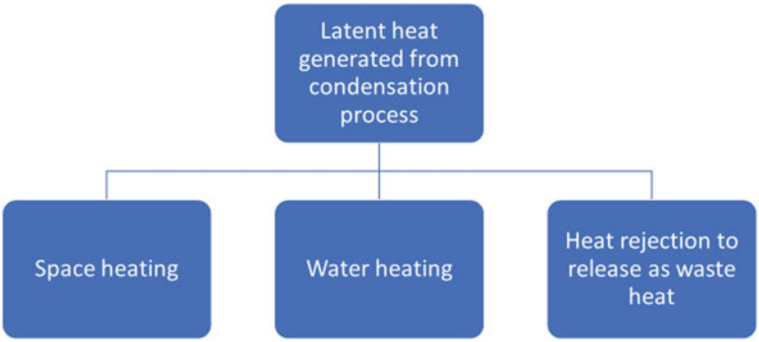


Fig. 7.3 Latent heat recovery and heat rejection

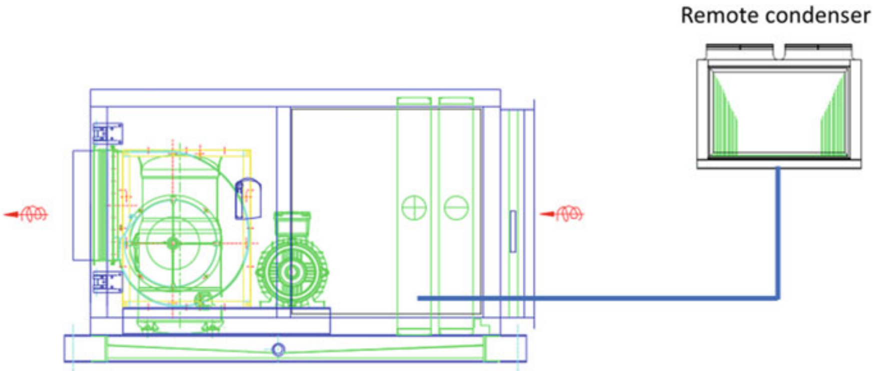


Fig. 7.4 Heat pump with remote condenser

Traditional HVAC (heating, ventilation, and air conditioning) system uses remote condenser to reject latent heat generated from cooling. The remote condenser of this innovative heat pump can perform two functions, i.e., heat rejection for residual waste heat and heat absorption for providing heat for indoor space heating. Remote condenser is useful to release residual recovered latent heat. In this state, the remote condenser performs as air-cooled condensers to remove residual waste heat by blowing air over the condenser coil. When there is no demand for dehumidification, space heating can be done by reverse cycle heating. In the state of reverse cycle heating, the remote condenser absorbs heat from outdoor cold air to perform the function of air source heat pump to provide heat via the DX reheating coil for comfort indoor air climate.

7.3 Cooling and Heating

Heat pump uses the principle of refrigeration cycle to provide cooling and heating. In cooling mode, the DX cooling coil peform cooling function to cool down the air temperature. To perform the function of dehumidification, the air is cooled down to below dew point. As air flows across the coil, the refrigerant within the refrigerant pipe absorbs latent in the air to lower the air temperature. In this state, heat pump can remove excess moisture and lower indoor humidity level. As the heat pumps remove moisture out of the air, there is an immediate drop in air temperature. Hence, the DX cooling coil can perform the functions of cooling and dehumidification. Condensation process is carried out when the air temperature is below dew point. The phase change occurs during the dew point cooling. If heating is required, the latent heat transfers from DX cooling coil to DX reheat coil for air heating. Excess heat recovered from latent is via heat rejection device.

Figure 7.5 illustrates the schematic drawing of heat pump to provide the functions of cooling, dehumidification, and heating. Control on air ventilation in managing fresh air and exhaust air dampers is also included. Natural air ventilation is important in energy saving in the building sector when the outdoor condition is comfortable. However, purely natural ventilation system is not enough to provide acceptable thermal comfort particularly in hot and humid regions [11]. The key components for air handling are DX cooling coil (i.e., cooling dehumidify) and DX heating coil for reheat. The DX cooling coil performs the functions of space cooling and dehumidification, which the DX reheat coil recovers latent heat from dehumidification (or condensation) for space heating.

In managing air movement for building, indoor air is returned to air-handling system. A certain amount of the return air is exhaust to outdoor and fresh air is intake to the system. The mixed air is then processed. The process is including air purification via air-filter, dehumidification (if required) and air cooling/heating. Supply air is the processed air delivered to the building. Then, the cycle starts again with returned air transports from the indoor room to the heat pump system for reprocessing. The air becomes stale if the same air is supplied to the room and returned to the heat pump system repeatedly. Hence, it is essential to have fresh air intake to the system and exhaust air discharge to outside.

This innovative heat pump with multiple functions and reverse cycle operations is energy conservation and energy efficiency. The elements of energy efficiency

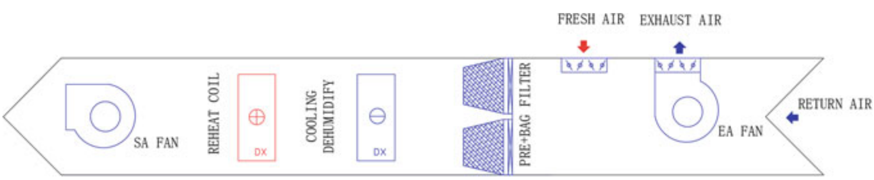


Fig. 7.5 Cooling and reheating coils

include heat recovery, reverse cycle operations, renewable energy, and built-in control system:

- Recovery heat: Latent heat can be recovered during dew point cooling dehumidification process. The latent is recovered for space and/or water heating. Recovery heat is fully utilized before rejecting excess heat via remote condenser.
- Reverse cycle operations: When there is no demand for dehumidification, reverse cycle operations are performed. In this operating mode, the remote condenser absorbs heat from outdoor air to air and water heating.
- Built-in control system: The built-in control system controls operating capacity and selects operating mode depending on the ambient environment. The built-in control system aims to maximize indoor air quality and minimize energy consumption.
- Renewable and sustainable energy: The innovative heat pump is a multifunctional air source heat pump uses air as source energy. Auxiliary energy of the heat pump is compressor and fan. Compressors are used for heat transfer through refrigeration cycle and fan performs the function of ventilation. Sustainable energy can be achieved through energy conservation and improved energy efficiency. It produces sustainable energy because the input power for heat pump is generally much less than traditional heating system.

7.4 Ventilation

The aims of ventilation in occupied space are to enhance indoor air quality and thermal comfort. Thermal comfort is associated with various indicators. Among them, the common indicators are air temperature and relative humidity. Besides thermal comfort, indoor air quality is an important parameter for human health. Inappropriate indoor air quality can cause sick-building syndrome and legionnaire disease [12]. There are two major types of ventilation, i.e., natural ventilation and mechanical ventilation. Natural ventilation is desirable when outdoor climate is appropriate because it is energy-free. Furthermore, mechanical ventilation is capable to control indoor temperature, relative humidity, and indoor air quality more precisely.

Ventilation consistently provides quality air circulation while ensuring saving energy to promote better health. Ventilation is particularly important for energy use in high-occupancy area [13]. It is important for researchers to conduct studies to holistically improve energy efficiency to not only meet existing standard for better ventilation, but also develop and promote better energy-efficient systems for providing building's ventilation [14]. Several studies have investigated the relationship of ventilation rates to health outcomes. Majority of these studies have found negative perceived air quality outcomes at lower ventilation rates and higher CO_2 concentrations. Demand control has been known to an energy-efficient and reliable strategy to provide enough fresh air to occupants. When the demand control in response to CO_2 level was implemented throughout the day, reduction of the total heating energy demand of more than 20% was realizable [15].

Ventilation is one of the most effective techniques to improve indoor air quality. Key indicator to evaluate indoor air quality is the CO_2 concentration level. The level of CO_2 concentration in the air potentially affects health is measured in ppmv (parts per million by volume). For IAQ criterion, a maximum CO_2 concentration of 1000 ppmv is commonly used as threshold [16]. Some common indicators of CO_2 level are listed as follows:

- 250–350 ppmv: normal outdoor air level.
- 350–1000 ppmv: typical CO_2 level in occupied spaces with good air exchange.
- 1000–2000 ppmv: poor air quality.
- 2000–5000 ppmv: poor concentration with potential health problems.
- >5000 ppmv: unusual air condition where toxicity could occur.
- >40,000 ppmv: immediate harmful.

To evaluate the ventilation strategies, the ventilation effectiveness (VEF, e) is commonly used [17]. Ventilation effectiveness (VEF) consists of thermal ventilation effectiveness (e_t) and concentration ventilation effectiveness (e_c).

The thermal ventilation effectiveness (e_t) can be calculated by using air temperature at the supply (t_o) and the exhaust (t_i) and the mean of room temperature ($\bar{t}$):

$$e_t = t_o - t_i/\bar{t} - t_i \tag{7.1}$$

According to Eq. (7.1), the heat is effectively remoted when the exhaust air temperature is high (holding the supply air temperature and mean of room temperature remain unchanged). Hence, the higher the e_t, the lower the energy consumption.

The concentration ventilation effectiveness (e_c) can be calculated by measuring pollution concentration at exhaust air (c_o), concentration at supply air (c_i), and the mean concentration ($\bar{c}$) at a given space:

$$e_c = c_o - c_i/\bar{c} - c_i \tag{7.2}$$

According to Eq. (7.2), e_c can be increased by reducing $\bar{c}$ and increasing c_o.

In the ventilation system, the fresh air intake is essential to improve indoor air quality. Figure 7.6 illustrates the ventilation operations of a heat pump system. The air flow processes across the heat pump system are as follows:

- Air from the indoor room is returned to the heat pump system.
- Part of the air is exhausted to outdoor.
- Fresh air from outdoor is introduced into the system.
- Fresh air mixed with return air.
- Mixed air passes through filtering system.
- Processed air is supplied to indoor room.

Maintaining optimal air circulation and temperature level is the basic of a comfortable indoor environment [18]. In the air flow system, supply air (SA), return air (RA), fresh air (FA), and exhaust air (EA) ducts operate together. The FA and the EA dampers open and close together to balance air entering and leaving the system.

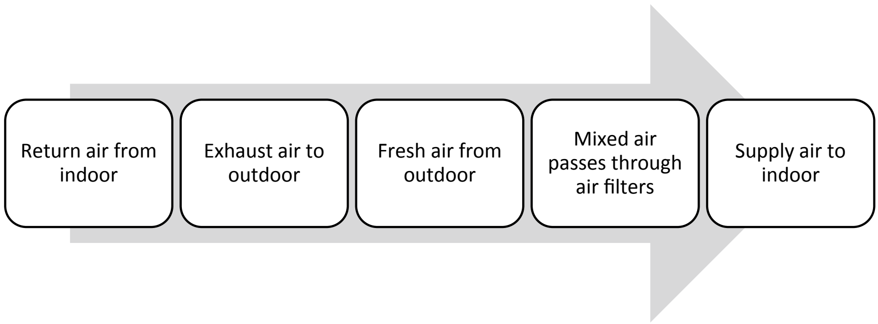


Fig. 7.6 Ventilation operating mode

A filtered fresh air intake system improves indoor air quality by diluting polluted or stale return air. Most of the heat pump systems provide two levels of filtering, i.e., pre-filter and high-efficiency bag-filter. Benefits of introducing filtered fresh air to indoor include: (1) clean indoor air when filtering return air, (2) prevent pollutants from entering the indoor air system, and (3) introduce clean fresh air to replace exhaust air.

In designing the air flow rate across the building envelope, the same amount of air is removed through exhaust air (EA) when outside fresh air (FA) enters the system. In some situations, the air pressure is controlled for exfiltration and infiltration. For instance, positive pressure prevents infiltration of outside air and other pollutants from entering the room. To maintain positive pressure, fresh air intake shall be higher than exhaust air. Under such circumstance, air exfiltration moves air out of the building. On the other hand, negative room pressure is an isolation technique for clinics or medical centers to prevent cross-contamination between rooms. If negative pressure is kept, the volume of exhaust air release to outdoor should be higher than fresh air intake. In that case, air infiltration occurs to move air into the building.

The energy impact of air infiltration has been classified as a product of the infiltration air mass flow rate, and the inside–outside enthalpy difference [19]. The expression of heat loss due to infiltrate is:

$$Q_{\text{inf}} = \dot{m}_{\text{inf}} \Delta h \tag{7.3}$$

where Q_{inf} is air infiltration energy load (W), $\dot{m}_{\text{inf}}$ is air infiltration mass flow rate (kg/s), and Δt is the difference of enthalpy.

Outside air flow into the building is driven by pressure differences. In some situations, the pressure difference is controlled for specific purposes. There are other types of air infiltration, namely concentration air infiltration and diffuse air infiltration. Concentration air infiltration is infiltration through doors and windows, while diffuse air infiltration occurs through cracks and paths overall the building envelope. Air infiltration due to air leakage plays a significant role in evaluating the heating/cooling load.

7.5 Case Study—Energy Simulation

This case study is a building energy simulation of an indoor swimming pool. It was conducted and simulated by using EnergyPlus software following the building design specifications and operating conditions. Based on the actual design, all the values affecting building cooling and heating loads were input into the simulation accordingly.

The project is located at Hong Kong, which is at climate zone 2A. The typical meteorological weather data for Hong Kong was used in the simulation for all calculations. The weather data was downloaded from EnergyPlus (https://energyplus.net/). The data is typical meteorological year (TMY) set and reflects coincident hourly data for temperature, solar radiation, humidity, and wind speed for the location. Such data covers a full calendar year (around 8760 h) and reflects coincident hourly data for temperature, solar radiation, humidity, and wind speed for the location. The climate data summary is shown in Table 7.1.

As shown in Fig. 7.7, the 3D geometry was built to calculate envelope loads of the swimming pool. The details of the indoor swimming pool are:

- Area: 257 m^2,
- Height: 1.6 m,
- Volume: 411.2 m^3.

The building design parameters of the swimming pool being modeled were inputted in EnergyPlus software. The values of the building design parameters are summarized as follows:

- Indoor air design conditions: The indoor air temperature was set at 29 °C which is 1 °C higher than pool water. For relative humidity of indoor air, it was maintained between 60 and 65%.
- Lighting load: 17 W/m^2 was used.
- Equipment load: 1 W/m^2 was used.
- Occupancy: For occupancy density, 3 m^2/person for indoor swimming pool.
- Fresh air rate: According to ASHRAE standard 62.1, outdoor air ventilation rate was set at 12 L/s per person to provide acceptable air quality in the swimming pool.
- Envelope information: U-value for envelopes can be automatically calculated in EnergyPlus Software.

The results are summarized in Table 7.2 with the maximum value of air flow rates, cooling and heating loads, and pool water heating load calculated from EnergyPlus model:

Table 7.1 Summary of climate data

Parameter	Value
Site: location	Hong Kong
Latitude	{N 22° 19′}
Longitude	{E 114° 10′}
Time zone	{GMT +8.0 h}
Elevation (m) above sea level	65
Standard pressure at elevation	100,547 Pa
Heating design temperature 99.6% (°C)	9
Heating design temperature 99% (°C)	10.8
Cooling design temperature 0.4% (°C)	33.8
Cooling design temperature 1% (°C)	33
Cooling design temperature 2% (°C)	32.2
Maximum dry bulb temperature (°C)	32.8
Maximum dry bulb occurs on	Jul 1
Minimum dry bulb temperature (°C)	9.2
Minimum dry bulb occurs on	Dec 17
Maximum dew point temperature (°C)	27.6
Maximum dew point occurs on	Sep 21
Minimum dew point temperature (°C)	−5.0
Minimum dew point occurs on	Dec 24
ASHRAE handbook 2009 cooling degree days (base 10 °C)	5114
Weather file cooling degree-days (base 10 °C)	4782
ASHRAE handbook 2009 heating degree days (base 18.3 °C)	182
Weather file heating degree-days (base 18 °C)	202
ASHRAE climate zone	2A
ASHRAE description	Hot-humid

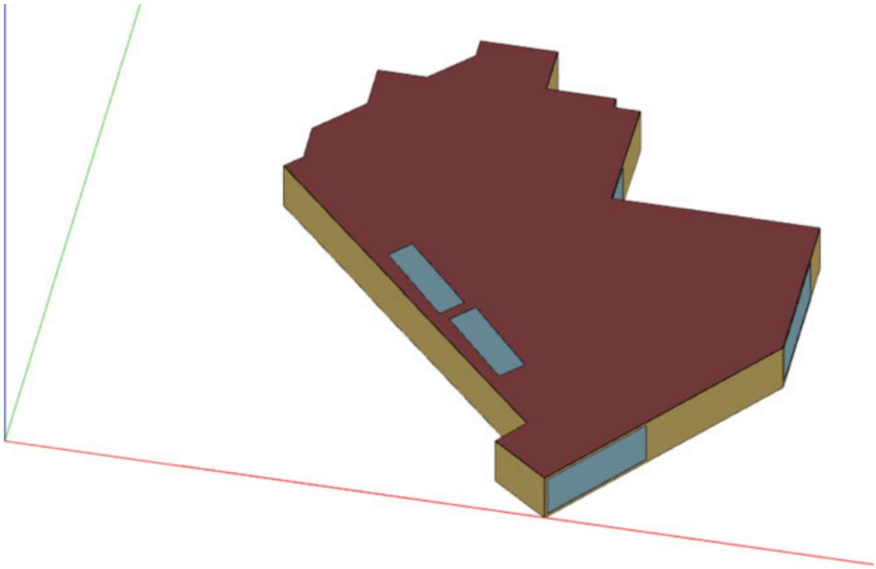


Fig. 7.7 3D geometry

Table 7.2 Maximum values during a typical meteorological year

	Winter	Summer
Air flow rate	(Heating)	(Cooling)
Supply air flow rate (m^3/s)	6.8	6.8
Fresh air flow rate (m^3/s)	1.03	1.03
Air side parameters		
(a) Dehumidification (latent) load (kg/h)	17.57	109.19
(b) Sensible heating load (kW)	60.83	
(c) Sensible cooling load (kW)		32.41
Water side parameters		
(d) Pool water heating (kW)	39.07	
Total		
Total cooling load (a) + (c) (kW)		166.06
Total heating load of heat pump (b) + (d) (kW)	99.90	

References

1. Qu M, Abdelaziz O, Yin H (2014) New configurations of a heat recovery absorption heat pump integrated with a natural gas boiler for boiler efficiency improvement. Energy Convers Manage 87:175–184
2. Bretsh SS, Roll EA (2008) Two-stage air-source heat pump for residential heating and cooling applications in northern U.S. climates. Int J Refrig 31:1282–1292
3. Kuang YH, Wang RZ (2006) Performance of multi-functional direct-expansion solar assisted heat pump system. Sol Energy 80:795–803
4. Bhullar HS, Kamboj VK (2011) Energy conservation of HVAC system with the help of fuzzy controller. Int J Sci Eng Search 2(1):1–8
5. Kelly NJ, Cockroft J (2011) Analysis of retrofit air source heat pump performance, results from detailed simulations and comparison to field trial data. Energy Build 42:239–245
6. Chua KJ, Chou SK, Yang WM (2010) Advances in heat pump system: a review. Appl Energy 87:3611–3624
7. Datt P (2011) Latent heat of condensation. In: Encyclopaedia of snow, ice and glaciers. Encyclopaedia of Earth Science Series. Springer, Netherlands
8. Yan YY, Lio HC, Lin TF (1999) Condensation heat transfer and pressure drop of refrigerant R-134a in a plate heat exchanger. Int J Heat Mass Transf 42:993–1006
9. Labban O, Chen T, Ghoniem AF, Lienhard JH (2017) Next-generation HVAC: prospects for and limitations of desiccant and membrane-based dehumidification and cooling. Appl Energy 200:330–346
10. Lazaro A, Dolado P, Marin JM, Zalba B (2009) PCM-air heat exchangers for free cooling applications in buildings: empirical model and application to design. Energy Convers Manage 50(3):444–449
11. Homod RZ, Sahari KSM, Almurib HAF (2014) Energy saving by integrated control of natural ventilation and HVAC systems using model guide for comparison. Renew Energy 71:639–650
12. Wargocki P, Lagercrantz L, Witterseh T, Sundell J, Wyon DP, Fanger PO (2002) Subjective perceptions, symptom intensity, and performance, a comparison of two independent studies, both changing similarly the pollution load in an office. Indoor Air 12(2):74–80
13. Chau KJ, Chou SK, Yang WM, Yan J (2013) Achieving better energy-efficient air condition: a review of technologies. Appl Energy 104:87–104
14. Seppanen OA, Fish WJ, Mendell MJ (1999) Association of ventilation rates and CO_2 concentrations with health and other response in commercial and institutional building. Indoor Air 9(226):252
15. Wchenfeldt B, Mysen M, Schild PG (2007) Air flow rates and energy saving potential in schools with demand-controlled displacement ventilation. Energy Build 39(10):1073–1079
16. ASHRAE 62—2004
17. Vardoompun J, Navvab M (2007) HVAC ventilation strategies: the contribution for thermal comfort, energy efficiency, and indoor air quality. J Green Build 2(2):131–150
18. Viswambharan A, Patidar SK, Saxena K (2014) Sustainable HVAC systems in commercial and residential buildings. Int J Sci Res Publ 4(4):1–4
19. Younes C, Shdid CA, Bitsuamlak G (2012) Air infiltration through building envelopes: a review. J Build Phys 35(3):267–302

Chapter 8
Reverse Cycle

Nomenclature

q Energy delivered or energy received
W Energy consumption
T Temperature
S Entropy generated due to internal irreversibility

Subscript

c Hot side (hot source)
f Cold side (cold source)

8.1 Cooling and Dehumidification

The continuing increase in energy demand and the associated negative impacts on environment leads to scientists to investigate ways to meet indoor comfort conditions with energy-efficient solutions [1]. Air source heat pumps provide cooling or heating have found increasingly applied in recent decades [2]. Air source heat pump can be connected with outdoor air coil. The functions of outdoor air coil is to reject heat when perform cooling or absorb heat from outdoor to generate heating. One of the obvious advantages of using heat pump unit is that it can generate both heating or cooling [3].

Cooling is one of the main areas of application of thermodynamics [4]. The vapor compression cycle is the most commonly used cooling cycles. Exergy analysis is useful as a tool to examine the performance in the thermodynamic process of the

Y. H. V. Lun and S. L. D. Tung, *Heat Pumps for Sustainable Heating and Cooling*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-31387-6_8

vapor compression system [5]. Exergy is a measure of the maximum useful work that can be done by a system interacting with ambient [6]. The exergy analysis combines the application of the first and the second law of thermodynamics. The first law of thermodynamics states that matter and energy must remain constant in quantity. The second law states that waste exists when energy transferred or transformed. According to Feidt [7], the first law and the second law of thermodynamics are shown in Eqs. 8.1 and 8.2, respectively:

$$q_c + q_f + W = 0 \tag{8.1}$$

where q_c is the energy delivered at the hot side, q_f is the energy received at the cold end, and W is the energy consumption.

$$q_c/T_c + q_f/T_f + S = 0 \tag{8.2}$$

where T_c is the temperature of the cycled fluid at the hot side, T_f is the temperature of the cycled fluid at the cold side, and S is the entropy generation due to the internal irreversibility.

Heat exchanger is one for the most important components of heat pumps. There are various studies on optimizing the geometry size and operating conditions of the heat exchanger to maximize the cooling effectiveness in terms of the energy efficiency of the dew point cooling system [8]. Studies also extend to the investigation on the system effectiveness at different inlet conditions including temperature, humidity, and velocity [9]. To remove moisture, all the air must be cooled below its dew point by a cooling coil. Air at the dew point temperature cannot supply to indoor directly to prevent overcooling leading to discomfort to occupants [10]. Hence, supply air is subsequently reheated by a heating coil.

The heat pump system has evolved to a mature technology over the past decade. With raising energy cost, the use of heat pump as a means of energy recovery becomes widely used in various sectors. Heat pump is the only known process that recirculates waste heat back to heat production process [11]. Figure 8.1 illustrates the heat pump with energy recovery for space reheating. The heat pump performs the functions of space cooling and dehumidification. The heat pump operations include filtering, cooling, and dehumidification. The heat pump operations can also extend to water heating.

The air handling process consists of a fan to intake return air-to-air chamber, discharge exhaust air, and mix with fresh air. The mixed air is then passed through the air pre-filter and bag filter for air filtering. Air filters protect the occupants from the negative effects of poor indoor air quality, dusts, and particles. Air filter also protects the heat pump equipment from contaminants to prevent unnecessary maintenance. Pre-filter is made of metal and is washable for low-cost maintenance. Bag filter (or called pocket filter) is constructed of a frame and contains fiberglass or synthetic media. Service life of bag filter depends on Minimum Efficiency Reporting Value (MERV) rating which is a method of stating the efficiency of a filter based on particle. The service life of bag filter can be extended with the use of pre-filter. In the

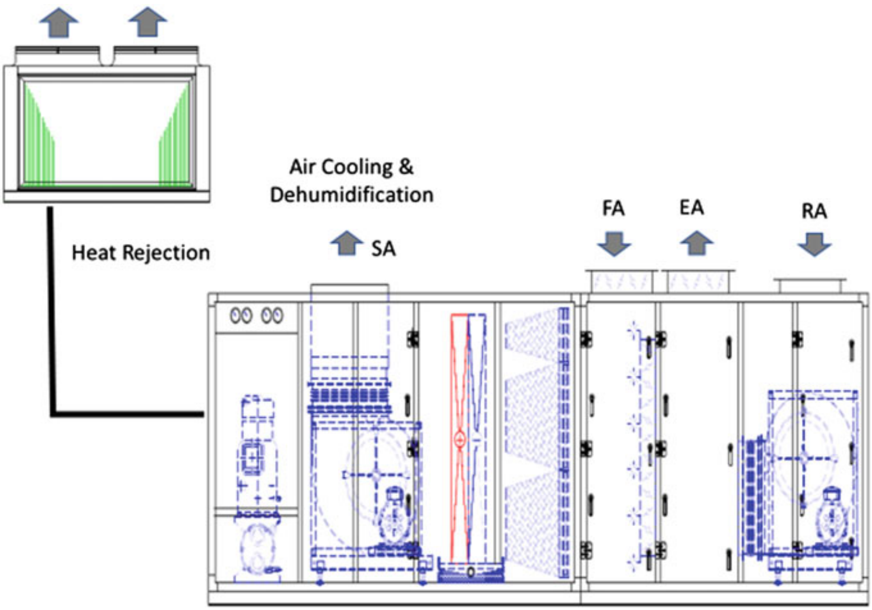


Fig. 8.1 Heat pump for space cooling and dehumidification

environments where biological or chemical particles exist, high-efficiency particulate air (HEPA) filter is often used. HEPA filter is not MERV rated as it is beyond the ASHARE standards. Common standards required for HEPA air filter is that air filter must remove at least 99.95% (EU) or 99.97% (ASME) of particles, which diameter is equal or greater than 0.3 μ, from the air that passes through.

The filtered air is then gone through the cooling and dehumidification process before supplying to indoor for thermal comfort as shown in Fig. 8.2. First, the air

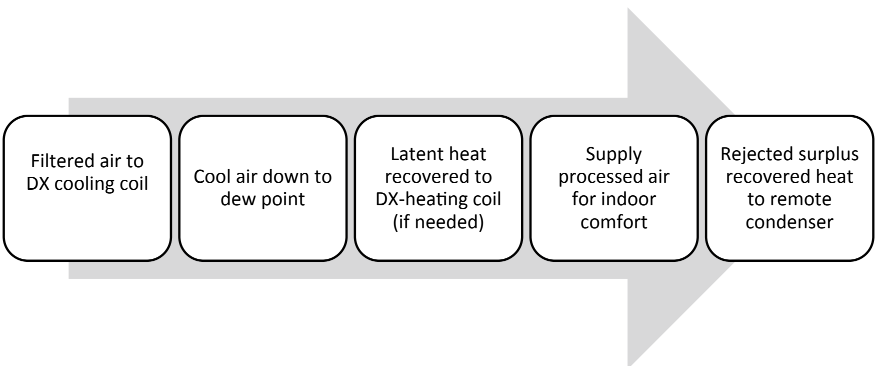


Fig. 8.2 Dew point cooling and air reheating

passes through the direct expansion (DX) cooling coil for cooling down to dew point for dehumidification. During the cooling and dehumidification process, latent heat can be recovered due to phase change from vapor to water. The latent heat is recovered for space reheat for heating air up to the setpoint, and surplus recovered heat is rejected to outdoor via remote condenser. The processed air is supplied for indoor comfort via supply air duct.

Free air cooling can be provided for energy saving when the outdoor temperature and humidity level are comfortable for occupants. To perform free cooling, the air damper insider the heat pump is closed, whereas the fresh air damper and exhaust air damper are fully opened. In that case, supply air fan becomes the fresh air intake fan, and the return air fan becomes the exhaust air fan.

8.2 Heat Recovery for Heating

Researchers have put efforts to develop innovative heat pumps meeting the needs of heating and cooling in a single system. According to Whaley [12], an integrated system which provides space heating, hot water, air dehumidification, and space cooling is an intelligent approach to maximize the system overall effectiveness and minimize the system cost. In addition to air dew point cooling, Fig. 8.3 illustrates the

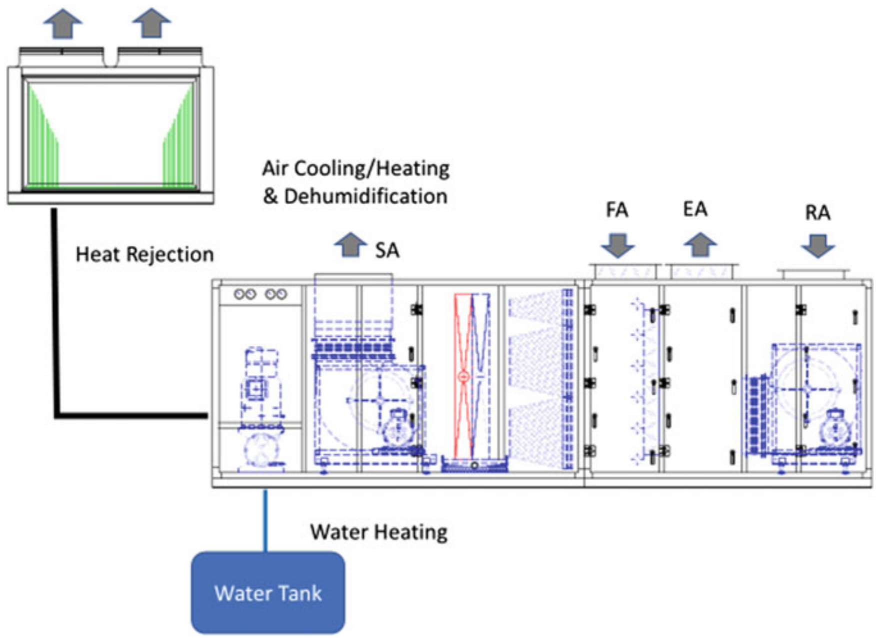


Fig. 8.3 Heat pump for space cooling/heating and water heating

use of recovery heat for heating. The heat pump system consists of indoor unit and outdoor unit. The outdoor unit is remote condenser. The remote condenser can serve dual purposes, i.e., heat rejection and heat absorption. All the modules of the indoor unit are assembled into one single vacuum tight container forming a sealed unit [13]. The indoor unit is connected to the surrounding by (1) air ducts to connect return air from indoor, discharge exhaust air, intake fresh air, and supply air to indoor, (2) refrigerant pipes to connect the heat pump with the remote condenser, and (3) water pipes to connect with hot water system.

The air source heat pump system consists of several sections:

- The first section is an air chamber with a return fan to intake return air from indoor. During the dew point cooling process, the return air serves as energy source of the air source heat pump. This chamber also performs the air exchange function to discharge exhaust air to outside and intake fresh air from outdoor.
- The second module is air filtering with two-stage air cleaning, i.e., washable pre-filter and bag filter. Air filtering plays an important role to protect the occupants from the negative effects of poor indoor air quality by preventing dusts and particles to enter to the indoor room. It also protects the heat pump equipment (including cooling coil and heating coil) from contamination.
- The third module is direct expansion (DX) cooling coil and DX heating coil. The DX cooling coil performs dew point cooling to generate cooling and latent heat during dehumidification process. The latent heat from dehumidification is recovered and discharge to DX heating coil to provide space reheating up to setpoint temperature.
- The next module is supply air chamber with supply air fan to delivery processed air to indoor for indoor thermal comfort. The delivery of supply air is via supply air duct. The most common method to determine the amount of air that needs to be supplied into a building is air change per hour (ACH). The common ACH for any commercial or industrial buildings is between 4 and 8 ACH. Depending upon the activities and level of occupancy, the total quantity of air supplied to be introduced into a building varies widely.
- The final module includes control panel, compressors, and hot water heat exchanger. The exceed waste heat recovered from dehumidification process can be discharged to the hot water heat exchanger to generate hot water.

The main functions of heat pump system are air filtering and heat exchange. Figure 8.4 illustrates the heat exchange operations of the heat pump system with water heating function:

- DX cooling coil: The mixed air passes through the direct expansion (DX) cooling coil for cooling down to dew point for dehumidification.
- DX heating coil: The latent heat recovered from dew point cooling is discharged to DX heating coil for space heating to heat air up to the setpoint temperature.
- Water heat exchanger: Exceed recovered heat is discharged to water heat exchanger for water heating.
- Remote condenser: Surplus recovered heat is rejected to outdoor through remote condenser.

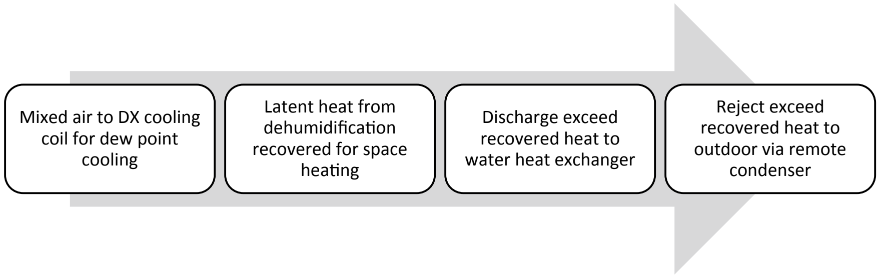


Fig. 8.4 Dew point cooling with space and water heating

8.3 Reverse Cycle Operations

In the case of dew point cooling heat pump system, latent heat is recovered for space heating and water heating. The heat recovery is dependent on the dew point cooling system. Dew point cooling is performed for dehumidification purpose. When there is no demand for dehumidification, supplementary heating equipment is needed. Heat pump can be both monovalent and bivalent [14]. A monovalent heat pump system is the system where the heat pump supplies heating and cooling for all seasons [15]. In a bivalent heat pump system, the heating capacity of heat pump may be supplemented by other heating equipment on cold days [16]. In other word, bivalent heat pump system is a system comprising heat pump and other heating equipment [11].

Many of heat pump design is bivalent system with supplementary heating equipment as backup particularly on cold climate. Traditional air source heat pumps have electric heating device or auxiliary heater to heat up the air in winter. However, the COP of electric heater is much lower than heat pump. With novel solution, reverse cycle operations can be applied to make monovalent heat pump system possible. The air source heat pump basically absorbs air from indoor (in terms of return air) and rejects the surplus air to outdoor. The heat transfer operations within the heat pump include: (1) cooling and dehumidification via DX cooling coil, (2) recovered latent heat for space heating via DX reheating and/or water heating via water heat exchanger, and (3) the residual latent heat reject to outdoor. When there is no demand for dehumidification, no latent heat can be recovered to perform space and water heating. Under such circumstance, the reverse cycle system can be operated to absorb heat from outdoor and discharge heat to heating coil for air heater and water heat exchanger for water heating.

Figure 8.5 illustrates the reverse cycle operations with the use of remote condenser for heat absorption. Instead of using return air from indoor as heat source, the reverse cycle system absorbs from outdoor via remote condenser. Hence, the remote condenser serves as heat rejection during the dew point cooling process and heat absorption at the time of reverse cycle operations. Remote condenser is usually of multicircuit structure to enhance heat transfer [17, 18].

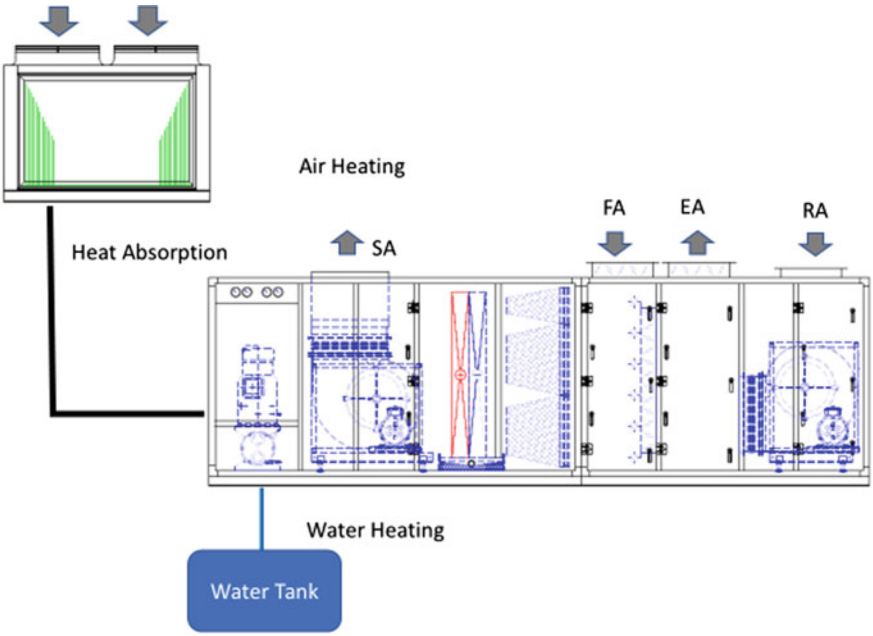


Fig. 8.5 Heat absorption for space and water heating

Heat pump operations involve the transfer of energy from a source of heat to heat sink [19]. The ratio of useful energy to electricity consumption of a heat pump at given conditions is defined as the coefficient of performance [20]. The COP of heat pump is generally higher than traditional heater. Hence, it is desirable to use monovalent heat pump system to avoid the use of supplementary heating device. The operations of heat pump are governed by the following control logic:

Condition		Heat source	Heat sink (air)	Heat sink (water)
Air temperature > setpoint	Water temperature > setpoint	N/A	N/A	N/A
	Water temperature < setpoint	Heat absorption via remote heat exchanger	N/A	Water heating
Air temperature < setpoint	Water temperature > setpoint	Heat absorption via remote heat exchanger	Air heating	N/A
	Water temperature < setpoint	Heat absorption via remote heat exchanger	Air heating	Water heating

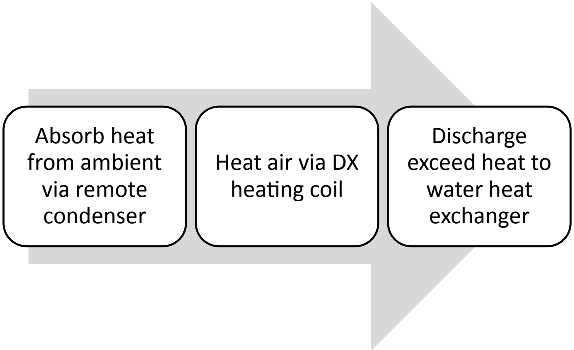


Fig. 8.6 Reverse cycle operations

Figure 8.6 illustrates the reverse cycle operations of the heat pump:

- Energy source: Remote condenser performs heat absorption as heat source of the air source heat pump.
- Space heating: DX heating coil as heat sink to receive heat generated from the heat pump for space heating.
- Water heating: Water heat exchanger as heat sink to receive heat generated from the heat pump for water heating.

8.4 Multifunction Heat Pump

Operational efficiency become important in heating and cooling. Most of the energy system rely on vapor compression cycle in which refrigerant undergoes phase changes [21]. The process of refrigeration uses the vapor compression refrigeration cycle to transfer heat from one place to another. The heat pump with reverse cycle can carry out multiple functions to meet users' requirements.

Advanced heat pump can perform multiple functions. Heat pump can serve as air handling unit to provide ventilation function. The DX cooling coil can perform dew point cooling for cooling and dehumidification. Waste heat generated from dehumidification can be recovered for space and water heating. When there is no demand for dehumidification, reverse cycle operations can be operated to generate heat for space and water heating. As shown in Fig. 8.7, the operational efficiency of the multiple functions heat pump can be viewed from the perspectives of reverse cycle operations, recover waste heat, sustainable energy, and control system.

For the reverse cycle operations, the most important component is the remote condenser. The remote condenser is a dual-purpose external heat exchanger to perform heat absorption when serving as heat source and heat rejection when serving as heat sink. The heat pump is an air source heat pump. Heat source is mixed air (i.e., quantity of return air plus quantity of fresh air minus quantity of exhaust air) when

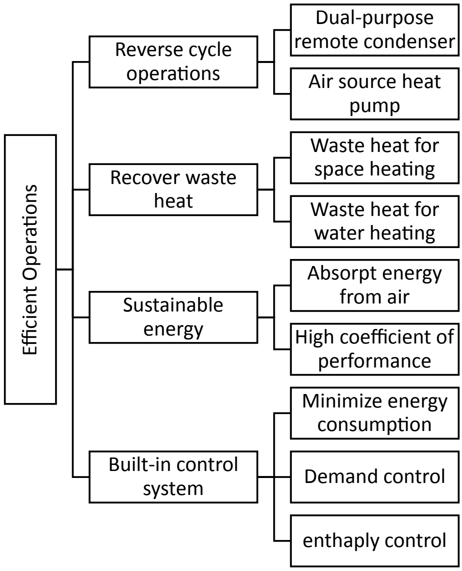


Fig. 8.7 Efficient operations of multifunction heat pump

demand for dehumidification exists. Heat source shifts to outdoor air when there is no demand for dehumidification.

The advanced heat pump recovers waste heat from dehumidification. Heat pump transfers heat from energy from air source to the DX cooling coil for cooling and dehumidification. During the dew point cooling, latent heat is generated. Latent heat is waste heat from the dehumidification process. Instead of discharging all waste heat, the heat pump recovers the waste heat and discharge to DX heating coil for space heating and water heat exchanger for water heating. Residual waste heat (if any) can be discharged to remote condenser in the form of heat rejection.

This innovative heat pump is an air source heat pump with air as source energy. From the aspect of energy sources, heat pump uses renewable energy since it uses air as energy source to provide heating and/or cooling. From the aspect of heat pump applications, it produces sustainable energy because the coefficient of performance of heat pump is higher than traditional heating equipment. In addition, the heat pump recovers waste heat for space and water heating.

The design of the heat pump aims to minimize energy consumption while meeting users' requirements. The built-in control system consists of sophisticated electronic controller and microprocessor for maximum system performance and minimum energy consumption. Moreover, the control system also provides the functions of enthalpy control and demand control for fresh air.

Function of enthalpy control can be included to the heat pump system to save energy cost. The enthalpy control can be performed under two situations. Free air cooling can be performed when (1) the outdoor enthalpy and moisture level is lower than the indoor enthalpy and (2) both the moisture level and the temperature level are comfortable for occupants.

The heat pump can also perform demand control for fresh air. A carbon dioxide concentration sensor can be installed at the return air chamber to measure the CO_2 concentration level which is an indicator of the number of the occupants in the conditioned areas. Fresh air intake rate can be adjusted by modulating air damper to provide demand control for fresh air depending on the CO_2 concentration level. Exhaust air can be proportional adjusted to maintain the air flow balance.

8.5 Case Study—Air Process

In this case study, the use of remote condenser as external heat exchanger connecting to the indoor unit with application in the indoor swimming pool is presented. The operating modes include summer mode and winter mode. Figure 8.8 illustrates the indoor thermal environmental in the indoor swimming pool in summer. The indoor climate is predicted by CFD method. In summer, the remote condenser which is the external heat exchanger is regarded as a supplementary condenser for heat rejection.

The air process of summer mode is presented in psychrometric chart. The heat pump performs the following function in summer mode: cooling and dehumidification, space heating and pool water heating. According to the air process listed in Fig. 8.9:

- The return air is mixed with outdoor hot and humid fresh air.
- The mixed air goes through the cooling and dehumidification process.

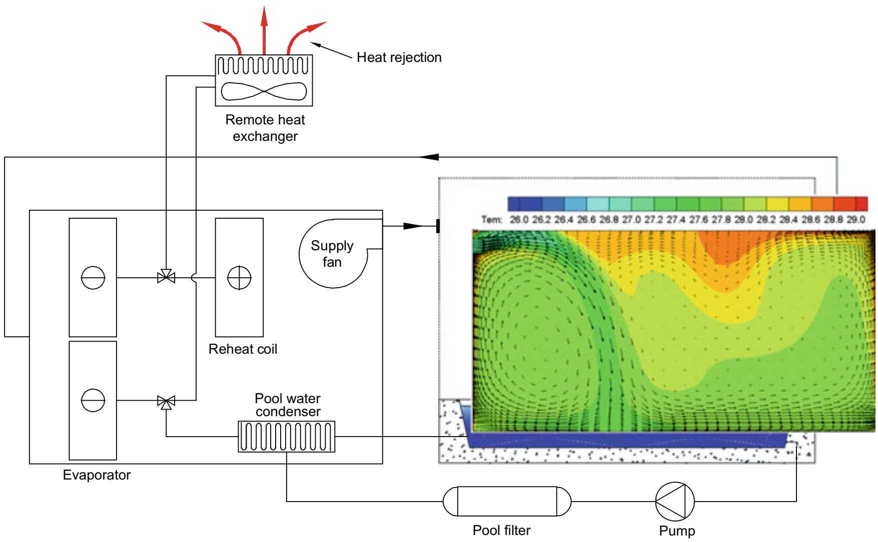


Fig. 8.8 Schematic of indoor swimming pool heat pump system in summer mode

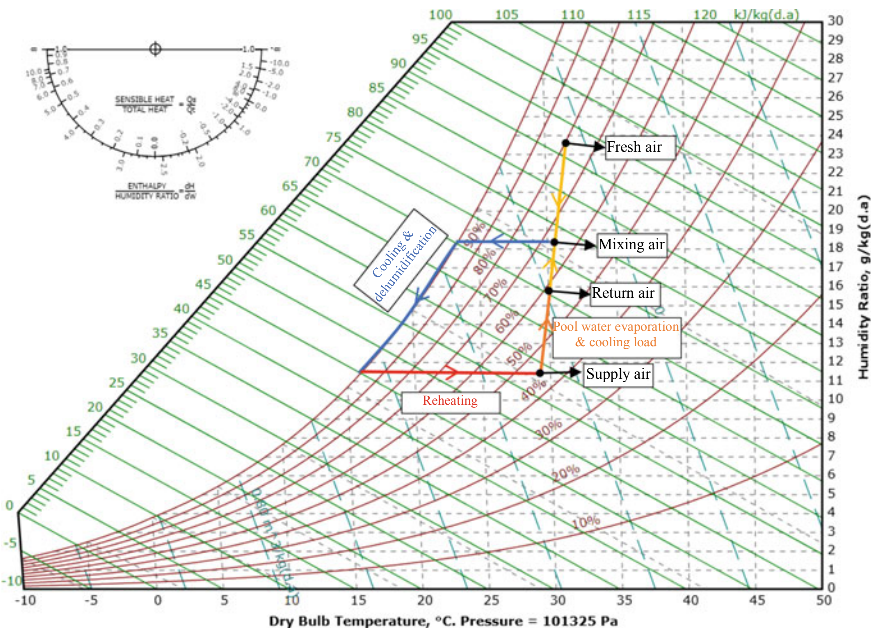


Fig. 8.9 Air process of summer mode in psychrometric chart

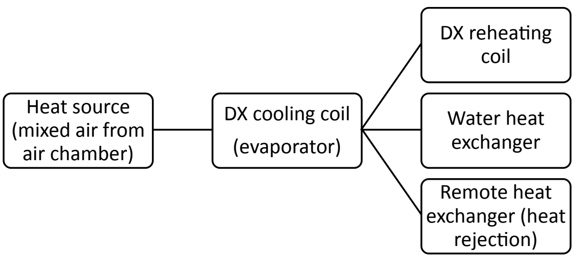
- The latent heat is recovered for space reheat and supply to the indoor swimming pool.
- The remaining latent heat is recovered for water heating.

As shown in Fig. 8.10, the latent heat recovered is sent to reheat coil for space heating and water heat exchanger for pool water. If there is still the remaining heat, heat rejection is performed by the remote heat exchanger.

Figure 8.11 illustrates the indoor thermal environmental in the indoor swimming pool in winter. The indoor climate is predicted by CFD method. In winter, the remote heat exchanger is regarded as an evaporator for heat absorption.

The outdoor ambient condition in winter is cold and dry. The functions performed by the heat pump are space heating and water heating. As there is no demand for dehumidification, no latent heat can be recovered for space and water heating. Under

Fig. 8.10 Heat transfer direction in summer mode



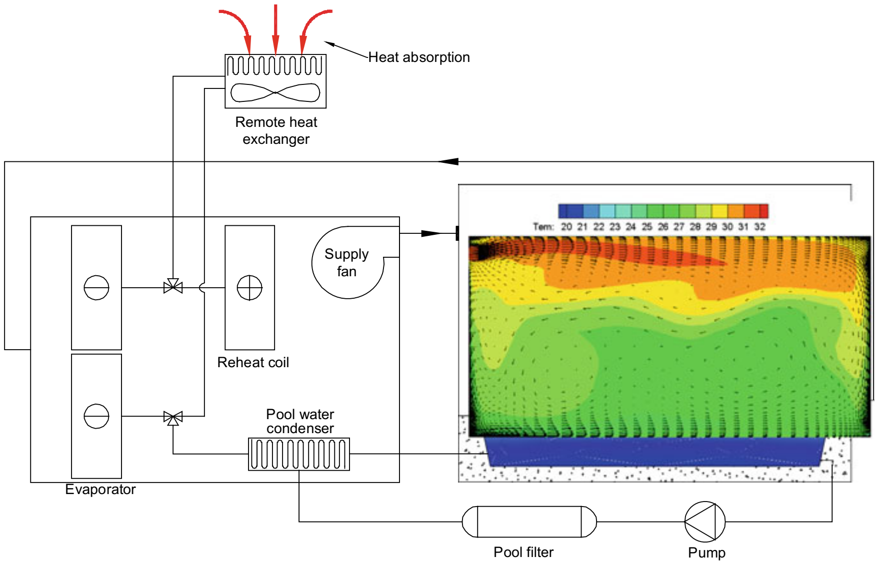


Fig. 8.11 Schematic of indoor swimming pool heat pump system in winter mode

such situation, the heat pump runs reverse cycle operations. The air process of winter mode is presented in psychrometric chart. According to Fig. 8.12, the reverse cycle process includes the following:

- Air mixing: Return air from indoor is mixed with dry and cold fresh air from outdoor.
- Air heating: Remote heat exchanger performs reverse cycle to absorb heat from outdoor to generate heat and discharges heat for space heating.
- Water heating: Remaining heat is discharged for water heating.

As shown in Fig. 8.13, the heat source of reverse cycle operations in winter mode is outdoor air. The heat absorbed by the remote heat exchanger is transferred to DX heating coil for space heating and water heat exchanger for water heating.

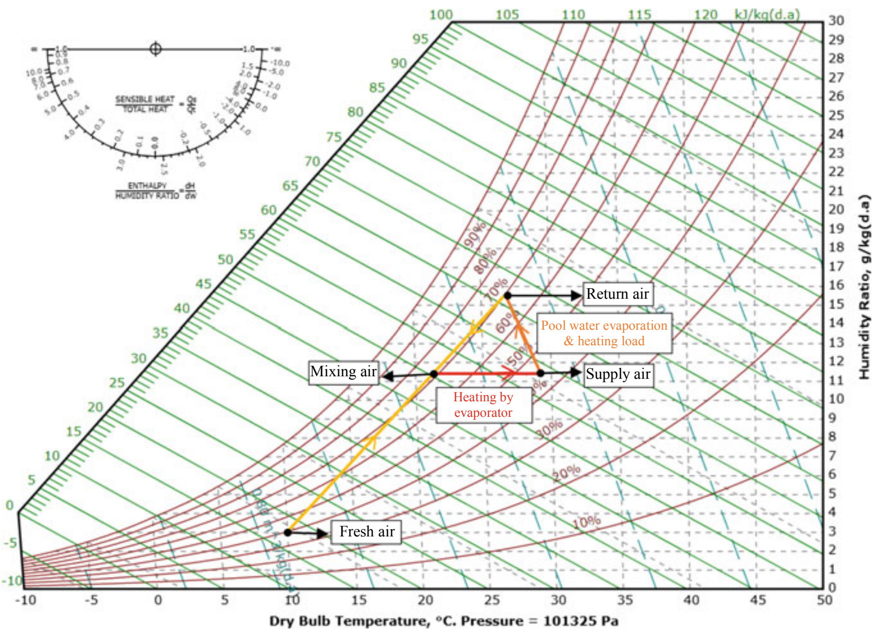


Fig. 8.12 Air process of winter mode in psychrometric chart

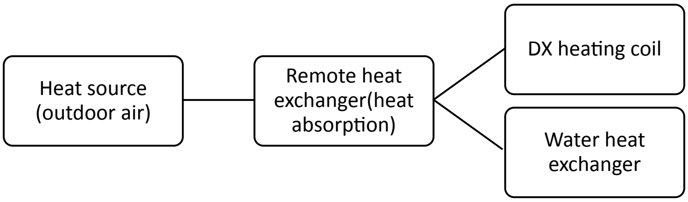


Fig. 8.13 Heat transfer direction in winter mode

References

1. Audah N, Ghaddah N, Ghali K (2011) Optimized solar-powered liquid desiccant system to supply building fresh water and cooling needs. Appl Energy 88:3726–3736
2. Song M, Deng S, Pan D, Mao N (2014) An experimental study on the effects of downwards flowing of melted frost a vertical multi-circuit outdoor coil in an air source heat pump on defrosting performance during reverse cycle defrosting. Appl Therm Eng 67:258–265
3. Byun JS, Jeon CD, Jung JH, lee J (2006) The application of photo-coupler for frost detecting in air source heat pump. Int J Refrig 29(2):191–198
4. Ochoa GEV, Castro SL, Narvaez MP (2014) Application of genetic algorithm to optimize the exergy performance of vapor compression refrigeration system. Contemp Eng Sci 11(25):1245–1252
5. Kumar S, Prevot M, Bougarel R (1989) Exergy analysis of compression refrigerant system. Heat Recovery Syst CHP 9(2):151–157

6. Li YW, Wang RZ, Wu JY, Xu YX (2007) Experimental performance analysis on a direct-expansion solar-assisted heat pump water heater. Appl Therm Eng 27:2585–2868
7. Feidt ML (1999) Thermodynamics and optimization of reverse cycle machine. In: Bejan A, Manut E (eds) Thermodynamic optimization of complex energy system, pp 385–401
8. Zhao X, Li JM, Riffat SB (2008) Numerical study of a novel counter-flow heat mass exchanger for dew point evaporative cooling. Appl Therm Eng 28(14/15):1942–1951
9. Riangvilaiku B, Rumar S (2010) An experimental study of a novel dew point evaporative cooling system. Energy Build 42(5):637–644
10. Zhang LZ (2006) Energy performance of independent air dehumidification systems with energy recovery measures. Energy 31:1228–1242
11. Chua KJ, Chou SK, Yang WM (2010) Advances in heat pump system: a review. Appl Energy 87:3611–3624
12. Whaley DM, Saman WY, Alemu AT (2014) Integrated solar thermal system for water and space heating, dehumidification and cooling. Energy Procedia 57:2590–2599
13. Nunez T, Mittelbach W, Henning HM (2007) Development of an adsorption chiller and heat pump for domestic heating and air conditioning application. Appl Therm Eng 27:2205–2212
14. Bagarella G, Lazzarin R, Noro M (2016) Annual simulation, energy and economic analysis of hybrid heat pump systems for residential buildings. Appl Therm Eng 99(25):485–494
15. Stene J (2005) Residential CO2 heat pump system for combined space heating and hot water system. Int J Refrig 28(8):1259–1265
16. Klein K, Huchtemann K, Muller D (2014) Numerical study on hybrid heat pump systems in existing buildings. Energy Build 69:193–201
17. Choi HJ, Kin BS, Knag D, Kim KC (2011) Defrosting method adopting dual hot gas bypass for an air to air heat pump. Appl Energy 88(12):4544–4555
18. Qu ML, Xia L, Deng SM, Jiang YQ (2012) An experimental investigation on reverse-cycle defrosting performance of air source heat pump using an electronic expansion valve. Appl Energy 97:327–333
19. Garimella SV, Singhal V (2004) Single-phase flow and heat transport and pump considerations in microchannel heat sink. Heat Transfer Eng 25(1):15–25
20. Scanner B, Karytsas C, Medrinos D, Rybach L (2003) Current status of ground source heat pumps and underground thermal energy storage in Europe. Geothermics 32:579–588
21. Park C, Lee H, Hwang Y, Radermacher R (2015) Recent advances in vapor compression cycle technologies. Int J Refrig 60:118–134

Chapter 9
Heat Pump Configuration

9.1 Heat Pump System

Heat pump operates on a compression cycle and pumps energy from heat source to useful energy. Heat pump systems offer economical means of recovering heat from renewable sources for use in various industrial, commercial, and residential applications [1]. Heat pump is an efficient heating and cooling generating system. Heat pump can also provide air circulation and air filtration functions with fan and filter. There are various designs of heat pump systems with applications in commercial, residential, and industrial buildings. Nevertheless, the main components of heat pump are still made up of compressor, condenser, expansion valve, evaporator, and refrigerant [2]. Due to the increased demand for indoor air quality and thermal comfort, energy consumption on HVAC has become an important issue. Recent research focuses on improvement of heat pump system to enhance operating efficiency.

Improvement in heat pump performance and its environmental impact has been an ongoing concern. To address these issues, recent progress on heat pump system focuses on hybrid system and heat recovery system. Another important issue in heat pump operations is the seasonal fluctuation in demand for heating and cooling [3]. Total energy heat pump is a novel solution to ensure heat pump system can be operated throughout all seasons. As heat pump system is widely applied, there is a movement toward multifunction heat pump as the combination of functions within a single system promises cost saving and efficiency operations. Figure 9.1 illustrates the recent development on heat pump system.

Recent heat pump system development in enhancing operational efficient focuses on the areas of multiple stage operations. Multiple stage operations have been rapidly developed in recent year to maintain the performance and reliability of heat pump [4]. According to Li and Su [5], a refrigeration system with two or more evaporators/condensers performs better because multiple stage operating system is equipped with large surface area resulting in reduced compressor work to drive the cycle. Multistage operating heat pump can also maintain the coefficient of performance of heat

Y. H. V. Lun and S. L. D. Tung, *Heat Pumps for Sustainable Heating and Cooling*, Green Energy and Technology,
https://doi.org/10.1007/978-3-030-31387-6_9

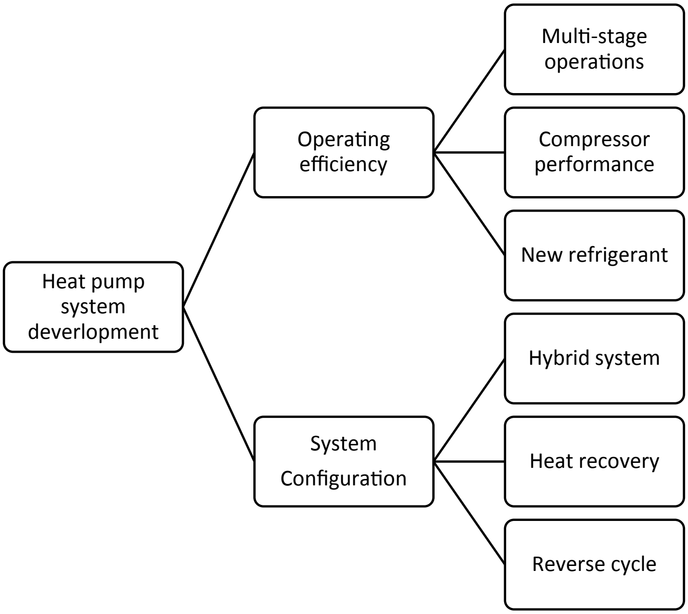


Fig. 9.1 Heat pump system development

pump with increasing temperature difference [6]. The compressors can be operated independently or together in series for maximum output.

Figure 9.2 illustrates a two-stage operating system to provide cooling for a cold room. Fresh air intake is required. In summer, the ambient air is hot and humid.

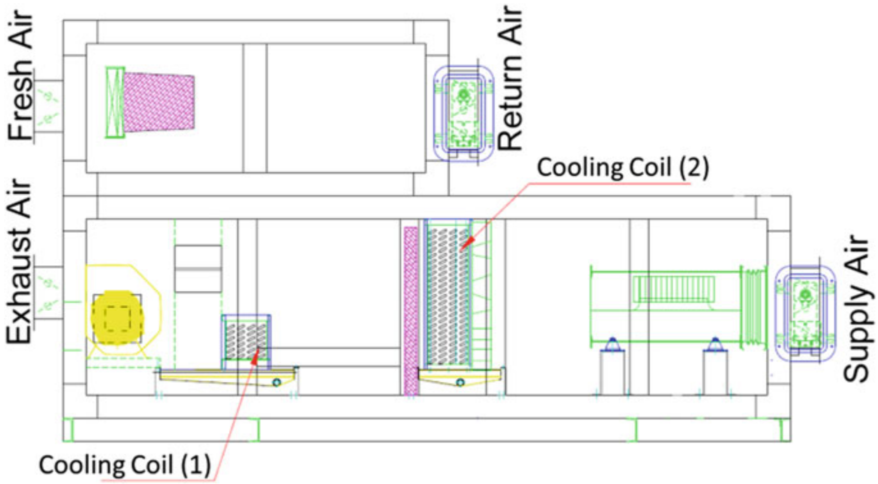


Fig. 9.2 Two-stage cycle heat pump

Due to huge load for cooling and dehumidification, it is, therefore, desirable to use two-stage operations. The air handling process of the two-stage operating heat pump is listed as follows:

- The first stage aims to handle fresh air, i.e., inlet air is first pre-cool by the first cooling coil. The first coil performs both the cooling and dehumidification functions.
- The return air separates into two parts. Part of the return air discharges to outdoor as exhaust air, and the rest of the return air mixes with the preprocessed air.
- The mixed air goes through the second stage, i.e., mixed air cool again by the second cooling coil down to the required setpoint. The processed air then supplies to the cold room.

Compressor is a critical part of the heat pump. The heat pump system has moved forward to next-generation technologies characterized using scroll compressor [7]. Scroll compressor is one of the most used compressors in heat pump system [8]. Scroll compressors are more durable, more resistant, and less vibrating. The compressor operations can be operated at single stage, two-stage, or variable speed. A single stage compressor uses only one speed and it uses its 100% capacity when operating. A two-stage compressor has two speeds, high and low, to meet different loads. A variable speed compressor, also known as inverter-driven compressor, can modulate its capacity to adjust the output in accordance with the demand.

The refrigerant R22 was used in air vapor compression system in the past decades. Due to the encourage of the use of alternative refrigerant to reduce the emission of CFCs, environmentally friendly refrigerants with nature do not deplete the ozone layer are used as replacement in the vapor compression system [9]. The available substitute refrigerants to replace R22 include R134A, R404A, R407C, and R410A [10]. There are studies on the performance of new refrigerant R1234ze, and the results indicate that R1234ze is enough to reach R134a cooling capacity in the different conditions tested [11].

9.2 System Configuration

Hybrid configuration is state-of-the-art method to maximize energy output and minimize energy consumption. The hybrid system consists of more than one heat source [12]. Figure 9.3 illustrates the configuration of hybrid heat pump system with air and water as heat sources. The hybrid heat pump system consists of the following module:

Module	Operations	Heat source	Function
Chilled water coil	Sensible cooling via chilled water cooling coil	Water	Space cooling
DX cooling dehumidifier	DX cooling coil for dew point cooling and latent heat recovery	Air	Space cooling and dehumidification
DX reheat coil	Latent heat discharges to DX reheat coil	Air	Space heating
Water heat exchanger	Latent heat discharges to hot water heat exchanger	Air	Water heating
Water heat exchanger	Surplus latent heat rejects to chilled water system	Air	Heat rejection
Water heat exchanger	Heat absorbs from chilled water system and discharges to DX heating coil	Water	Space heating

Although very high in efficiency, vapor compression cycle is questioned due to the need of electricity power to drive the cycle. Heat recovery system using waste heat to provide useful energy is the preferable option for heat pump system [13]. Heat recovery operation is the most direct way to improve efficiency of heat pump system [14]. Figure 9.4 illustrates the configuration of heat pump with heat recovery operations:

- Air-to-air heat exchanger: Heat exchanger is equipment used for transferring energy from one medium to another. The air-to-air heat exchanger is a means of heat recovery by allowing hot and cold air transfers through a cross-sectional area with no additional power input to the system. The energy from exhaust air is utilized to cool the hot fresh air in summer and heat the cold fresh air in winter.

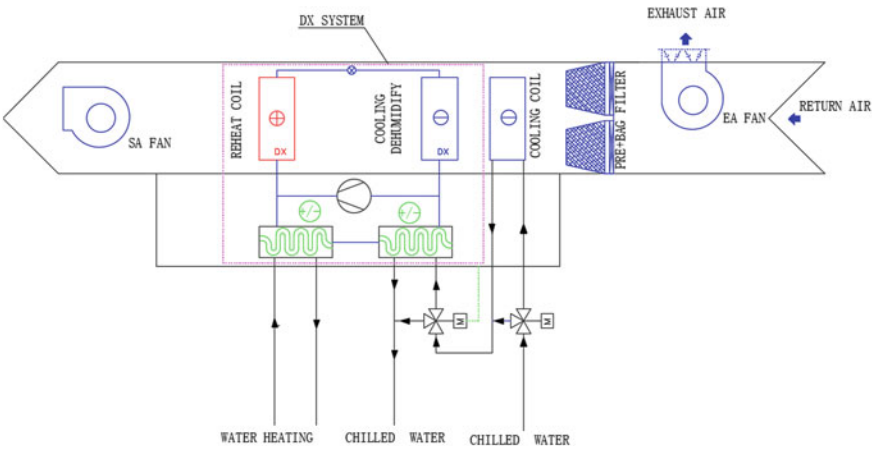


Fig. 9.3 Hybrid heat pump system

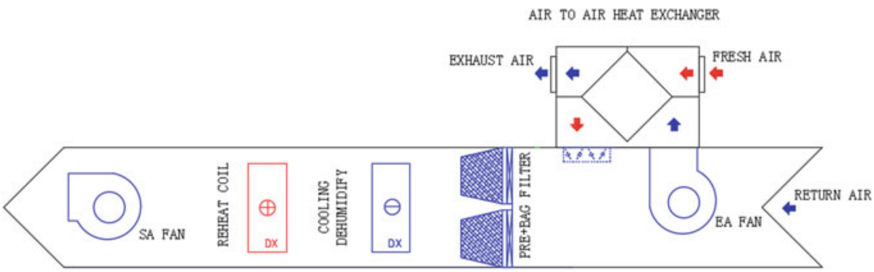


Fig. 9.4 Heat recovery heat pump

- DX system: The direct expansion (DX) system operates to provide dew point cooling for dehumidification. The latent heat from dehumidification is recovered for space reheat. For the heat recovery operations, the system includes DX cooling coil for cooling and dehumidification and DX heating coil to recover latent heat. The heat recovery system aims to provide air handling.

Heat pump system transfers energy from heat source to provide useful energy for indoor comfort. Figure 9.5 illustrates a heat pump system with reverse cycle operations, i.e., remote condenser to perform both heat rejection when providing cooling for indoor space and heat absorption when providing heating for indoor space. When demand for dehumidification exists, the DX cooling coil also performs dehumidification, and latent heat can be recovered from dew point dehumidification to discharge to DX reheat coil for space heating and water heat exchanger for water heating. Exceed heat rejects to outdoor via remote condenser. When there is no demand for

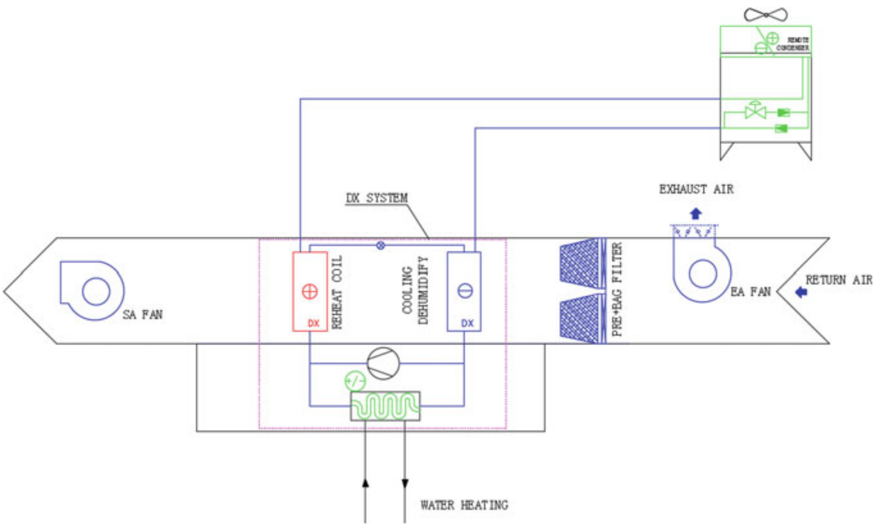


Fig. 9.5 Heat pump with reverse cycle operations

dehumidification, no latent heat can be recovered. Under such circumstance, the heat pump performs reverse cycle operations by heat absorption from outdoor. The energy is then discharged to DX heating coil for space heating and water heat exchanger for water heating.

Air temperature, relative humidity, and water temperature sensors can be installed to control the reverse cycle operations with remote condenser to absorb heat from outdoor ambient air:

Parameter			Heat pump operations			Remote condenser	
Relative humidity	Air temp	Water temp	Cooing coil	Heating coil	Water heating	Heat rejection	Water absorp-tion
↓	↑	↓	Off	Off	On	N/A	On
↓	↓	↑	Off	On	Off	N/A	On
↓	↓	↓	Off	Off	On	N/A	On

Notes ↓ = Below setpoint; ↑ = Above setpoint

9.3 Control System

Heat pump is the technology to provide indoor environment comfort based on principles of thermodynamics and heat transfer. The control and monitoring system become more intelligent with the application of Internet of Things (IoT). The implementation of IoT technology into control system allows wireless communications. According to Yang et al. [15], IoT is "a collection of things embedded with electronics, software, sensors, actuators, and connected via the Internet to collect and exchange data with each other." The IoT enables objects to be sensed using sensors and controlled remotely across network infrastructure [16]. The IoT system enables the use of sensors as devices to detect or measure physical properties and make responses via actuators which is a device that control a machine or other device to operate. The actuators can be defined as "system the received control signal that categorized as low power signal usually generated by microcontroller to operate the devices" [17]. In addition to control the system operations, another focus of the IoT system is to minimize the energy consumption. Power meter and/or current transducer can be installed to control and monitor the power consumption.

IoT-based control system development includes several stages. The control system development is usually initiated with the creation of graphical user interface (GUI) to allow users to interact with electronic devices through graphical icons and visual indicators. Next, hardware and software requirements are identified. It is then followed by the construction of control logic and coding of the control prototype.

The system can implement the proportional-integral-derivative (PID) or fuzzy logic control. The control system can also apply the IoT technology to achieve wireless information transfer. Testing on hardware and software including IoT communication is required before implementation.

From the perspective of heat pump system, the IoT devices are equipped with sensors to measure the physical properties, and the control system uses actuators to operate the heat pump for indoor air quality and thermal comfort. At present, there are two main approaches to address thermal comfort: the rational method and the adaptive method. The rational method or thermal balance is based on the predicted mean vote (PMV) index or predicated percentage dissatisfied (PPD) index to define thermal comfort level on an indoor environment [18, 19]. The adaptive method is to use the final users' satisfaction to optimize the thermal acceptability of the indoor environment [20, 21]. The state-of-the-art to access the thermal comfort level is still a challenge [22].

Figure 9.6 illustrates an IoT-based heat pump control and monitor system. Sensors to measure return air temperature and return air humidity are installed inside the heat pump to control the air side operations of the heat pump. For the water side operations, sensors to measure the inlet water and outlet water are installed. Other information (e.g., air flow rate, carbon dioxide concentration level) can also be obtained to monitor the indoor air quality. Based on the data obtained from various sensors, the operating mode of the system can be auto-selected:

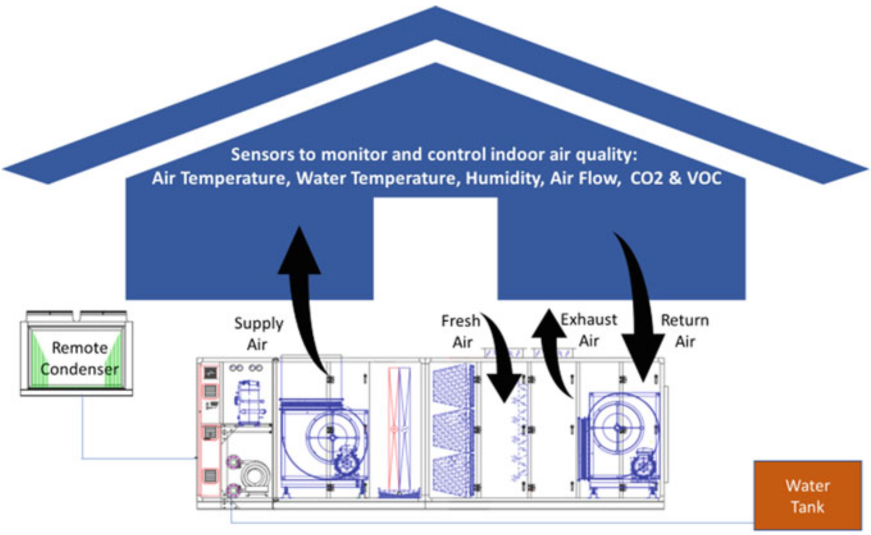


Fig. 9.6 IoT-based heat pump control and monitoring

Operating mode	Selection criteria
Cooling and dehumidification	• Air temperature > setpoint • Relative humidity > setpoint
Cooling and dehumidification + space reheating (recovery heat)	• Relative humidity > setpoint • Air temperature < setpoint
Cooling and dehumidification + water heating (recovery heat)	• Air temperature > setpoint • Relative humidity > setpoint • Water temperature < setpoint
Cooling and dehumidification + space reheating + water heating (recovery heat)	• Air temperature < setpoint • Relative humidity > setpoint • Water temperature < setpoint
Space heating only (reverse cycle operations)	• Relative humidity < setpoint • Air temperature < setpoint
Water heating only (reverse cycle operations)	• Relative humidity < setpoint • Water temperature < setpoint
Space heating + water heating (reverse cycle operations)	• Relative humidity < setpoint • Air temperature < setpoint • Water temperature < setpoint

As the design of comfortable and healthy indoor environment is important, researchers constantly investigate new methodologies and tools to control the system operations. The IoT operations can also be extended to enhance indoor air quality. A typical example is installation of CO_2 sensor to measure the ppm level. The controller reduces the fresh air intake to save energy when the CO_2 level is low. When the CO_2 level is higher than the setpoint, the control system keeps the fresh air damper fully open to increase the intake level of fresh air. The control system also adjusts the discharge of exhaust air proportionally. A sample control logic to control fans and dampers in response to CO_2 level is shown in Fig. 9.7.

9.4 Case Study—Integrate with Cooling Tower

In central air-conditioning system, cooling towers have been increasingly used for heat rejection due to relatively higher energy efficiency when compared to an air-cooled air-conditioning system. However, in the cool and humid climate, air plume emitted from cooling towers is considered as a nuisance to the public, even sometimes mistaken as smoke from fire. Therefore, it becomes necessary to develop a method to avoid the occurrence of the visible plume and mitigate the severity of the visible plume from cooling towers.

Visible plume usually occurs as the discharged air from cooling towers mixes with the ambient air in the cool and humid climate. As seen in Fig. 9.8, the discharged air with a high humidity level is rapidly cooled by the ambient air, thus the capacity of hold moisture reduced, which results in water vapor condensation. Therefore, water

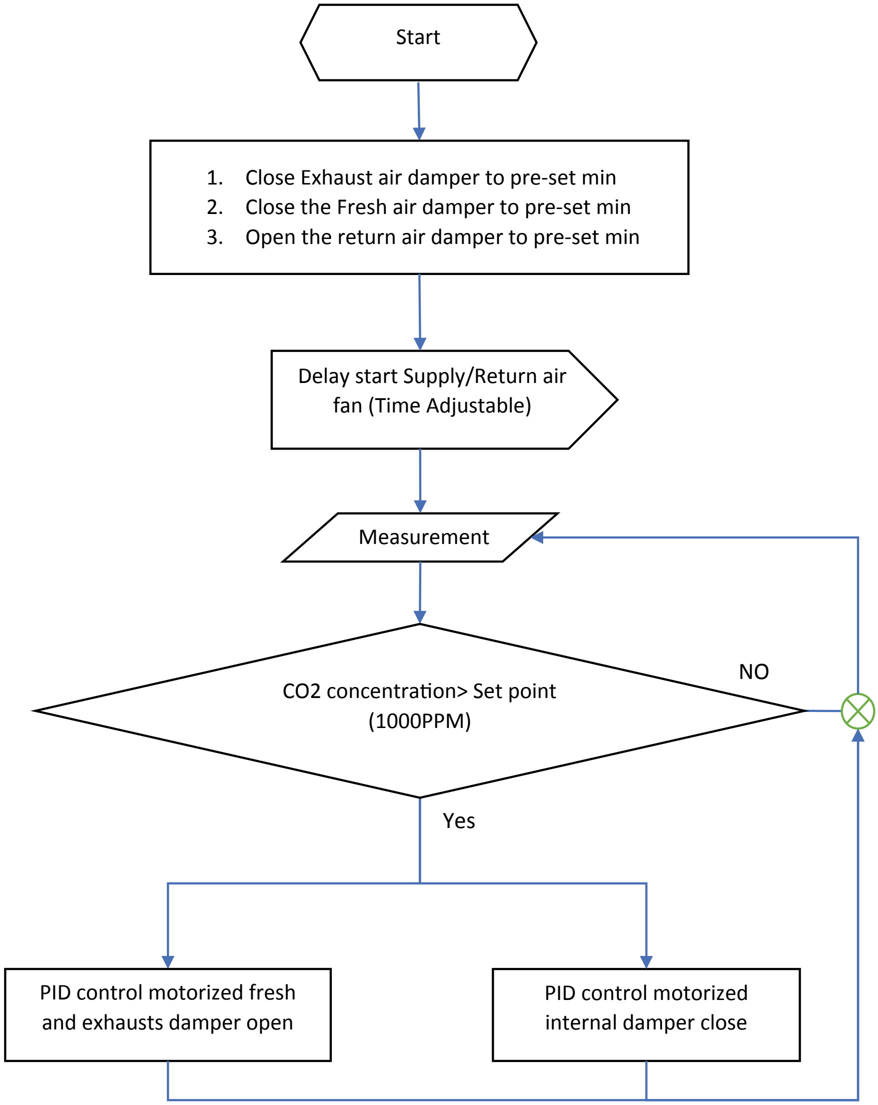


Fig. 9.7 Control logic

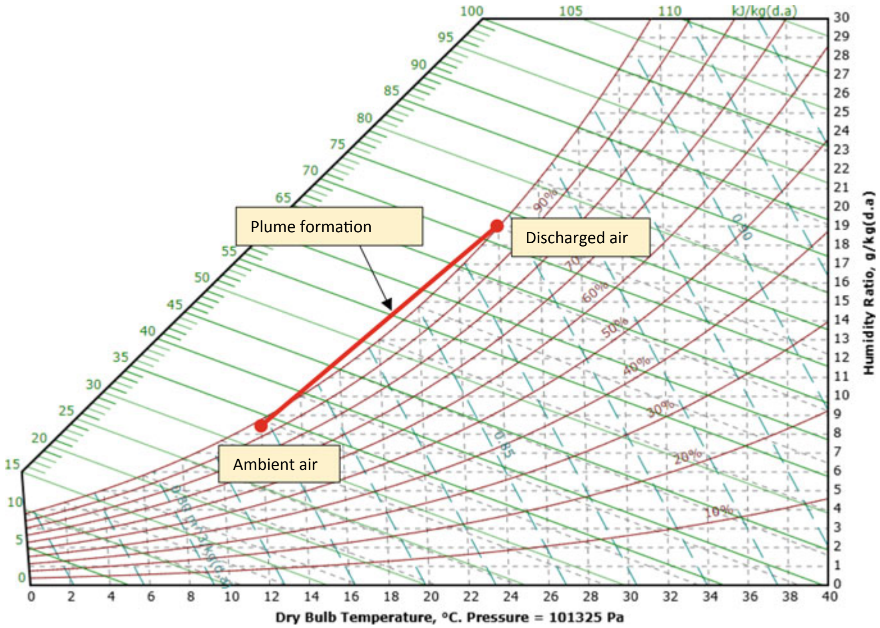


Fig. 9.8 Plume formation in psychrometric chart

vapor becomes moist, consisting of countless droplets in the discharged air from cooling tower, that is, visible plume.

The occurrence of visible plume is very annoying since it may cause many problems:

- The inhalation of the air plume from cooling towers may lead to the outbreak of Legionnaires' disease.
- The plume may cause corrosion of the surrounding equipment.
- The air plume may cause short circuit of the nearby electrical system.
- The visible plume may be mistaken as smoke from fire by the pedestrians.

To solve the cooling tower plume problem, the mixture line between the exhaust air and the ambient air must be on the right of the saturated line in psychrometric chart. Therefore, heating coil is added to heat exhaust air before mixing with the ambient air. It can be seen from Fig. 9.9 that the heat pump system is used to absorb heat from outlet water and transported the energy to heating coil. Therefore, it is more energy saving compared fired gas burners/steam coils. The air processing is shown in Figure. As seen, the exhaust air "B" is heated by heating coil and turned into "C," so that the mixture line (AC) is on the right of the saturated line.

The air processing is shown in Fig. 9.10. The original discharge line is "AB." As seen, the exhaust air "B" is heated by heating coil and turned into "C," so that the mixture line "AC" is on the right of the saturated line.

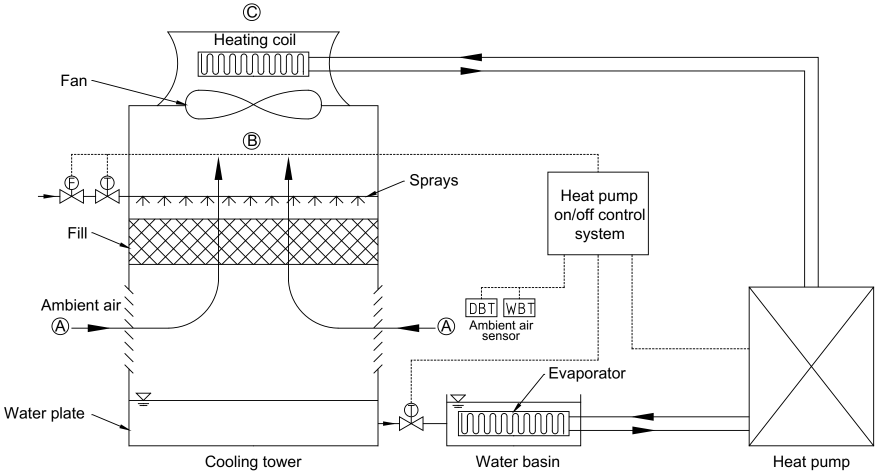


Fig. 9.9 Cooling tower plume abatement schematic

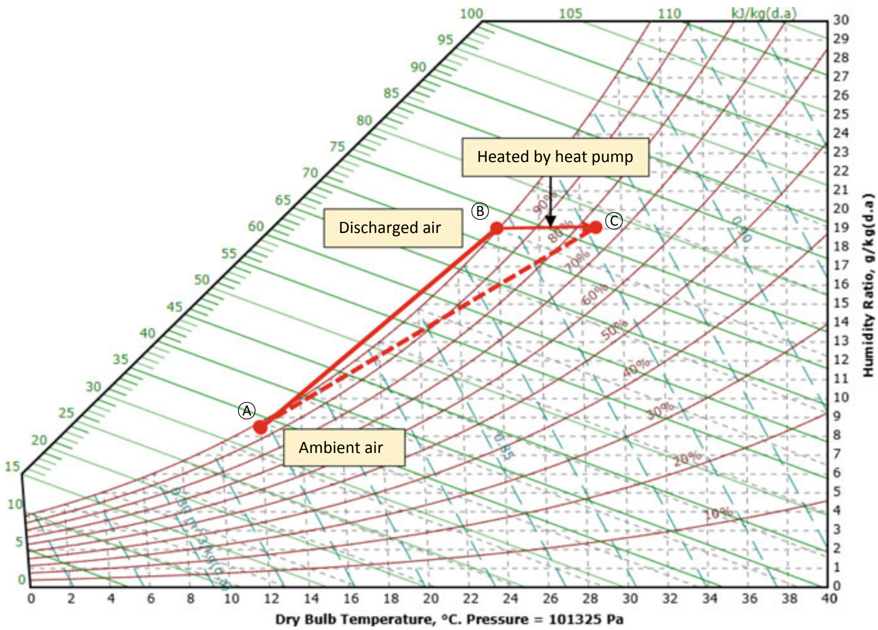


Fig. 9.10 Air processing using heating exhaust air approach

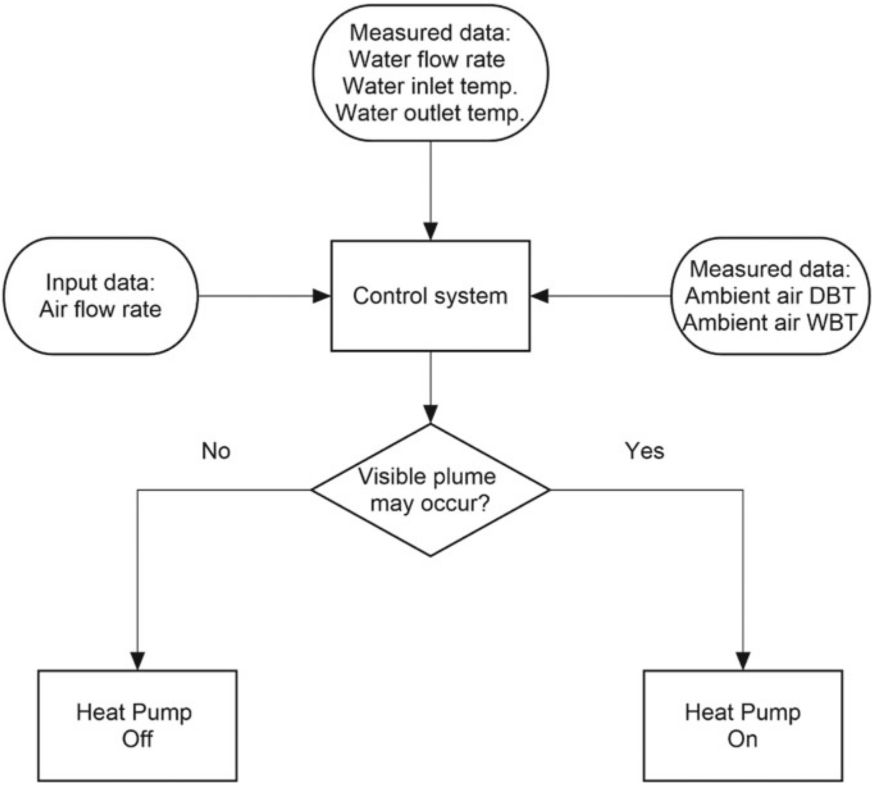


Fig. 9.11 Logic of the on/off control system

Since the phenomenon of visible plume does not occur during all the time of a year, an on/off control system is necessary to determine when to operate the heat pump system. And the control logic is shown in Fig. 9.11:

- Firstly, the real-time measured data including water flow rate, water inlet and outlet temperature, ambient air dry-bulb and wet-bulb temperature are sent to the control system.
- Secondly, based on the measured data and input data, the built-in algorithm is automatically run and can determine whether visible plume may occur.
- Finally, the decision of operate or shut off the system is sent to the heat pump system to do the order.

For the built-in algorithm, it is programmed based on the Poppe method [23]. It was developed in the 1970s and the predictions from the Poppe method are generally accepted with full scale cooling tower test results. With the built-in algorithm, the moisture content in the exhaust air from cooling towers can be accurately predicted. Hence, whether visible plume occurs can be decided.

References

1. Chua KJ, Chou SK, Yang WM (2010) Advanced in heat pump systems: a review. Appl Energy 87:3611–3624
2. Goh LJ, Othamn MY, Mat S, Ruslan H, Sopain K (2011) Review of heat pump systems for drying application. Renew Sustain Energy Rev 15:4788–4796
3. Morrison GL, Anderson T, Behnia M (2004) Seasonal performance rating of heat pump water heaters. Sol Energy 76:147–152
4. Park C, Lee H, Hwang Y, Radermacher R (2015) Recent advances in vapor compression cycle technologies. Int J Refrig 60:118–134
5. Li CJ, Su CC (2003) Experimental study of a series-connected two-evaporator refrigerating system with propane as the refrigerant. Appl Therm Eng 23:1503–1514
6. Lindler KW (1998) Use of multi-stage cascades to improve performance of thermoelectric heat pumps. Energy Convers Manag 39(10):1009–1014
7. Underwood C, Royapoor M, Sturm B (2017) Parametric modelling of domestic air-source heat pumps. Energy Build 139:578–589
8. Tello OFM, Navarro-Peris E, Gonzalvez MJ, Carberan SJM (2016) Performance of a scroll compressor with vapor-injection and two-stage reciprocating compressor operating under extreme conditions. Int J Refrig 63:144–156
9. Halimic E, Ross D, Agnew B, Anderson A, Potts I (2003) A comparison of the operating performance of alternative refrigerants. Appl Therm Eng 23:1441–1451
10. Fannou JC, Rousseau C, Lamarche L, Kajl S (2015) A comparative performance study of direct expansion geothermal evaporator using R410A and R407C as refrigerant alternatives to R22. Appl Therm Eng 82:306–317
11. Mota-Babiloni A, Navarro-Esbri J, Barragan-Cervera A, Mole F, Peris B (2015) Analysis based on EU regulation No 517/204 of new HFC/HFO mixtures as alternatives of high GWP refrigerants in refrigerationa nd HVAC systems. Int J Refrige 52:21–31
12. Ni L, Dong J, Yao Y, Shen C, Qv D, Zhang X (2015) A review of heat pump systems for heating and cooling of buildings in China in the last decade. Renew Energy 84:30–45
13. Saha SS, Koyama S, Kashiwagi TK, Akisawa A, Ng KC, Chua HT (2003) Waste heat driven dual -mode, multi-stage, multi-bed regenerative adsorption system. Int J Refrig 26:749–757
14. Chau KJ, Chou SK (2005) A modular approach to study the performance of a two-stage heat pump system for drying. Appl Therm Eng 25:1363–1379
15. Yang Y, Wu L, Yin G, Li L, Zhao H (2017) A survey on security and privacy issues in IoT. IEEE Internet of Things J 4(5):1250–1258
16. Gbbi J, Buyya R, Narysuc S, Palaniswami M (2013) IoT: a vision, architectural elements, and future directions. Future Gener Comput Syst 29(7):1645–1660
17. Shenan ZF, Marhoon AF, Jasim AA (2017) IoT based intelligent greenhouse monitoring and control system. Basrah J Eng Sci 17(1):61–69
18. Fanger PO (1967) Calculation of thermal comfort: introduction of basic comfort equation. ASHARE Trans 73:1114.1–1114.20
19. Fanger PO, Toftum J (2002) extension of PMV model to non-air-conditioned buildings in warm climates. Energy Build 34:533–536
20. Humphreys MA, Nicol JF (1998) Understanding the adaptive approach to thermal comfort. ASHARE Trans 104:991–1004
21. Halawa E, van Joof J (2012) The adaptive approach to thermal comfort: a critical review. Energy Build 51:101–110
22. Salamone F, Belussi L, Curro C, Danza L, Ghellere M, Guazzi G, Lenzi B, Megale V, Meroni L (2018) Integrated method for personal thermal comfort assessment and optimization through users' feedback, IoT and machine learning: a case study. Sensor 18:1602
23. Kloppers JC, Kröger DG (2005) A critical investigation into the heat and mass transfer analysis of counterflow wet-cooling towers. Int J Heat Mass Transf 48(3–4):765–77