Chapter 5

Energy-Efficient Air-Conditioning Systems for Nonhuman Applications

Muhammad Sultan and Takahiko Miyazaki

Additional information is available at the end of the chapter

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Abstract

In addition to humans' thermal comfort, air-conditioning (AC) could be required for various nonhuman applications, for example, animals' AC, greenhouse AC, food storage and transportation, industrial processes, and so on. In this regard, optimum conditions of air temperature and humidity are explored and compared on psychrometric charts. Thermodynamic limitations of existing AC systems are discussed from the subject point of view. Consequently, four kinds of low-cost energy-efficient AC systems, namely: (i) direct evaporative cooling (DEC), (ii) indirect evaporative cooling (IEC), (iii) Maisotsenko cycle (M-Cycle) evaporative cooling (MEC), and (iv) desiccant AC (DAC), are investigated for climatic conditions of two cities, that is, Multan (Pakistan) and Fukuoka (Japan). In addition, systems' fundamentals and principles are explained by means of schematic diagrams and basic heat/mass transfer relationships. According to the results, performance of all systems is influenced by ambient air conditions; therefore, a particular AC system cannot provide optimum AC for all nonhuman applications. However, one or other AC system can successfully provide desired conditions of temperature and relative humidity. It has been concluded that evaporative cooling systems provide low-cost AC for dry climates, whereas DAC system is found energy efficient and viable for humid climates.

Keywords: air-conditioning, nonhuman applications, evaporative cooling, desiccant

1. Introduction

The word air-conditioning (AC) literally means conditioning of subjected air according to required conditions of air temperature (T_a) and relative humidity (*RH*) [1]. The AC phenomena usually involve five modes of conditioning, that is, (i) heating, (ii) cooling, (iii) humidification, (iv) dehumidification, and (v) ventilation. More than one AC mode could be required depending upon the nature of AC application as well as ambient conditions [2]. For example, cooling and humidification is required in summer season of Multan (Pakistan), whereas heating and humidification is required in dry winters of Fukuoka (Japan) [3]. Certainly, there could be numerous AC applications which may require specific conditions of T_a and *RH*, for example, animals' AC [4], greenhouse AC [2, 5], agricultural products' storage and preservation [6, 7], and so on. The requirements of T_a and *RH* vary dynamically with respect to time and may even vary from species to species [4]. On the other hand, the AC term is mostly associated with humans' thermal comfort as far as conventional literature and primary objectives are concerned [8, 9]. Therefore, lots of AC technologies have been established for humans' thermal comfort and are under practice in order to obtain typical conditions of T_a and *RH*, particularly for summer and winter seasons [1, 10]. Out of them, most popular and highly efficient systems are based on electric-driven compressors. Although compressor-based AC systems achieve desired T_a and *RH* conditions efficiently, these are thermodynamically inefficient and consume huge amount of primary energy [1, 10]. Moreover, these systems are based on environmentally harmful technologies and consume hydro-fluorocarbons (HFCs)/chlorofluoro-carbons (CFCs)/hydrochlorofluoro-carbons (HCFCs). Consequently, the conventional vapor compression–based AC (VAC) systems possess certain global warming potential (GWP) and ozone layer depletion potential (ODP). Thermodynamic limitations as well as merits/demerits of typical VAC system are highlighted in Section 3.

In the twenty-first century, lots of energy-efficient and low-cost AC systems have been studied, designed, developed and are under practice for various AC applications, for example, data center [11–13], museums [14–16], hospitals [17], automobiles [18, 19], wet markets [20], marine ships [21], greenhouses [22], agricultural products storage [7], animals' thermal comfort [6], industrial processes [23], electronic cooling [24], turbine inlet air cooling [25], and so on. Most of these systems are either thermally driven or based on evaporative cooling conception. These systems are not involved in the use of any kind of refrigerants, thus enabling zero GWP and ODP. As heat is the input energy source for thermally driven AC systems, these systems can be employed for efficient utilization of low-grade waste heat, solar thermal energy, and biogas or biomass, and so on. On the other hand, evaporative cooling-based AC systems are always handy (wherever applicable), because they only require water with small energy to run the fan. However, evaporative cooling or thermally driven AC systems are highly influenced by ambient air conditions; therefore, systems optimization will be required for each and every AC application.

From the above perspective, this chapter discusses sensible and latent load of AC required for various nonhuman AC applications. Ideal temperature and humidity zones are represented and compared on psychrometric charts. Consequently, various low-cost energy-efficient AC systems are proposed and discussed for the subjected applications. In addition, thermodynamic limitation of VAC system and scope of proposed systems is also highlighted.

2. Nonhuman air-conditioning (AC)

Apart from humans' thermal comfort, ideal temperature and humidity could be required in many situations as discussed in the introduction section. The intensity of the required AC is

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typically based on the nature of application which could be static and dynamic. This section presents some of the key nonhuman AC application. The upcoming subheading will explain each application in detail.

2.1. Animals' thermal comfort

In general, designing of animals' housing according to the required temperature and humidity is usually complicated due to the environmental factors which affect the well-being and production of animals [26]. Similarly, designing of animals' AC system is directly affected by the economic factor; therefore, animals' AC is not very popular especially in developing countries, for example, Asia and Africa regions. However, lots of low-cost techniques are adopted in these regions in order to achieve the desired conditions that may not be sufficient in many cases. It is worth mentioning that the air-flow/ventilation rate is an important parameter for animals' AC similar to temperature and humidity. Therefore, designing of sensible and latent load of AC is provided after finalizing the optimum air-flow rates. Air-flow rate is a dynamic parameter in case of animals' AC, and it varies from season to season as well as from species to species. American society of heating, refrigeration, and air-conditioning engineers (ASHRAE) provides basic guidelines for animals' AC which can be found from references [26–29]. For example, according to ASHRAE, ventilation rate of 17–22 L/s is required for cows (weight 500 kg each) in winter season, whereas it is 67–90 L/s and 110–220 L/s for spring and summer seasons, respectively. Similarly, growing pigs (weight 34–68 kg) require 3–35 L/s flow, whereas finishing pigs (weight 68–100 kg) require 5–60 L/s. **Figure 1(a)** shows typical constraints while selecting the optimum ventilation rate for livestock buildings [30, 26]. It can be observed that there are many factors which need to be addressed for selecting optimum ventilation rate. In addition, supplied air temperature and humidity from the AC unit is directly associated with the air-flow rates [3]. Consequently, the ideal temperature and humidity required for various animals is shown in **Figure 1(b)** [4, 26]. It can be noticed that the animals require higher relative humidity in general as compared to human beings [3]. On the other hand, animals are relatively less sensitive to temperature but require distinctive conditions for each breed. Moreover, potential of livestock industry can also be determined from **Figure 1(b)** simply by plotting the ambient air conditions of different cities and/or regions.

2.2. Greenhouse AC

Agricultural plants are living things; they grow, move, eat, and reproduce. They are basic entities for food production and associated industries. Plants are sensitive to temperature and humidity similar to human beings and, therefore, require proper AC.

However, plants' AC phenomena are quite complicated due the photosynthesis and evapotranspiration processes by which they require CO_2 and/or O_2 from the air. Therefore, plants' AC is quite different in day times (active photosynthesis and evapotranspiration) and night times (active evapotranspiration only) [2]. According to a study [31, 32], plants grow well when its vapor pressure deficit (VPD) is ranging from 0.45 kPa to 1.25 kPa, and ideal yield could be obtained for VPD = 0.80–0.90 kPa. In this regard, influence of greenhouse conditions on plants' VPD has been determined as shown in **Figure 2(a)**. Moreover, the figure provides a comparison of ideal VPDs for different growth stages of tomatoes [33]. It can be noted that plants are very sensitive to air conditions and require dynamic humidity and temperature at different growth stages. Similarly, using the concept of VPD, the ideal AC zones can be formulated for various greenhouse products as shown in **Figure 2(b)**. It can be seen that each agricultural product requires typical thermal conditions, which may or may not be achievable for many AC systems.

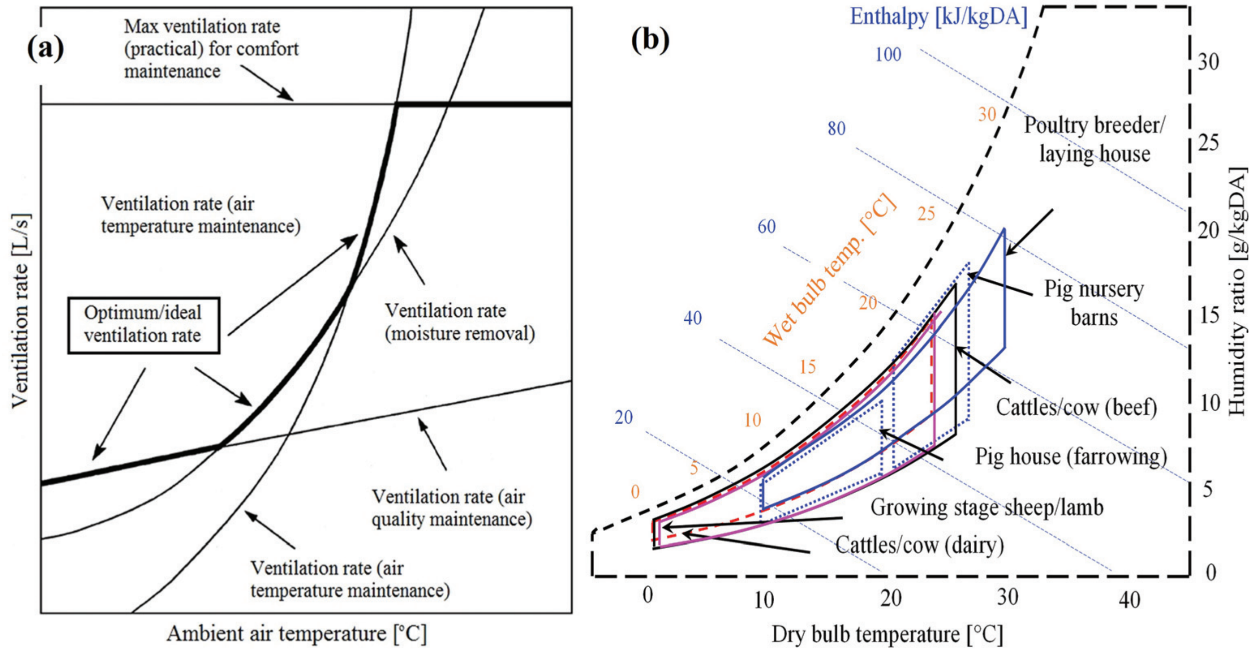

Figure 1. Animals' air-conditioning (AC): (a) optimum ventilation rate for livestock building [26, 30]; and (b) optimum air temperature and humidity levels.

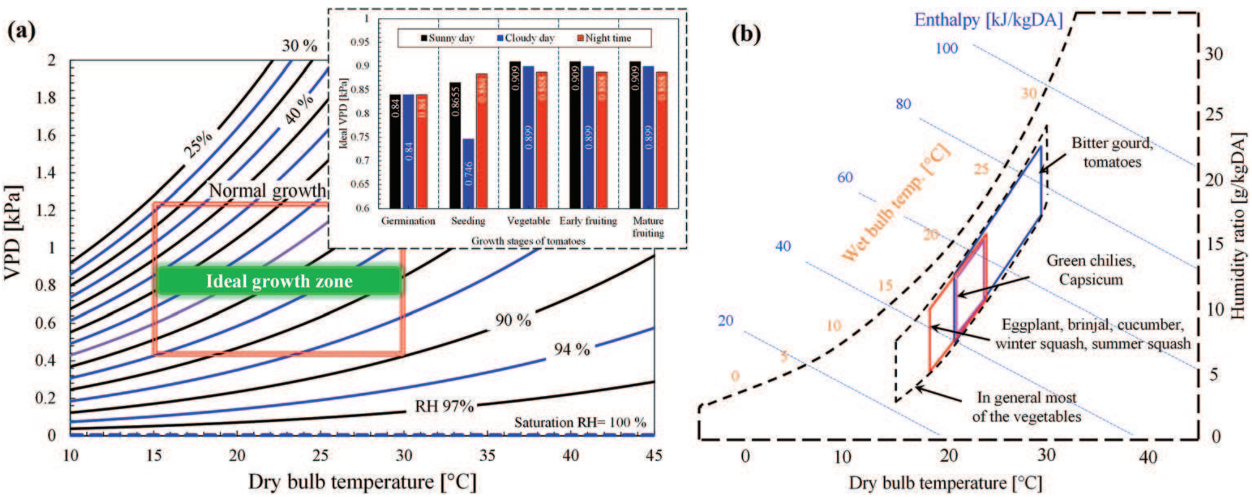

Figure 2. Greenhouse AC: (a) influences of greenhouse conditions on plants' vapor pressure deficit (VPD); and (b) optimum air temperature and humidity levels.

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2.3. Food storage and transportation

Post-harvest storage and handling of agricultural products is one of the burning issues of the twenty-first century where we have lots of food but still many people are suffering from food shortage and malnutrition. It is mainly due to food wasting, improper management, and high cost of food storage and transportation. Food storage is usually expensive and complicated due to the involvement of numerous physiochemical and biological processes, for example, respiration, transpiration, fermentation, and so on [7]. Moreover, storage conditions and nature of storage are completely different for different types of food, which may be categorized as follows:

- Grain, cereal, beans, and pulses storage
- Vegetable storage (fresh and frozen)
- Fresh fruit storage
- Dry fruit storage
- Meat and seafood storage
- Milk, cheese, and dairy food storage
- Cooked and processed food storage

As far as conventional storage practices used for above-mentioned food types are concerned, most popular storage techniques are: (i) drying, (ii) mechanical isolation, (iii) refrigeration, (iv) chemical treatment, (v) vacuum, (vi) ionizing radiation, (vii) silo and storage structures, and so on. On the other hand, it is important to mention here that the AC systems could be extremely required in many cases of food storage and transportation, for example, storage of fresh dates. In addition, AC storage method could be considered on top priority for the food products involved in transpiration, respiration, and/or fermentation (i.e., supply or removal of O_2 and CO_2) [34]. However, AC is not popular for longtime storage of food products due to the expensive technology of VAC systems and lack of distinctive control of T_a and *RH*. Therefore, low-cost and technically viable AC technology is the dire need for the food industry. From the discussion point of view, ideal temperature and humidity requirements for the storage of fruits and vegetables are compared on psychrometric chart as shown in **Figure 3** [4]. The fundamental knowledge used in **Figure 3** is obtained from the guidelines provided by the reference [34]. The shelf life of vegetables and fruits can be increased considerably by storing them at desired conditions of T_a and *RH* (**Figure 3**). The AC systems can generate these conditions effectively and can also control level of O_2 and CO_2 by means of fresh/return air flow and, therefore, can be considered for food storage and transportation. Similarly, the AC use could be crucial for the storage and transportation of dry fruits which may require particular moisture contents. In this regard, water vapor mass transfer between air and food (role of water activity) can be controlled by means of relative humidity, *RH*.

2.4. Industrial processes AC

Lots of industrial processes require particular AC in order to increase the industrial productivity, and it is usually dissimilar to humans' thermal comfort [1]. Intensity of required

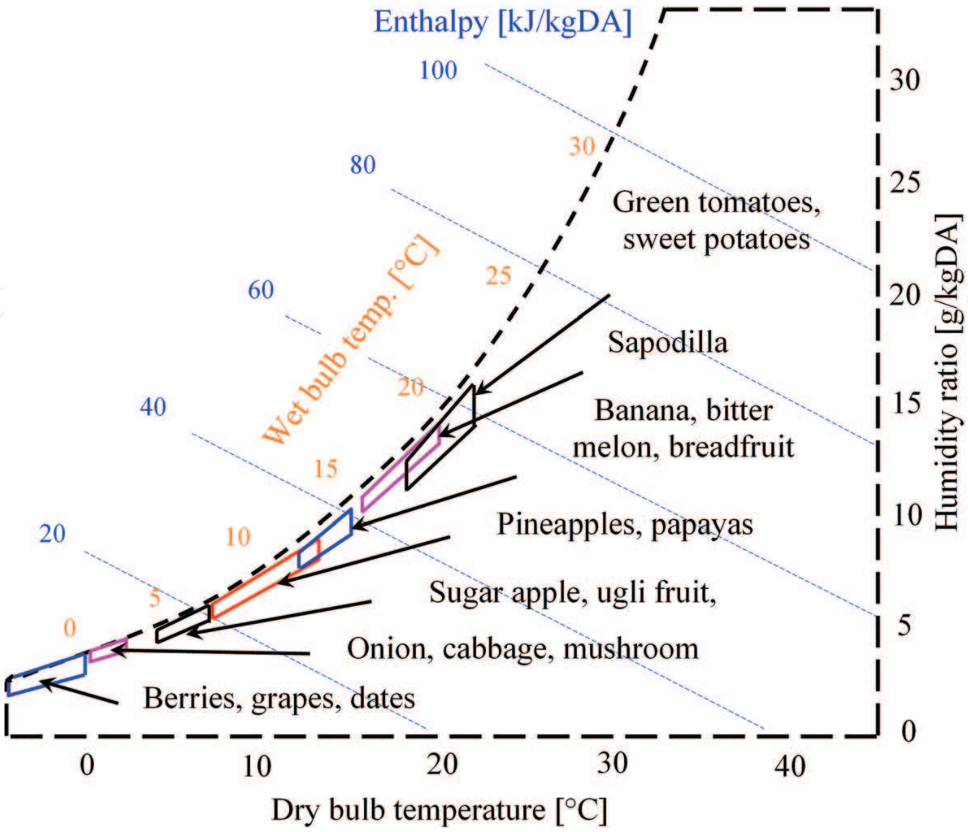

Figure 3. Optimum air temperature and humidity level for the storage of fruits and vegetables.

temperature and humidity control is based on nature of industry and its manufactured products [3]. The industrial processes can be categorized in many ways depending upon the industry type, objectives, and/or productivity [26–29]. Some of the typical industrial processes that require AC include agricultural implements and machinery industry, leather and paper industry, fur and gum industry, water/wastewater treatment industry, medicine/pharmaceutical industry, electronic products industry, paints and plywood industry, tea and tobacco industry, insect/pest/fungus control process, fuel purification–based petrochemical processing, metallurgy-based processes, food and beverages process, clinical processes, heat treatment processes, surface coating processes, manufacturing of additives, and so on. It is worth mentioning that the employees' requirements must be considered in the designing of the industrial processes AC. In this regard, ASHRAE provides fundamental guidelines for the AC of various industrial processes [26]. Nature of industrial construction, building usage, operational conditions, and insurance are the key parameters needed to be considered for proper designing. Similarly, AC loads (sensible/latent) need to be calculated carefully from the viewpoint of heat generation (internal/external), transmission/solar load, fresh air-flow rate including O_2 and CO_2 requirements. The details can be found from reference [26]. For the comparison and general viewpoint, optimum air temperature and humidity required for few industrial processes is presented on psychrometric chart as shown in **Figure 4** [26]. It can be noticed that each industrial process requires different scheme of T_a and RH, which cannot be achieved by a particular AC system. Therefore, this is a dire need of the twenty-first century to transform and

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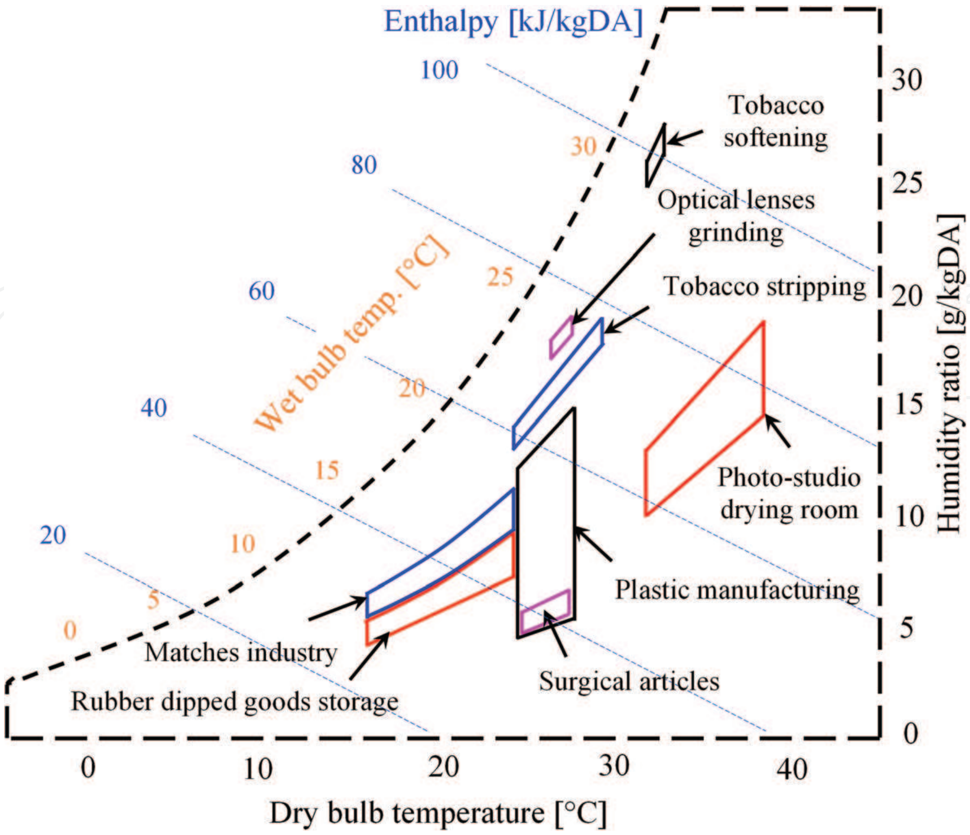

Figure 4. Optimum air temperature and humidity level for industrial processes AC.

optimize the existing AC technologies, including hybrid systems for the establishment of low-cost energy-efficient AC systems for industrial processes.

2.5. Miscellaneous applications

Similar to Sections 2.1–2.4, there could be many more nonhuman AC applications that require distinctive control of humidity and temperature. Some of them can be listed as follows:

- Data center AC [11, 13, 35]
- Turbine inlet air cooling [25, 36, 37]
- Museum AC [15, 16, 38, 39]
- Ships and marine AC [40, 41]
- Storage of machinery, pharmacy, artifact, and electronic devices [42]

Lots of research have been conducted worldwide in order to establish low-cost energy-efficient AC system for above-mentioned AC applications. Therefore, many systems have been resulted suitable depending upon the nature of AC application, availability of low-cost energy type, economics, efficiency, and sustainability. In this regard, upcoming sections will present some suitable low-cost AC options for these applications.

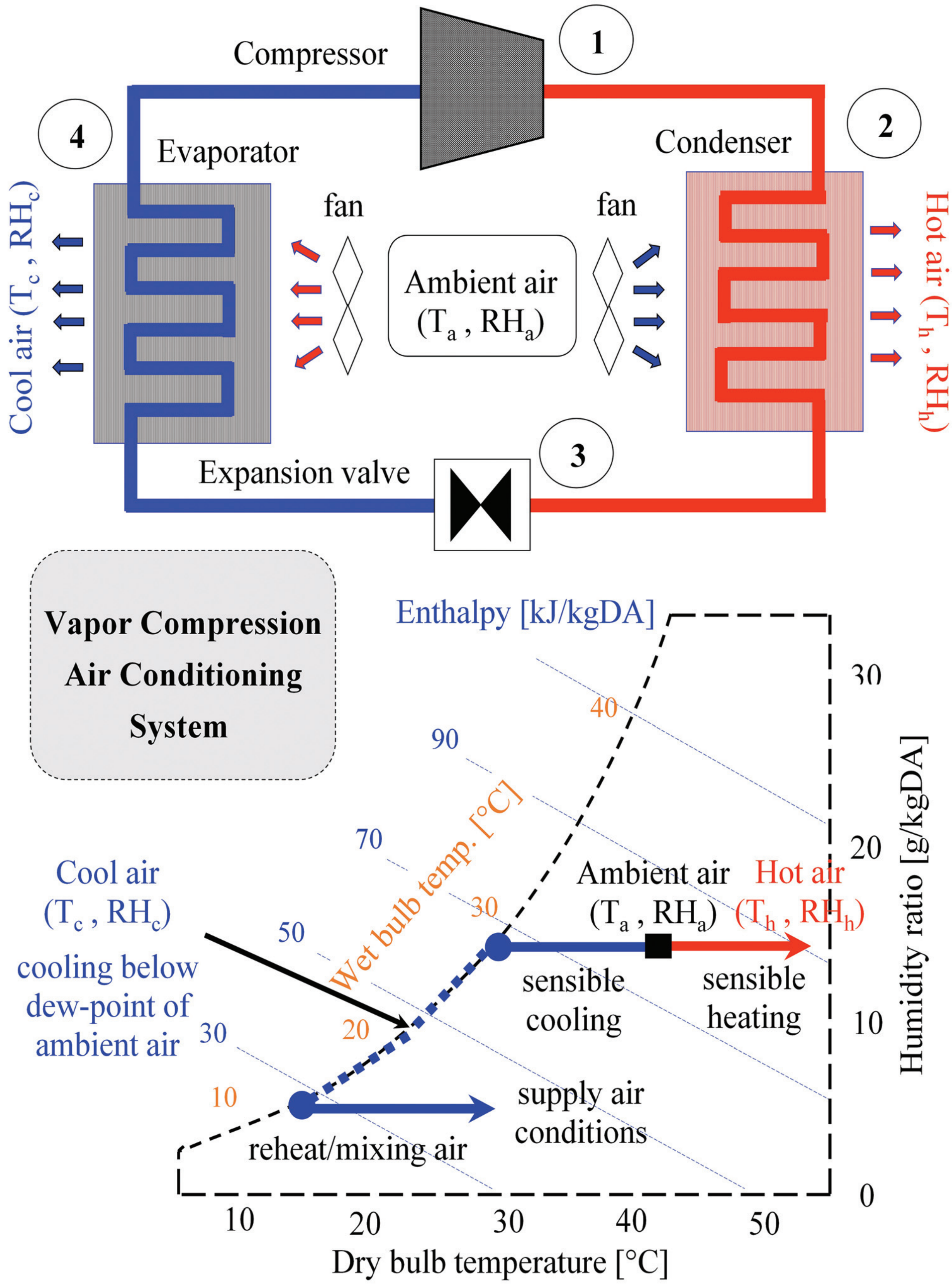

Figure 5. Working principle of conventional vapor compression air-conditioning (VAC) systems.

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3. Conventional AC system

Before we discuss the low-cost energy-efficient AC systems, it is important to highlight the scope, significance, and thermodynamic limitations of existing AC technology, that is, vapor compression–based AC systems (VAC). Vapor compression refrigeration cycle is one of the basic and key thermodynamic cycles [43–45]. Therefore, it has been well known in the literature and, consequently, millions of refrigeration and heating, ventilation, and air-conditioning (HVAC) units are working worldwide on this conception due to its consistency and higher coefficient of performance (COP) [1]. Basic VAC cycle and its psychrometric representation for heating and cooling processes are expressed in **Figure 5**. It can be observed that the VAC cycle can provide cooled air (via evaporator) by cooling below dew-point of the ambient air. However, RH is controlled indirectly by means of dry-bulb temperature (DBT), which is one of the key thermodynamic limitations of VAC cycle. Similarly, it can provide sensible heating (via condenser) while providing reduced RH for the identical humidity ratio. Overall, it can be concluded that VAC cannot control the temperature and RH distinctly. In addition, it uses environmentally harmful refrigerants which are responsible for global warming and ozone layer depletion. Moreover, it consumes huge primary energy, thus indirectly responsible for environmental pollution too.

4. Energy-efficient AC systems

Numerous energy-efficient AC are working worldwide which are mainly based on evaporative cooling, adsorption, absorption, membrane, ejector, renewable energy, solar photovoltaic, solar thermal, low-grade waste heat, and hybrid technologies. From the perspective of nonhuman applications, this chapter focuses on low-cost AC systems particularly based on evaporative cooling and thermally driven technologies. The upcoming three headings discuss evaporating cooling options, followed next by the heating of thermally driven AC. Evaporative cooling is one of the ancient techniques (~2500 B.C.) for providing AC. It is popular worldwide (wherever applicable) due to its low-cost and simple designing. In principle, evaporative cooling produces the cooling effect by means of water vapor evaporation. In literature and worldwide market, numerous arrangements and designing of evaporative cooling systems are available. However, upcoming three headings are important from the subject of thermodynamic conception, that is, isenthalpic cooling [46, 47], sensible cooling, and dew-point (or below wet-bulb) cooling [10, 48, 49]. In order to highlight the significance of temporal and spatial variations on AC performance, 24 h–based ambient air conditions of two cities, that is, Multan (Pakistan) and Fukuoka (Japan), are investigated for nonhuman AC applications. **Figure 6** shows ambient air conditions of both cities, archetypally for summer season [3].

4.1. Direct evaporative cooling (DEC)

Direct evaporative cooling [46, 49] (DEC) is the fundamental sense of typical evaporative cooling conception in which water vapors continuously evaporate into air until condition of air saturation arises. Therefore, cooling effect is produced by means of heat of water

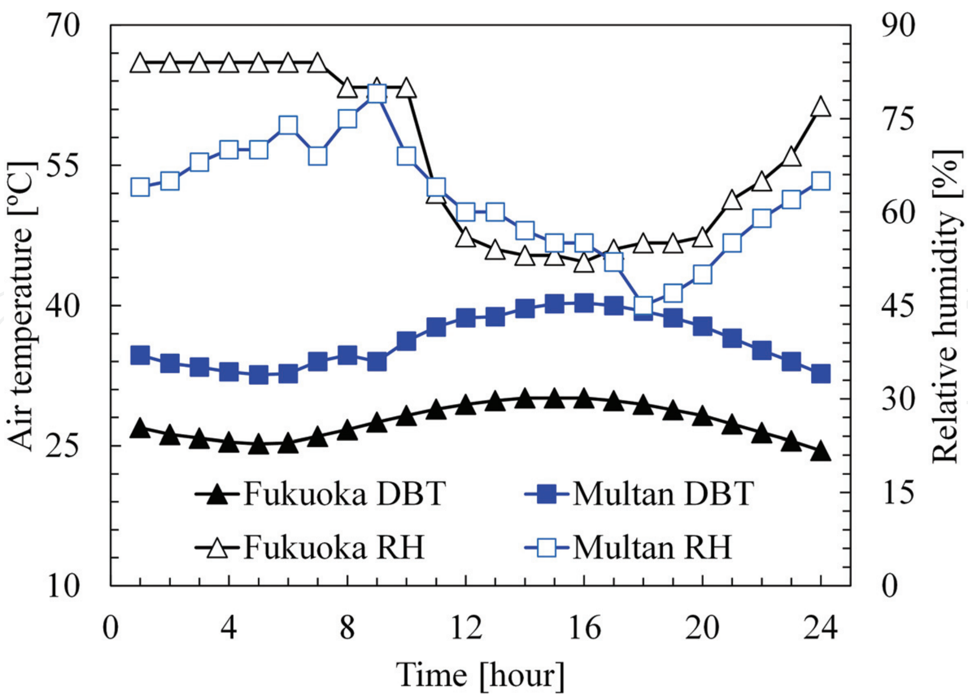

Figure 6. Ambient air conditions of Multan and Fukuoka archetypally for summer season. Each point represents hourly value (average) for 24 h in a day.

vaporization as shown in **Figure 7(a)**. The process can be realized from the fundamental equation of air enthalpy given by Eq. (1) [29].

$$h_a = 1.006\ T_a + w\ (2501 + 1.86T_a) \tag{1}$$

where h_a represents enthalpy of moist air [kJ/kg], T_a represents dry-bulb temperature [°C] and w represents humidity ratio [kg_w/kg_{DA}]. It is worth mentioning that the term 1.006 $T_a$expresses specific enthalpy of dry air, whereas the term w (2501 + 1.86T_a)embodies specific enthalpy of saturated water vapors. In DEC system, enthalpy of the inlet and outlet air streams remains constant, thus cooling limit of DEC system is ambient air wet-bulb temperature. Hence, isenthalpic cooling potential of DEC will be function of $(T_{in})_{db} - (T_{in})_{wb}$. For insight of DEC, inlet and outlet air conditions are described by Eqs. (2)–(5).

$$(T_{out})_{db} \geq (T_{in})_{wb} \tag{2}$$

$$RH_{out} > RH_{in} \tag{3}$$

$$w_{out} > w_{in} \tag{4}$$

$$h_{out} = h_{in} \tag{5}$$

where h and w represent enthalpy of moist air [kJ/kg] and humidity ratio [g/kgDA], respectively. Subscripts *in*, *out*, *db*, and *wb* represent inlet, outlet, dry-bulb, and wet-bulb, respectively. Similarly, wet-bulb effectiveness ε_{wb} [–] of the DEC systems can be written as:

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$$(\varepsilon_{wb})_{DEC} = \frac{(T_{in})_{db} - (T_{out})_{db}}{(T_{in})_{db} - (T_{in})_{wb}} \tag{6}$$

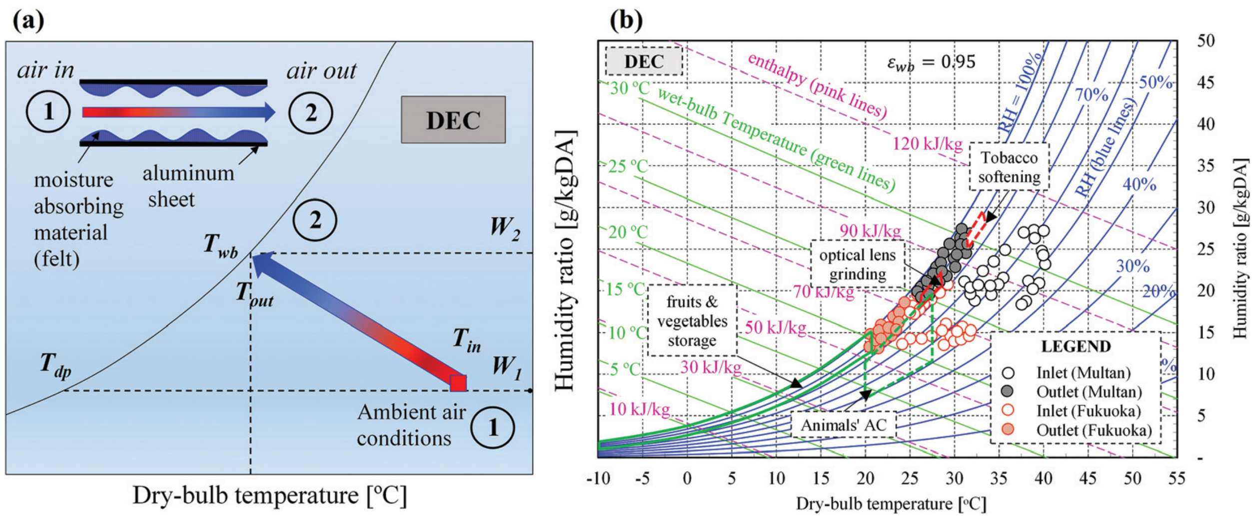

Figure 7. Direct evaporative cooling (DEC) system: (a) schematic representing the fundamentals and thermodynamic principle; and (b) system performance for nonhuman AC applications for Multan and Fukuoka, where each legend point represents hourly value (average) of a day.

Performance of DEC system is analyzed for Multan and Fukuoka cities, archetypally for summer season. Results are expressed on psychrometric chart for ε_{wb}= 0.95, in order to highlight its applicability for nonhuman AC applications as shown in **Figure 7(b)**. It can be observed for both cities that the DEC system cannot provide required conditions for "tobacco softening" and for "storage of fruits & vegetables." On the other hand, DEC can support/assist conventional AC unit for "optical lens grinding" and "animals' AC" for Multan and Fukuoka climates, respectively. Similarly, all the nonhuman AC applications can be examined for DEC system applicability using **Figure 7(b)**.

4.2. Indirect evaporative cooling (IEC)

Increase in product air humidity is the key limitation of typical DEC system; therefore, indirect evaporative cooling (IEC) system can be employed for constant absolute humidity [49]. As no moisture is added in the air by IEC, it enables hygiene air quality. Fundamentals and thermodynamic principle of IEC system is expressed by the schematic diagram shown in **Figure 8(a)**. Referring to **Figure 8(a)**, the IEC cooling is achieved by combination of two thermodynamic processes: (i) isenthalpic cooling by water vapor evaporation into the air, that is, DEC process (wet-channel) and (ii) sensible heat transfer from process (i) (dry-channel). As the cooling effect is based on water vapor evaporation, the cooling limit of IEC is also wet-bulb temperature. Thus, the cooling potential of IEC will be function of $(T_{in})_{db} - (T_{in})_{wb}$, similar to DEC. In addition of DEC efficiency parameters, the net efficiency of IEC device is influenced by air-flow ratio and heat transfer between dry and wet channels. For insight of IEC, inlet and outlet air conditions along with wet-bulb effectiveness are expressed by Eqs. (7)–(11).

$$(T_{out})_{db} \geq (T_{in})_{wb} \tag{7}$$

$$RH_{out} > RH_{in} \tag{8}$$

$$w_{out} = w_{in} \tag{9}$$

$$h_{out} < h_{in} \tag{10}$$

$$(\varepsilon_{wb})_{IEC} = \frac{(T_{in})_{db} - (T_{out})_{db}}{(T_{in})_{db} - (T_{in})_{wb}} \tag{11}$$

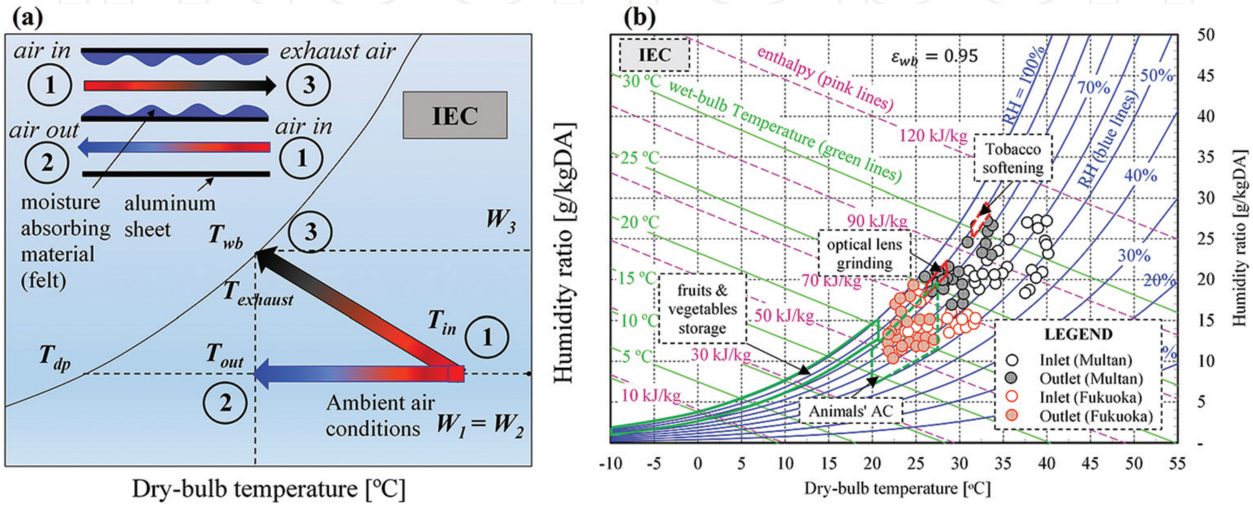

Figure 8. Indirect evaporative cooling (IEC) system: (a) schematic representing the fundamentals and thermodynamic principle; and (b) system performance for nonhuman AC applications for Multan and Fukuoka, where each legend point represents hourly value (average) of a day.

It can be observed from Eqs. (2)–(11) that the numerical value of outlet temperature by DEC and IEC units will be identical for same effectiveness; however, humidity makes the difference in cooling performance. In this regard, IEC system performance is investigated for summer season of Multan and Fukuoka cities for nonhuman AC applications as shown in **Figure 8(b)** for ε_{wb} = 0.95. According to the results, "tobacco softening" and "storage of fruits & vegetables" cannot be entertained by IEC system for both cities. On the other hand, unlike DEC, the IEC can provide optimum conditions for "animals' AC" for Fukuoka city. In addition, IEC can support/assist conventional AC system for the industrial AC process of "optical lens grinding" for Multan. Similarly, rest of the nonhuman AC applications can be examined by **Figure 8(b)**.

4.3. M-Cycle evaporative cooling (MEC)

The Maisotsenko cycle (M-Cycle) evaporative cooling (MEC) is an advance thermodynamic conception of IEC by which the product air can be cooled to the ambient air dew-point temperature [10]. The fundamental scheme of MEC operation is presented by **Figure 9(a)**, whereas details can be found from reference [10]. The MEC apparatus (dry and wet channels in **Figure 9(a)**) exploits the psychrometric renewable energy (available from the latent heat of water vaporization) in such a way that product air can be cooled to the ambient air dew-point.

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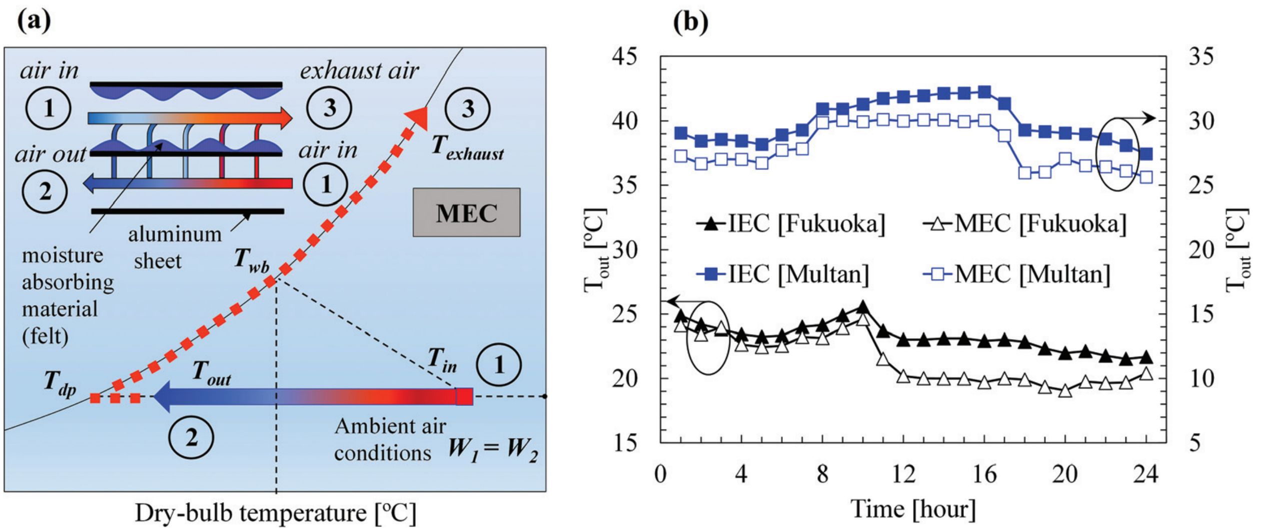

Figure 9. Maisotsenko cycle evaporative cooling (MEC) system: (a) schematic representing the fundamentals and thermodynamic principle; and (b) comparison of outlet air temperatures with DEC/IEC system for Multan and Fukuoka, where each point represents hourly value (average) of a day.

According to experimental results available in the literature, MEC systems have resulted the wet-bulb effectiveness substantially more than unity, which means that MEC can sensibly cool the product air below the ambient air wet-bulb temperature. For insights into MEC, inlet and outlet air conditions are presented by Eqs. (12)–(15).

$$(T_{in})_{dp} \leq (T_{out})_{db} \leq (T_{in})_{wb} \tag{12}$$

$$RH_{out} > RH_{in} \tag{13}$$

$$w_{out} = w_{in} \tag{14}$$

$$h_{out} < h_{in} \tag{15}$$

Unlike DEC and IEC systems, the thermodynamic limit of MEC cooling is dew-point temperature; therefore, cooling potential of MEC is function of $(T_{in})_{db} - (T_{in})_{dp}$. Accordingly, dew-bulb effectiveness of MEC ε_{dp} [–] can be expressed as follows:

$$(\varepsilon_{dp})_{MEC} = \frac{(T_{in})_{db} - (T_{out})_{db}}{(T_{in})_{db} - (T_{in})_{dp}} \tag{16}$$

For general overview, outlet air temperature of MEC unit for Fukuoka and Multan climates is calculated for ε_{dp} = 0.95, and the results are compared with IEC as shown in **Figure 9(b)**. It can be seen that the MEC can provide much better conditions as compared to conventional IEC throughout the day for both cities. Moreover, the performance of MEC can be further improved as compared to IEC at drier ambient air conditions. For brief understanding, the applicability of standalone MEC can be considered limited when $w \geq 11.2$ g/kgDA [10]; however, it may not be limited if utilized intelligently, for example, pre-dehumidification of ambient air (by desiccant dehumidifier) before it passes through MEC channels. As the results presented in **Figure 9(b)** are based on constant ε_{dp}, they may not be exactly similar to real experiments. In this regard, lots of studies have reported experimental results along with numerical models for MEC which can be found from references [50–52]. In addition, a recent study [6] provides basic correlation for performance evaluation of MEC, which can be represented by Eq. (17). The correction is valid for the range of T_{in} = 20–45°C and w_{in} = 10–25 g/kgDA.

$$(T_{out})_{db} = A_1 + B_1(T_{in})_{db} + C_1(w_{in}) \tag{17}$$

where w_{in}, T_{in}, and T_{out} represent inlet humidity ratio [g/kgDA], inlet, and outlet air temperatures [°C], respectively. The values of constant A_1, B_1, and C_1 are 6.70, 0.26, and 0.53, respectively.

4.4. Desiccant AC (DAC)

It can be noticed from Sections 4.1–4.3 that cooling potential of evaporative cooling techniques is function of $(T_{in})_{db} - (T_{in})_{wb}$ or $(T_{in})_{db} - (T_{in})_{dp}$; therefore, it can be only applied in dry regions/climates. In contrary, desiccant AC (DAC) could be an energy-efficient and viable solution for humid climates [1]. The DAC possesses ability to deal sensible and latent load of AC distinctly and can be operated on low-grade waste heat, biogas, and/or solar energy. The ability of desiccant material to adsorb water vapors from ambient air makes DAC system a suitable choice for AC in high humidity regions [3]. A typical DAC system based on solid desiccant rotor is shown in **Figure 10(a)**. First, ambient air (1) is passed through the desiccant dehumidifier where it is dehumidified due to water vapor pressure difference between air and desiccant (process 1–2). This process will be isenthalpic in case of ideal situation, that is, neglecting sorption heat. Thus, the temperature of dehumidified air (2) is increased due to heat of water vapor condensation. Second, the dehumidified air (2) is sensibly cooled initially by heat exchanger (process 2–3) followed by low-cost cooling processes (process 3–4), for example, IEC. On the other hand, desiccant will be saturated with water vapor adsorption after some time. Therefore, regeneration/hot air (6) is passed through the desiccant (process 6–7) which removes the adsorbed water vapors for cyclic usage of desiccant. Referring to **Figure 10(a)**, inlet and outlet air conditions of DAC can be simply expressed by Eqs. (18)–(25), while detailed DAC models can be found from references [4, 53].

$$(T_2)_{wb} = (T_1)_{wb} \tag{18}$$

$$(T_3)_{db} = (T_2)_{db} - \varepsilon_{HX}\left((T_2)_{db} - (T_1)_{db}\right) \tag{19}$$

$$(T_4)_{db} = (T_3)_{db} - \varepsilon_{IEC}\left((T_3)_{db} - (T_1)_{wb}\right) \tag{20}$$

$$(T_5)_{db} = (T_1)_{db} + \varepsilon_{HX}\left((T_2)_{db} - (T_1)_{db}\right) \tag{21}$$

$$(T_6)_{db} = f(w_1, RH_2) \tag{22}$$

$$RH_6 \le RH_2 \tag{23}$$

$$w_4 = w_3 = w_2 \tag{24}$$

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$$w_6 = w_5 = w_1 \tag{25}$$

where subscript numbers are associated with **Figure 10(a)**. Effectiveness of heat exchanger (HX) and cooling source (IEC), that is, ε_{HX} and ε_{IEC}, is considered 0.95 for analysis. For the analysis of DAC system, ambient air conditions of both cities (**Figure 6**) are considered on average basis, that is, T = 36.2°C, RH = 62% for Multan and T = 27.6°C, RH = 69% for Fukuoka. Consequently, effect of regeneration temperature (T_6) on supply air condition (4) is investigated as shown in **Figure 10(b)**. It can be seen that supply air relative humidity is reduced linearly with the increase in regeneration temperature for both cities. Similarly, supply air enthalpy is also reduced at higher regeneration temperatures by which the conditioning is improved. While the supply air temperature at all regeneration temperatures is found 30 ± 0.1°C and 23.5 ± 0.10°C for Multan and Fukuoka, respectively. It can be observed that DAC system can provide variety of supply air conditions by manipulating regeneration temperature; therefore, it can be considered a viable AC system for various nonhuman applications expressed in Section 2.

Finally, it can be summarized that evaporative cooling systems (Sections 4.1–4.3) could provide low-cost AC for dry regions, whereas DAC system can be used efficiently for humid climates. Additionally hybrid systems based on evaporative cooling and/or DAC can also be established for efficient and sustainable AC performance. Hence, it can be concluded that one or other AC system (presented in Section 4) can provide optimum AC for presented nonhuman applications.

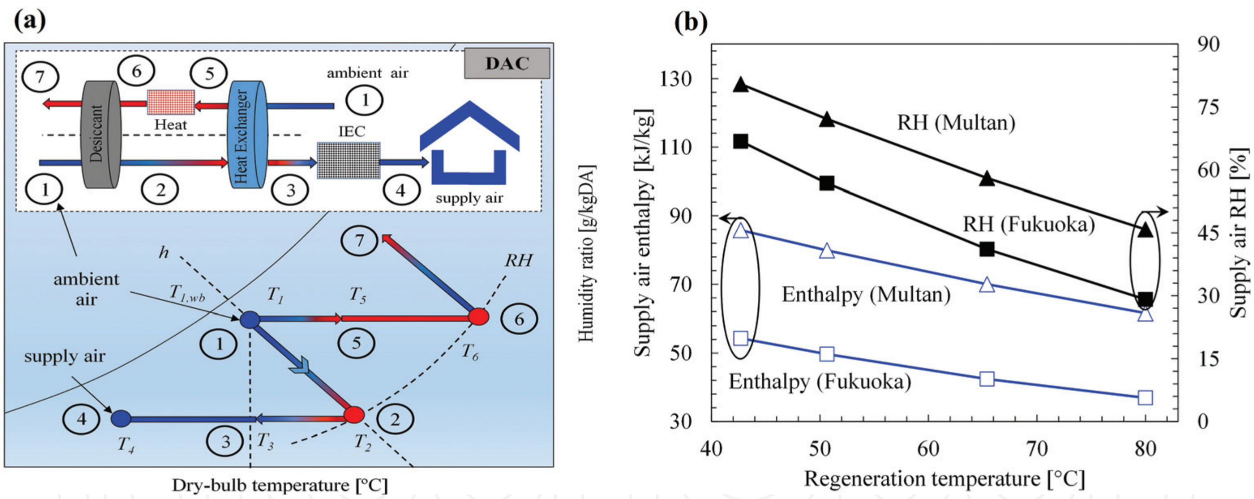

Figure 10. Desiccant air-conditioning (DAC) system: (a) schematic representing the fundamentals and thermodynamic principle; and (b) effect of regeneration temperature on supply air enthalpy and relative humidity.

5. Conclusions

The chapter discusses the fundamentals of various nonhuman air-conditioning (AC) applications from the viewpoint of low-cost and energy-efficient AC. In this regard, optimum conditions are explored and compared on psychrometric charts for numerous nonhuman AC applications. Most of them require dissimilar conditions as compared to conventional humans' thermal comfort. Conventional vapor compression based AC systems are found thermodynamically inefficient and expensive; therefore, it has been realized that low-cost energy-efficient AC is direly needed. Thus, study proposes four kinds of low-cost energy-efficient AC systems which are based on evaporative cooling and thermally driven conceptions. Fundamentals and principle of each system is explained by means of basic heat/mass transfer relationships. Moreover, system performance is evaluated for climatic conditions of two cities, that is, Multan and Fukuoka. According to the results, performance of all systems is highly influenced by ambient air conditions, and, therefore, a particular AC system cannot provide optimum AC for all applications. However, one or other AC system can successfully provide desired conditions of temperature and relative humidity. In general, following conclusions have been made for this study.

- Evaporative cooling systems provide low-cost AC, which can be utilized for various non-human applications. However, the cooling potential is the function of $(T_{in})_{db} - (T_{in})_{wb}$ or $(T_{in})_{db} - (T_{in})_{dp}$ and, therefore, can be only employed for dry climatic conditions. Due to simple designing and operation, these systems should be considered on top priority for AC wherever applicable.
- Instead, desiccant AC systems are found to be an energy-efficient and viable solution for humid climatic conditions and can be operated on low-grade waste heat, biomass, and/or solar thermal energy. As DAC performance is directly related to regeneration temperature, they can provide various supply air conditions, which are required by many non-human AC applications.
- Additionally, hybrid systems based on evaporative cooling and/or desiccant AC can also be established for efficient and sustainable AC.

Nomenclature

AC	Air-conditioning
ASHRAE	American society of heating, refrigeration, and AC engineers
CFCs	Chlorofluoro-carbons
COP	Coefficient of performance [–]
DAC	Desiccant air-conditioning
DBT	Dry-bulb temperature [°C]
DEC	Direct evaporative cooling
GWP	Global warming potential
h	Enthalpy [kJ/kg]
HCFCs	Hydrochlorofluoro-carbons
HFCs	Hydro-fluorocarbons

HVAC	Heating, ventilation, and air-conditioning
IEC	Indirect evaporative cooling
L/s	Litter per second
M-Cycle	Maisotsenko cycle
ODP	Ozone layer depletion potential
RH	Relative humidity [–] or [%]
T	Temperature [K] or [°C]
VAC	Vapor compression–based air-conditioning
VPD	Vapor pressure deficit [kPa]
w	Humidity ratio [g_w/kg_{DA}]
ε	Effectiveness [–]
Subscripts	
a	Air
db	Dry-bulb
dp	Dew-point
in	Inlet/input
out	Outlet/output
wb	Wet-bulb

Author details

Muhammad Sultan[1]* and Takahiko Miyazaki[2]

*Address all correspondence to: muhammadsultan@bzu.edu.pk

1 Department of Agricultural Engineering, Bahauddin Zakariya University, Multan, Pakistan

2 Faculty of Engineering Sciences, Kyushu University, Kasuga-shi, Fukuoka, Japan

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