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Two-stage evaporative cooling systems in hot and humid climate

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ABSTRACT

Evaporative cooling is an environmentally friendly and energy efficient cooling method that only uses water as the working fluid to cool air through the simple evaporation of water. It is a technology that could substantially reduce the air-conditioning cooling energy requirement in buildings and provide other important environmental benefits. However, traditional direct evaporative coolers will increase the humidity of the air to a level that makes occupants uncomfortable under humid climatic conditions. Two-stage evaporative cooling systems can improve efficiency and reduce the amount of moisture added to the air.

This research paper explains the working principles of two-stage evaporative cooling systems and assesses their performance in Hong Kong which has a hot and humid climate. The local climatic factors are investigated and the characteristics of the systems are evaluated. It is found that the high humidity conditions throughout the year in this climate do not permit regular use of the evaporative cooling systems. However, there are still good potential for applying them to precool outdoor air and achieve significant energy savings in the air-conditioning. The efficiency of the systems will depend on the system configuration, component design and control strategies.

(190 words)

Keywords: Two-stage evaporative cooling systems, hot and humid climate, Hong Kong.

兩個階段的蒸發冷卻系統在炎熱潮濕氣候的應用分析

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摘要: 蒸發冷卻是一種環保和節能的有效的冷卻方法，它只使用水作為工作液，通過簡單的水蒸發來冷卻空氣。這一技術可以大大減少建築物要求的空調冷卻能源，及提供其他重要的環保效益。可是，傳統的直接蒸發冷卻器將增加空氣相對濕度的水平，讓人們處於不舒適的潮濕氣候條件下。兩個階段的蒸發冷卻系統可以提高效率和減少水分添加到空氣中。本研究論文闡述了兩個階段的蒸發冷卻系統之工作原理，和評估該系統在香港這個炎熱而潮濕的氣候之下的性能。分析當地的氣候因素的影響和評價系統的特質。結果表明，全年在這種高濕度的氣候條件下，不允許經常利用蒸發冷卻系統。然而，這裡仍然有很好的潛力，運用它們來預先冷卻室外空氣，以取得重大的空調節能。該系統的效率將取決於系統配置，組件設計和控制策略。

關鍵詞: 兩個階段的蒸發冷卻系統，炎熱潮濕氣候，香港。

1. Introduction

Evaporative cooling is an environmentally friendly and energy efficient cooling method that only uses water as the working fluid to cool air through the simple evaporation of water (ASHRAE, 2007; Watt and Brown, 1997). It is a technology that could substantially reduce the air-conditioning cooling energy requirement in buildings and provide other important environmental benefits (Bom, *et al.*, 1999; Dartnall, *et al.*, 2008; Xu, 1998). Evaporative cooling systems (ECSs) work best in hot, dry climates (Datta, *et al.*, 1987), and it can also be used in more humid climates (Costelloe and Finn, 2003; Heidarinejad, *et al.*, 2009; Zhao, *et al.*, 2009).

The major benefits of ECSs include (ASHRAE, 2008; Bom, *et al.*, 1999):

- Avoiding the use of ozone-depleting chlorofluorocarbons (CFCs)
- Substantial energy and cost savings
- Possible reduction of peak power demand
- Reduction in greenhouse emissions that come from the energy efficiency
- Potential life cycle cost effectiveness
- Improved indoor air quality when higher ventilation is adopted
- Easily integrated into built-up systems
- Simple manufacturing technology (suited to developing countries)

ECSs can be used for many commercial (e.g. kitchens and laundry houses), industrial (e.g. spot-cooling in factories and warehouses) and agricultural applications (e.g. greenhouses and poultry sheds). As determined by local climates and comfort preferences, they can also be useful in some comfort cooling applications such as offices and retails (Jain, 2008; Xu, 1998). For comfort cooling, evaporative cooling is most suited to dry climatic regions; simple direct ECSs with wetted pads (also known as desert coolers) have been widely applied in the dessert climate (Datta, *et al.*, 1987; Watt and Brown, 1997).

However, traditional direct evaporative coolers will increase the humidity of the air to a level that makes occupants uncomfortable under humid climatic conditions. In recent years, two-stage ECSs with advanced and improved designs have been studied and developed in many countries (Al-Juwayhel, *et al.*, 2004; Al-Juwayhel, *et al.*, 1997; Davis Energy Group, 2004; El-Dessouky, Ettouney and Al-Zeefari, 2004; Heidarinejad, *et al.*, 2009; Jain, 2007; Jain, 2008). These systems can improve efficiency and reduce the amount of moisture added to the air. If the right conditions and applications are identified, they could be applied to a wider range of climatic zones.

To develop effective systems for utilizing ECSs in different climates and seasons, it is important to study the fundamental principles and operating characteristics of the systems. This research paper explains the working principles of two-stage ECSs and assesses their performance in Hong Kong which has a hot and humid climate. The local climatic factors are investigated and the characteristics of the systems are evaluated.

2. Basic Principles

Evaporative cooling is a physical phenomenon in which evaporation of a liquid, typically into surrounding air, cools an object or a liquid in contact with it. Adiabatic evaporation of water provides the cooling effect. Latent heat is needed to evaporate the liquid and this heat comes from the liquid itself and the surrounding gas and surfaces.

2.1 Types of Evaporative Cooling Systems

There are many possibilities for evaporative cooling configurations (El-Refaie and Kaseb, 2009). Table 1 shows five common methods of air-cooling using water as the primary coolant (Dartnall, *et al.*, 2008). In most cases the performance of these systems surpasses vapour compression systems because the power requirements for compressors is eliminated.

Table 1. Five methods of air-cooling by water (Dartnall, *et al.*, 2008)

DEC: Direct Evaporative Cooling	Uses wetted porous media (typically cellulose fibres), colloquially known as “Swampies”
IEC: Indirect Evaporative Cooling	Employs a heat exchanger to separate coolant water from cooled air
IDEC: Indirect Direct Evaporative Cooling	Employs both a heat exchanger and wetted media in series
ICER: Indirect Cycle Energy Recovery	Employ a heat exchanger that serves to cool in summer and recover heat from waste air in winter
DICER: Dual Indirect Cycle Energy Recovery	Employ a heat exchanger that serves to cool in summer and recover heat from waste air but also having a small “chiller” coil for de-humidification

The single effect direct evaporative cooling (DEC) system is a very simple configuration and includes suction fan, water circulation pump, packing material, water spray nozzles, and water collection tank (ASHRAE, 2007). The cooling path of the air during the process is represented by an adiabatic saturation curve. On the other hand, the indirect evaporative cooling (IEC) system combines the evaporative cooling effect in a secondary airstream with a heat exchanger to produce cooling without adding moisture to the primary airstream.

In general, the wet-bulb temperature (WBT) of the entering airstream limits DEC. The WBT of the secondary airstream limits IEC.

2.2 Two-stage Evaporative Coolers

Two-stage indirect/direct evaporative coolers (see Figure 1) can cool air to lower temperatures than are attainable with direct (“one-stage”) evaporative coolers, and add less moisture to the indoor air. In these coolers, a first-stage indirect evaporative cooler lowers both the dry-bulb temperature (DBT) and WBT of the incoming air. After leaving the indirect stage, the supply air passes through a second-stage direct evaporative cooler. Figure 2 shows the cooling process on a psychrometric chart. First-stage cooling follows a line of constant humidity ratio as no moisture is added to the primary airstream; the second stage follows the WBT line at the condition of the air leaving the first stage (ASHRAE, 2008).

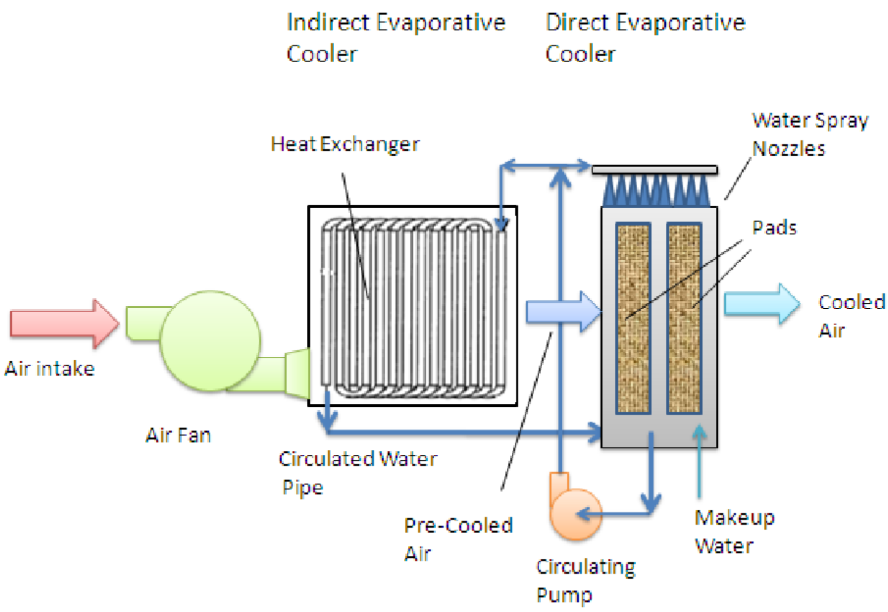

Figure 1. Indirect-direct evaporative cooling system [adapted from Al-Juwayhel, *et al.* (2004)]

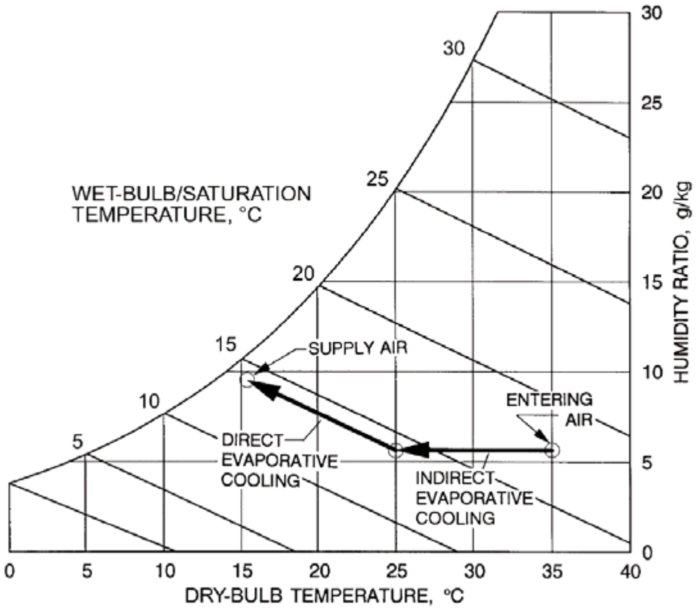

Figure 2. Indirect-direct evaporative cooling process (ASHRAE, 2008)

2.3 System Configurations

Evaporative cooling and vapour-compression air conditioning are sometimes used in combination to yield optimal performance. For instance, in areas with a higher design WBT or where the design requires a supply air temperature lower than that attainable using IDEC, a third cooling stage (e.g. a direct-expansion refrigeration unit or a chilled-water coil) may be applied. This stage could be located either upstream or downstream from the DEC stage, but always downstream from the IEC stage (El-Refaie and Kaseb, 2009). Refrigerated cooling is energized only when evaporative stages cannot achieve the required supply air temperature. This hybrid configuration allows indirect cooling when the WBT is low and mechanical cooling when the WBT is high or when dehumidification is necessary. Some evaporative coolers may also serve as humidifiers in the heating season (ASHRAE, 2008).

In practice, IEC and IDEC systems may be applied in two configurations to substitute for part of the refrigeration load: the first is as a pre-conditioner for fresh air supply of a normal vapour compression system and the second as a dedicated air-conditioning system (ASHRAE, 2008). When used for fresh air treatment, the indirect evaporative cooler should be designed to use both outside air and building exhaust as the secondary airstream; whichever source has the lower WBT would be used. Dampers and an enthalpy sensor are used to control this process. If the latent load in the space is significant, the WBT of the building exhaust air in cooling mode may be higher than that of the outside air. In this case, outside air may be used more effectively as secondary air to the IEC stage. Under some conditions, indirect evaporative precoolers can also provide limited dehumidification capabilities.

3. Climate Analysis

By their very nature, ECSs are more dependent on climatic conditions than mechanically cooled systems (El-Refaie and Kaseb, 2009). Therefore, to study the characteristics and performance of ECSs, local climate analysis is very important.

3.1 Wet Bulb Depression

The wet-bulb depression (WBD) is the difference between the DBT and the WBT. It is a measure of the potential for evaporative cooling. The greater the WBD, the greater the evaporative cooling effect. The WBD data for Hong Kong were developed by analyzing the hourly DBT and WBT data from the Hong Kong Observatory (www.hko.gov.hk). The hourly data for a Test Reference Year (Year 1989) were used in this research to represent the long-term climatic conditions in Hong Kong (Hui and Lam, 1992).

Table 2 gives a summary of the annual temperatures and humidity in Hong Kong. It is found that the WBD in Hong Kong is not large (the annual mean WBD is only 2.6 °C) and the relative humidity (RH) is quite high throughout the year (the annual mean RH is 78%).

Table 2. Summary of annual temperatures and humidity in Hong Kong

	DBT (°C)	WBT (°C)	RH (%)	WBD (°C)
Absolute maximum	33.7	28.6	99.0	12.4
Absolute minimum	7.6	6.2	25.0	0.1
Annual mean	23.0	20.4	78.0	2.6

Notes:

1. DBT = dry-bulb temperature; WBT = wet-bulb temperature; RH = relative humidity; WBD = wet-bulb depression (determined from hourly DBT and WBT).
2. The data are calculated for the Test Reference Year of Hong Kong (Year 1989)

3.2 Major Properties of WBD in Hong Kong

Figure 3 and Figure 4 show respectively the average monthly WBD and average hourly WBD in Hong Kong. The monthly profile indicates that September, October and November have the highest WBD (from 3.1 to 3.5 °C) and offer the largest potential for evaporative cooling; the months January, April and May have the lowest WBD (from 1.6 to 1.9 °C). From Figure 4, the hourly profile shows that the hours 12:00-14:00 have the highest WBD (about 3.6 °C) and the daytime WBD at 09:00-18:00 is above 2.5 °C. The evaluation of WBD at different times of the day month after month is the basis for an economic analysis for the ECSs.

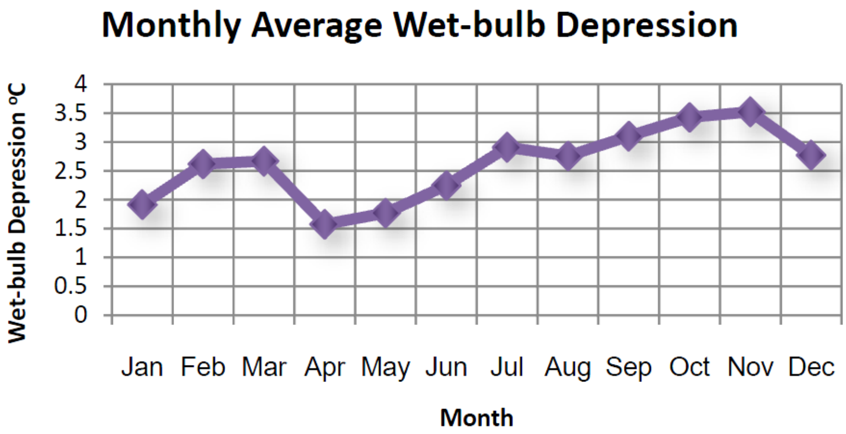

Figure 3. Average monthly wet-bulb depression in Hong Kong

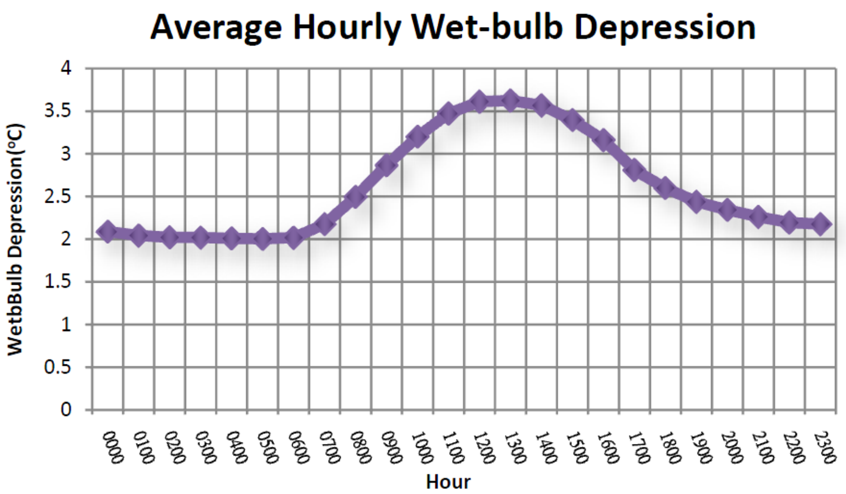

Figure 4. Average hourly wet-bulb depression in Hong Kong

Table 3. Cumulative occurrence of wet-bulb depression in Hong Kong

Wet-bulb depression greater than (°C)	Percentage of cumulative occurrence
0.5	95.98
1.0	86.26
1.5	74.28
2.0	59.87
2.5	45.72
3.0	32.53
3.5	22.49
4.0	15.67
4.5	11.15
5.0	7.01
5.5	4.27
6.0	2.63

In order to evaluate the WBD distribution over the year, the percentage of cumulative occurrence of the WBD is shown in Table 3. These data can be a useful tool for predicting the applicability and effectiveness of ECSs.

3.3 Psychrometric Indication

Hui and Tsang (2005) have analyzed the climatic data in Hong Kong for sustainable building design and developed the frequency of occurrence of the Hong Kong's climatic conditions plotted on a psychrometric chart (see Figure 5). The frequency of occurrence of the DBT/WBT pairs can be studied from the percentage numbers shown on the chart. To investigate the potential and operation of ECSs in Hong Kong, the WBD lines for 2, 3 and 4 °C were constructed on this chart (the thick lines in Figure 5). It should be noted that the WBD lines are similar in shape to the RH lines because both of them are related to the humidity level.

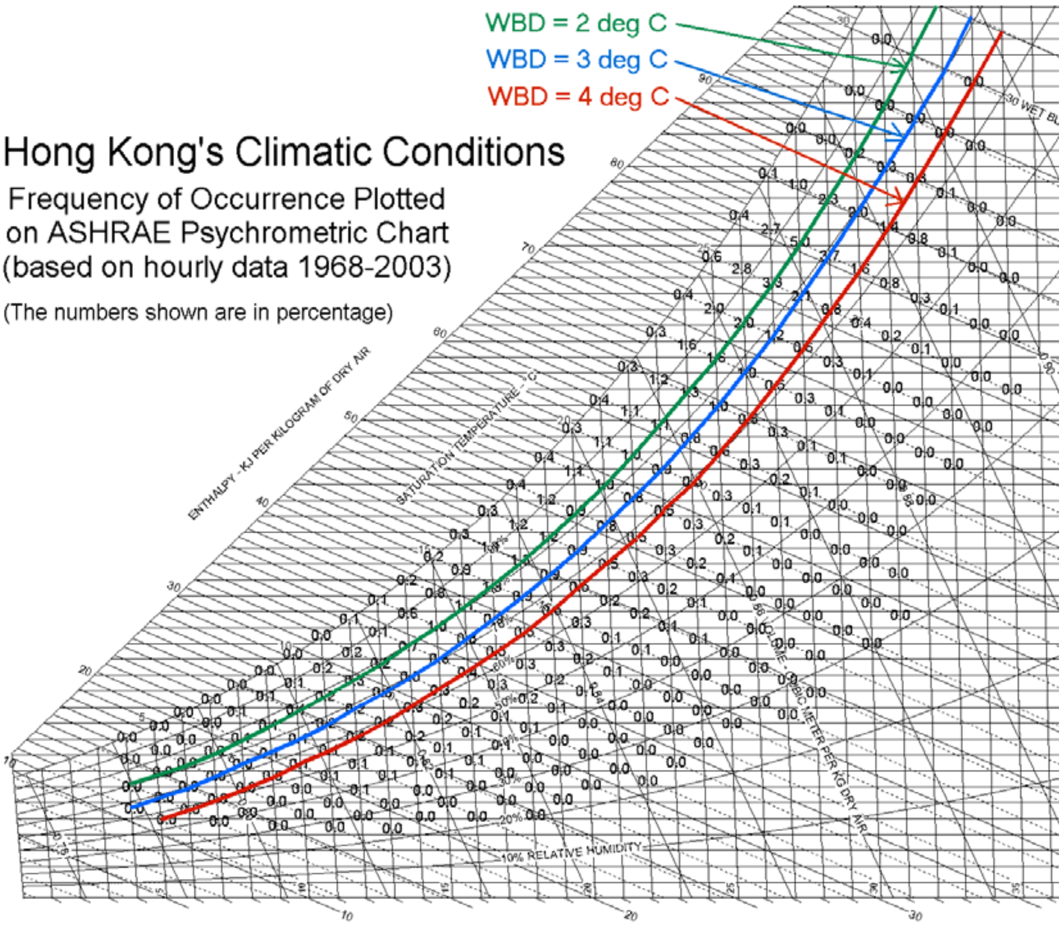

Figure 5. Wet-bulb depression lines and Hong Kong's climatic conditions plotted on a psychrometric chart [adapted from (Hui and Tsang, 2005)]

The information on Figure 5 is very useful for assessing the design and operation of heating, ventilation and air-conditioning (HVAC) systems when ECS is being considered. Lazzarin (2007) has used the psychrometric chart and simple diagrams to analyze evaporative cooling and free cooling operation. Every climatic condition represented on the chart suggests the most suitable treatment of the air; the knowledge of the climatic data of a particular site allows us to evaluate the possible energy savings deriving from free-cooling by evaporation.

4. System Performance

The use of ECS for comfort air conditioning depends on the climatic conditions and the specific nature of application (El-Refaie and Kaseb, 2009). The decision to use an ECS in a building project depends largely on an assessment of net energy saved against capital investment (Costelloe and Finn, 2003). Analysis of the system efficiency will be helpful.

4.1 System Effectiveness

The adiabatic effectiveness of ECSs is defined as the ratio of the actual drop in the DBT of the air to the maximum possible temperature drop (Al-Juwayhel, *et al.*, 2004). Based on this, the cooling efficiency (ε) of the IEC and DEC units is given by the following equations (El-Dessouky, Ettouney and Al-Zeefari, 2004):

$$\varepsilon = (DBT_i - DBT_o) / (DBT_i - WBT_i) \quad (1)$$

$$= (DBT_i - DBT_o) / (WBD_i) \quad (2)$$

$$= R / (R + A) \quad (3)$$

where ε is the cooling efficiency (%)
DBT_i and DBT_o are the inlet and outlet DBTs of the air stream (°C)
WBT_i is the inlet WBT of the air stream (°C)
WBD_i is the wet-bulb depression of the inlet air (°C) (= $DBT_i - WBT_i$)
R is the cooling range (°C) (= $DBT_i - DBT_o$)
A is the cooling approach (°C) (= $DBT_o - WBT_i$)

Both the cooling range, R, and the cooling approach, A, depend on the degree of cooling required and the system characteristics. The design characteristics are the type and thickness of the packing material as well as the type of water nozzles; the operating variables are the water-to-air mass flow ratio (Al-Juwayhel, *et al.*, 2004). The cooling efficiency of the stand-alone IEC and DEC units are lower than one, but that of the combined two-stage system may be greater than one, because the outlet DBT of the air stream can be lower than the inlet WBT (El-Dessouky, Ettouney and Al-Zeefari, 2004).

In theory, adiabatic DEC is less than 100% effective, although evaporative coolers are often up to 85 to 95% effective (ASHRAE, 2007). The effectiveness of DEC and IEC depends on the entering air condition. Where outside air is used in a DEC system, the design is affected by the prevailing outside DBT and WBT as well as by the application. Where conditioned exhaust air is used as secondary air for IEC, the design is less affected by local weather conditions, which makes the ECS viable in hot and humid environments.

4.2 Energy Efficiency Ratio

The energy efficiency ratio (EER) is often used to determine the efficiency of various air cooling systems. In general, EER is defined by the following equation:

$$EER = [\text{Cooling output (Btu/h or W)}] / [\text{Input power (W)}] \quad (4)$$

The cooling output, Q, in kW, for the different arrangement of ECS is evaluated from the following relations (Al-Juwayhel, *et al.*, 2004):

(a) Direct Evaporative Cooling (DEC)

$$Q_{DEC} = m_a(W_i - W_o)\,\lambda \qquad (5)$$

(b) Indirect Evaporative Cooling (IEC)

$$Q_{IEC} = m_a Cp_a\,(DBT_i - DBT_o) \qquad (6)$$

(c) Two-Stage Evaporative Cooler

$$Q_{DEC/IEC} = Q_{IEC} + Q_{DEC} = m_a Cp_a(DBT_i - DBT_o) + m_a(W_{ei} - W_i)\,\lambda \qquad (7)$$

(d) Three-Stage Evaporative Cooler

$$Q_{DEC/IEC-MVC} = Q_{IEC} + Q_{DEC} + Q_{MVC}$$

$$= m_a Cp_a(DBT_i - DBT_o) + m_a(W_{ei} - W_i)\,\lambda + m_a(W_{ei} - W_{eo})\,\lambda \qquad (8)$$

where W_i and W_o are the inlet and outlet absolute humidity (kg/kg)
m_a is the mass flow rate of air (kg/s)
λ is the latent heat of evaporation evaluated at 0°C (kJ/kg)
DBT_i and DBT_o are the inlet and outlet DBT (°C)
Cp_a is the air specific heat at constant pressure (kJ/kg/K)
W_{ei} and W_{eo} are the absolute humidity of air before and after the evaporator of the air conditioning unit, respectively (kg/kg)

For the two- and three-stage ECSs, IEC lowers both the DBT and WBT of the air entering a DEC stage and, consequently, lowers the supply air temperature. When used with mechanical cooling on 100% outside air systems, with the secondary air taken from the conditioned space, the precooling effect may reduce peak cooling loads between 50 and 70% (ASHRAE, 2007). Total cooling requirements may be reduced between 40 and 85% annually depending on location, system configuration, and load characteristics. Indirect evaporative coolers may also function as heat recovery systems, which expands the range of conditions over which the process is used. In fact, IEC, when used with building exhaust air, is especially effective in hot and humid climates.

ASHRAE (2007) also pointed out that DEC systems in low humidity regions typically yield energy savings of 60 to 80% over traditional vapour compression systems. IDEC systems yield 40 to 50% energy savings in moderate humidity zones. Indirect systems with vapor-compression second stages can provide adequate comfort cooling in high-humidity zones with savings of up to 25%.

4.3 Performance Evaluation for Hong Kong

A simple two-stage IDEC system as shown in Figure 6 was taken for the investigation. The system parameters being studied include supply air temperature, possible cooling effects and EER. When performing the system calculations, the following assumptions have been made:

- No heat gain or loss to the surrounding
- No fan heat is added to supply air
- Effectiveness of the IEC sub-system (ε_{IEC}) is 70%
- Effectiveness of the DEC sub-system (ε_{DEC}) is 90%
- Building exhaust air is taken as the secondary airstream
- Power input is 650 W and air flow rate is 600 l/s (both are constant over the year)

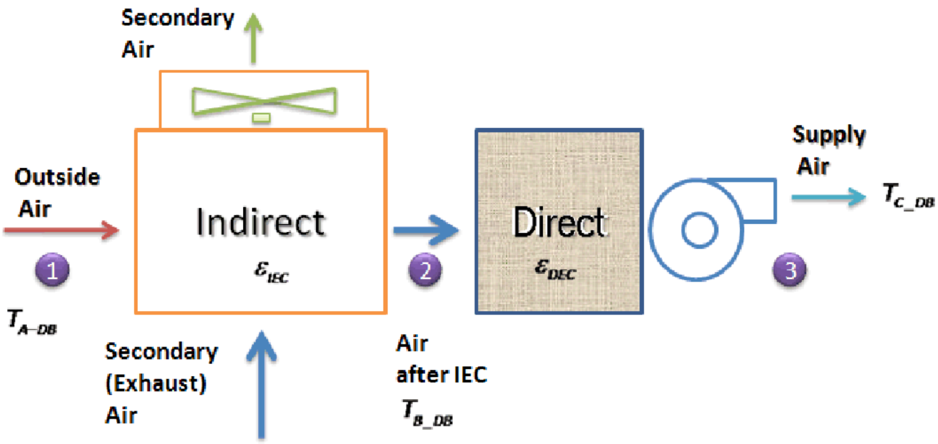

Figure 6. A simple two-stage indirect/direct evaporative cooling system

Table 4 shows a summary of the system performance estimated over the 12 months for the two-stage IDEC system. It can be seen that the supply air DBTs range from 12.1 °C (February) to 24.0 °C (August). The two-stage sensible EER vary from 2.77 (April) to 6.00 (November). As compared with other worldwide locations with less humid climates, Hong Kong does not have a very attractive potential for ECSs. However, if suitable projects and comfort controls are considered (e.g. in some commercial, industrial, agricultural applications), the ECSs can still bring and achieve significant energy savings in the HVAC systems. To explore the optimal system design and operation, more innovative ideas are needed from the designers.

Table 4. System performance of the two-stage indirect/direct evaporative cooling system

Month	Outside air mean DBT/WBT (°C)	Outside air mean DBT - mean WBT (°C)	Two-stage indirect DBT/WBT (°C)	Supply air DBT (°C)	Two-stage sensible capacity (W)	Two-stage sensible EER (W/W)
Jan	15.7 / 13.8	1.93	14.3 / 12.1	12.3	2179	3.35
Feb	16.6 / 14.0	2.60	14.8 / 11.8	12.1	2906	4.47
Mar	18.6 / 15.9	2.67	16.7 / 13.7	14.0	2976	4.58
Apr	22.0 / 20.4	1.58	20.9 / 19.1	19.2	1803	2.77
May	25.1 / 23.4	1.77	23.9 / 21.8	22.0	2041	3.14
Jun	27.5 / 25.3	2.25	26.0 / 23.3	23.6	2574	3.96
Jul	28.8 / 25.9	2.91	26.8 / 23.4	23.8	3296	5.07
Aug	28.9 / 26.1	2.76	26.9 / 23.7	24.0	3137	4.83
Sep	28.1 / 25.0	3.10	25.9 / 22.4	22.7	3479	5.35
Oct	25.1 / 21.7	3.43	22.7 / 18.8	19.1	3830	5.89
Nov	21.5 / 18.0	3.52	19.1 / 15.1	15.5	3904	6.00
Dec	17.8 / 15.0	2.77	15.9 / 12.7	13.1	3084	4.74

Notes: The data are calculated for the Test Reference Year of Hong Kong (Year 1989)

5. Discussions

Two-stage ECSs could have better thermal and energy performance than single-stage systems. For a hot and humid climate like Hong Kong, they can be applied during the relatively dry period of the year and can provide moderate relief cooling during more humid period. The systems may be used to increase capacity and reduce the electrical demand of a direct expansion air conditioner or chiller. Both the condenser and makeup air may be evaporatively cooled by DEC and/or IEC. By using a combination of DEC and IEC with recirculation of part of the process air, a regenerative evaporative cooler can also been achieved.

The thermal performance of different arrangements of ECSs has been evaluated by other researchers (Al-Juwayhel, *et al.*, 2004; Al-Juwayhel, *et al.*, 1997; El-Dessouky, Ettouney and Al-Zeefari, 2004). The variables include packing thickness, mass flow rate of water to the precooler, and mass flux of water irrigating the packing. Recently, theoretical and numerical studies on the heat and mass transfer process of ECSs have also been established (Wu, Huang and Zhang, 2009). The information will be useful for designing and optimizing the ECSs.

To understand the latest trends of development, some emerging technologies for advanced ECSs are described and discussed in the followings.

5.1 Desiccant Technologies

Desiccant (e.g. silica gel or zeolite) is a hygroscopic material that can be used to absorb moisture from the air. Desiccant cooling system using indirect evaporative cooler desiccant-assisted systems has the potential to enhance the overall system performance (Belding and Delmas, 1997). It is believed that desiccant technologies can widen the scope of ECSs for comfort cooling to even the most humid regions (Bom, *et al.*, 1999). In such systems, the desiccant is used first to dehumidify the ventilation air to a desired state; then, ECS (either direct or indirect or a combination thereof) is used to cool the air to the desired supply air temperature. When coupled with desiccant technologies, ECS could displace traditional vapour compression systems in many applications.

Zhao, *et al.* (2009) found that the ECS is suitable for most China regions, particularly Harbin, Kunming, Shijiazhuang, Beijing and Xian, where hot and dry climate conditions are the common situations. When implemented with a pre-dehumidification device e.g. a desiccant system, the ECS can be used effectively in the humid areas, like Shanghai and Guangzhou.

5.2 Solar Evaporative Cooling

ECSs require little energy to run, and because the presence of strong sunshine coincides with the need for cooling, a link with solar energy appears to be attractive. Small ECS units using solar photovoltaics (PV) have been developed in some countries (Davis Energy Group, 2004); some of the products can provide cost-efficient cooling in grid-and non-grid settings.

Dartnall, *et al.* (2008) has investigated how to derive the energy of IEC from the solar source so as to power the fans and small water pumps of the ECSs. He discovered that a humid climate also yields a very high COP when a relatively small PV powered vapour compression heat pump augments the system, in an energy recovering configuration. This can reduce the system's dependence on non-renewable energy.

5.3 Sustainable Building Design

ECSs have a good potential for use within environmentally sustainable buildings because of the environmental benefits they can offer (Dartnall, *et al.*, 2008). Since many of the IEC systems are 100% fresh air systems, they are particularly suited to applications where high quantities of fresh air are required, e.g. hospitals and health centres. With the high fresh air rates of the systems, indoor environment quality is greatly improved.

If a sustainable building employs a mixed mode air conditioning system where natural ventilation and mechanical air conditioning systems are used concurrently (when required), the ECSs could be integrated into the different modes of HVAC operation to reduce the building energy consumption. Also, ECSs work well with new types of energy efficient air distribution systems, such as underfloor air distribution systems (UFAD). In addition, when coupled with a rainwater harvesting system, ECS has little or no potable water consumption.

6. Conclusions

Low energy and environmentally friendly air-conditioning has received more and more attention. Evaporative cooling can be an alternative to mechanical cooling depending on climatic conditions and building load characteristics. However, up to now, ECSs have not been widely accepted and known in hot and humid climates, even though they could potentially provide energy savings and other environmental benefits. Many inland regions have high summer temperatures with low humidity ratios which is suitable for ECSs. In practice, the coupling of a third cooling stage can extend the cooling range to other climates.

From the analysis of Hong Kong conditions, it is found that the high humidity conditions throughout the year in this climate do not permit regular use of the ECSs. However, there are still good potential for applying them to precool outdoor air and achieve significant energy savings in the air-conditioning. The efficiency of the systems will depend on the system configuration, component design and control strategies.

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