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ON-SITE TESTING OF EXHAUST AIR HEAT RECOVERY FOR AN ALL-FRESH-AIR A/C SYSTEM IN HONG KONG

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ABSTRACT

Application of heat recovery units in building HVAC systems can significantly save the energy consumed by conditioning fresh air. The indirect evaporative cooler (IEC), used as a pre-cooling device for fresh air in the hot-humid area, recovers both latent and sensible energy from the exhaust air. In this paper, a year-around on-site performance test was carried out in a wet market located in Hong Kong. The energy performance of the two A/C systems with exhaust air heat recovery units was analyzed and compared: an IEC coupled to an AHU; a traditional heat recovery wheel (HRW) coupled to an AHU. The heat recovery of IEC and HRW were collected under typical summer operation conditions. The results show that the HRW has better dehumidification performance than IEC, but the IEC can largely reduce the fresh air temperature by handling the sensible cooling load. During the whole year, the difference in the total heat recovery between IEC and HRW is within 2%. In cooling seasons, the energy efficiency of the two systems with IEC and HRW for exhaust air heat recovery can be improved by 27.6% and 25.7% respectively.

Keywords: Fresh air, indirect evaporative cooler, heat recovery wheel, air-conditioning system, building energy efficiency

NONMENCLATURE

Abbreviations

IEC	Indirect evaporative cooler
HRW	Heat recovery wheel
AHU	Air handling unit
COP	Coefficient of performance

Symbols

η	Wet-bulb effectiveness
ε	Enlargement coefficient
ΔP	Pressure drop
f_{Re}	Friction coefficient
Re	Reynolds number
d_e	Hydraulic diameter of air channel
L	Length of the channel
u	Air velocity

1. INTRODUCTION

Currently, with the growing concern of occupants on the indoor air quality, the demand increases in the fresh air flow rates in buildings [1]. The use of energy for fresh air handing accounts for approximately 30% of total energy consumption of air-conditioning systems, and it can be a higher proportion in some public buildings with high population density. Hybrid systems composed of heat recovery units and AHUs could achieve considerable energy saving by capturing a fraction of energy from exhaust air to the supply air [2]. As large amounts of energy were consumed by fresh air handling, more and more research and applications on alternative hybrid air-conditioning systems have been developed to improve the building energy efficiency in recent years.

The fresh air handling under a hot and humid climate requires a high-energy cost for both sensible and latent cooling loads [3]. The heat recovery wheels (HRW), have been widely used in hot and humid regions as a traditional method for the energy recovery in A/C systems. In the HRW, the desiccant wheel with small channels rotates continuously between the fresh air chamber and exhaust air chamber. By transferring the

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excess heat and moisture to exhaust air and then taken away, the fresh air can be cooled and dehumidified. In order to evaluate the performance and energy saving effectiveness of HRW, experiments have been carried out by Chen et al. [4] to investigate the effects of process air temperature and humidity on the system's performance. Yamaguchi and Saito [5] developed the mathematical model of the desiccant air-conditioning system and validated it by experimental results under various operating conditions. Ke et al. [6] estimated the applicability of the ventilators for only sensible or total heat recovery in the four climate zones of China, with the consideration of both the energy saving and operation cost.

As a promising alternative air-cooling solution, the conventional indirect evaporative cooler (IEC) has been widely applied in hot and dry (or moderate) climate regions with only sensible cooling involved. In humid areas, the IEC can be used as a pre-cooling device in A/C system for energy recovery. The cold and dry exhaust air is worked as secondary air in IEC to evaporate the spraying water. The primary air (fresh air) in adjacent channels can be cooled and dehumidified by lowering the temperature to the dew point, with condensation occurred in the heat exchanger. Chen et al. [7] firstly proposed the numerical model of IEC in the presence of condensation based on heat and mass transfer mechanism. Cui et al. [8] theoretically investigated the performance of an IEC used as a heat exchanger of A/C system and indicated it can fulfill 47% of fresh air cooling load under humid tropical climate. However, few studies focused on the tested performance of hybrid A/C system with IEC for total heat recovery in building applications under wide varying ambient conditions.

In this regard, on-site testing has been conducted in a wet market which adopted both the IEC and HRW units for the energy recovery of the all-fresh-air A/C systems. The heat recovery and energy efficiency have been compared between the two systems during the year-around test duration. The results can provide references for the applications of IEC and HRW coupled to the AHU in hot and humid regions like Hong Kong.

2. PERFORMANCE INDEX

2.1 Cooling and dehumidifying

In the IEC, the exhaust air absorbs heat from the heat exchanger plates wetted by spraying water with aid of water evaporation. The fresh air on the other side of the cold plates can be cooled, and can even be dehumidified under condensation states. To rate the installed IEC, two indexes are adopted by considering both the cooling and dehumidifying performance. One is in Eq. (1), the wet-bulb efficiency (η_{wb}), used as an evaluation metric for rating the IEC in handling sensible heat. Another is the enlargement coefficient (ε) in Eq. (2), calculated as the ratio of the total heat transfer rate to the sensible heat transfer rate. It can estimate the enlarged heat transfer rate associated with condensation.

$$\eta_{wb} = \frac{t_{p,in} - t_{p,out}}{t_{p,in} - t_{wb,s}} \tag{1}$$

$$\varepsilon = \frac{Q_{tot}}{Q_{sen}} = \frac{c_{pa} \cdot m_p \cdot (t_{p,in} - t_{p,out}) + h_{fg} \cdot m_p \cdot (\omega_{p,in} - \omega_{p,out})}{c_{pa} \cdot m_p \cdot (t_{p,in} - t_{p,out})} \tag{2}$$

The HRW cools the fresh air by recovering energy from cold and dry exhaust air, and dehumidifies fresh air by the solid desiccants in the moisture absorption core. Two efficiencies (ε_{sen} and ε_{lat}) can be used to estimate the sensible and latent heat transfer rate of HRW, as shown in Eq. (3) and (4). They vary according to different operation conditions affected by inlet air velocity, temperature and humidity.

$$Q_{sens} = \varepsilon_{sens} \cdot m_{\min} \cdot c_p \left(t_2^{'} - t_1^{'} \right) \tag{3}$$

$$m_{transfer} = \varepsilon_{lat} \cdot m_{\min} \cdot \left(w_2^{'} - w_1^{'} \right) \tag{4}$$

2.2 Power consumption

The power consumption of IEC consists of three parts: the primary air fan, secondary air fan and a water pump. The fan power is dominated by air pressure drop which calculated in Eq. (5). Due to the counter-flow of secondary air and spraying water drops, the pressure drop in the exhaust air channel is 2~3 times larger than the fresh air channel.

$$P_{fan} = Q \cdot \frac{f_{Re}}{Re} \cdot \frac{L}{d_e} \cdot \frac{\rho u^2}{2} \cdot K \tag{5}$$

$$P_{IEC} = P_{p,fan} + P_{s,fan} + P_{pump} \tag{6}$$

The electric components of HRW include the supply air fan, exhaust air fan and a rotating motor. Due to the rotary wheel, a high pressure drop is experienced across the fresh air and exhaust air ducts, usually exceed 150Pa [9] depending on the configuration.

$$P_{HRW} = P_{s,fan} + P_{e,fan} + P_{motor} \tag{6}$$

3. TEST OVERVIEW

3.1 Building information

The two AHUs with exhaust air heat recovery units were installed in a wet market located in Hong Kong. All-fresh-air A/C system was adopted in the one storey building with a conditioned floor area of 260m^2 and height of 6.7m. The total fresh air volume is 14000m^3/h which is provided by two same AHUs combined with both IEC and HRW for energy recovery. These two systems were operated simultaneously under the same outdoor climates. The operation scheme of the AHUs is shown in Figure 1, with one for IEC bypassed and another for HRW bypassed.

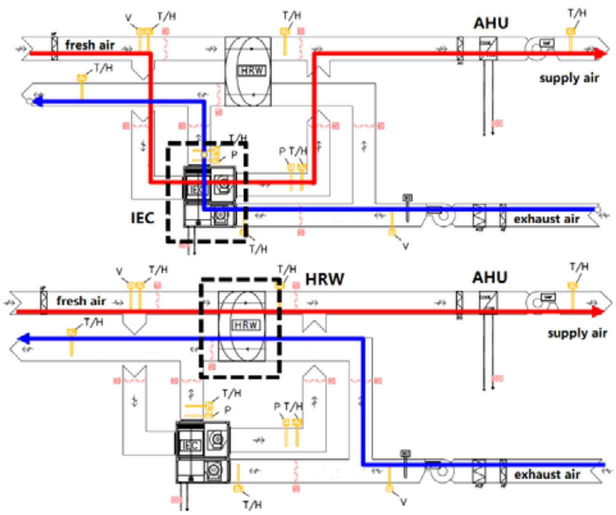

Fig 1. Device connection of the two hybrid A/C systems

The installed IEC was a prototype produced by a cooperated manufacturer based on previously published data on configuration optimization [10]. The operating performance of the IEC for total heat recovery was comprehensively analyzed and correlated by practical models [11]. The installed HRW is a commercial product from Holtop Co. with nominal design parameters. The design parameters of the main components of HRW are provided by the manufactory.

3.2 Sensors and parameters

In this project, various types of transmitters are used to transmit real-time data to the central management unit through the data logger. The tested parameters and selected sensors for the hybrid A/C system are listed in Table 1.

Table 1 Sensors and tested parameters

Parameter	Range	Accuracy	Supplier
Temp.,	-15~60℃	±0.3℃	E+E Co., Pt1000,
Humidity	10~95% RH	±2.5% RH	Model: EE160
Air velocity	0~10 m/s	±0.2m/s	E+E Co., Model: EE65
Pressure drop	< 250, 500, 1250 Pa	±1%	Dwyer Co., MS-112
Data logger	Graphtec, Model GL240, 10-channel,		

4. RESULTS DISCUSSION

The set-point temperature and relative humidity for the air-conditioned space in the wet market are 24°C, 60%, and the supply air temperature of AHU is set at 13°C to control the cooling and humidity load. Hong Kong has a humid subtropical climate, with an average temperature of 17°C and relative humidity of 78% in winter. According to the simulation result, the cooling load exists all year round in the wet market. The two hybrid A/C systems operated from 6:30 to 20:30 for a whole year.

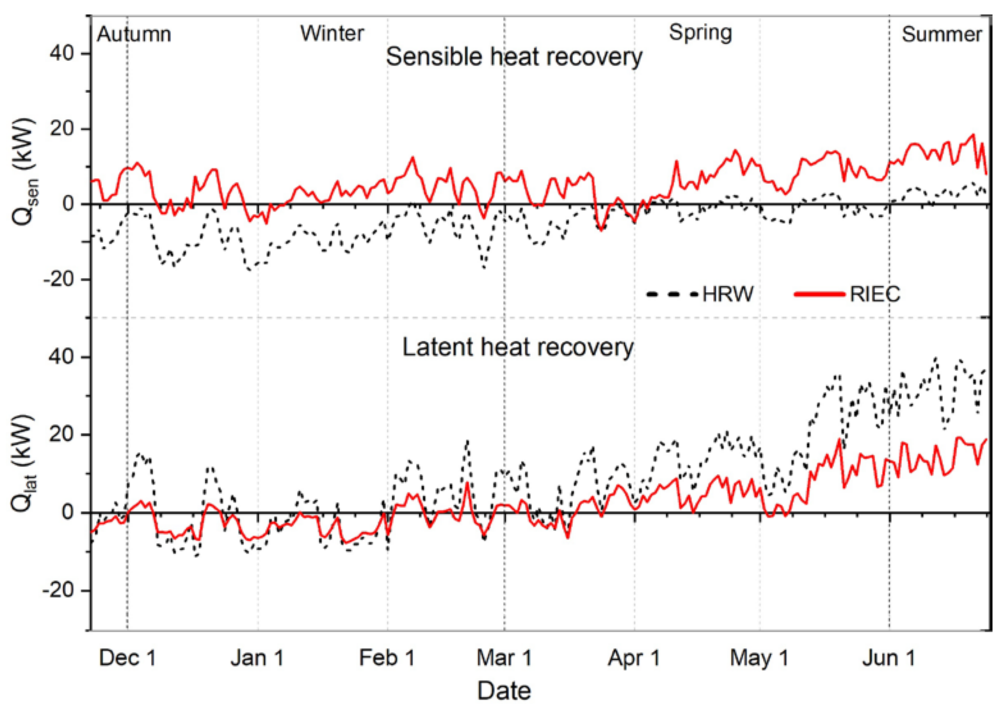

Fig. 2 Sensible and latent heat recovery of IEC and HRW.

4.1 Heat recovery

Based on the inlet and outlet air states of IEC and HRW, the sensible and latent heat recovery can be obtained, as shown in Figure 2. By using exhaust air and water evaporation, the IEC achieved higher sensible heat recovery than the HRW throughout the year. However, the latent heat recovery of the HRW is always higher than that of the IEC due to the usage of solid desiccant. In general, the processed fresh air temperature from the HRW gets 2°C higher than that processed by the IEC, while the relative humidity can be reduced to 63% in the HRW instead of 78% in the IEC. The total heat recovery of the RIEC consists of 60% sensible heat recovery and 40% latent heat recovery. However, the latent heat recovery is dominated for thein HRW, which contributes to nearly 90%.

The monthly total heat recovery of the IEC and HRW for per square meter are as shown in Figure 3. In winter and transition seasons, the IEC achieved higher heat recovery rate than the HRW. In winter, the fresh air is cold and almost in the same humidity with the exhaust air. The HRW achieved no total heat recovery in winter due to the inversed heat transfer between fresh air and exhaust air. However, during cooling seasons (Apr, May, Jun, Jul, Aug and Sep), the total heat recovery of the HRW exceeds that of the IEC due to the improved dehumidification performance in humid weather. The annual total heat recovery of the HRW and IEC are 271 kWh/m^2 and 267 kWh/m^2, respectively, in which the difference between them is within 2%.

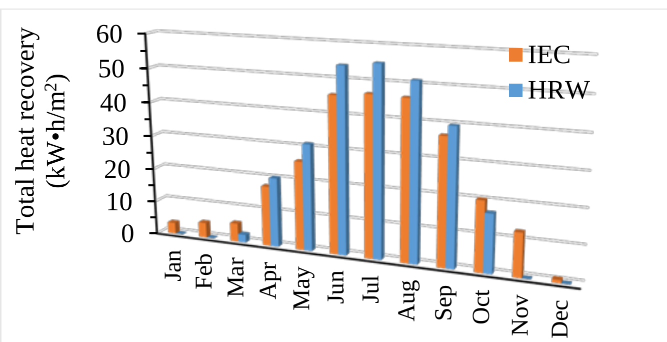

Fig. 3 Total heat recovery of IEC and HRW.

4.2 Energy efficiency

Although the IEC and HRW perform similarly on the annual total heat recovery, the energy efficiency of the two systems should be further investigated. To estimate the power consumption of the two systems, the pressure drop among the two heat recovery units was tested. It shows the pressure drop in HRW (nearly 200Pa) is much higher than that in RIEC (lower than 100Pa), results in larger fan power. Based on calculated pressure drops, the selected fan power of IEC and HRW are listed in Table 4. Moreover, there is a rotating motor (0.18kW) inside the HRW, and a small water pump (0.55kW) inside the IEC. As a result, the total power consumption of HRW is 1.3 times higher than that of IEC.

Table 2. Fan power in IEC and HRW

Parameter	Fresh air		Exhaust air	
	RIEC	HRW	RIEC	HRW
Air flow rate Q (m^3/h)	6228	6228	6840	6840
Internal efficiency η_0	0.75	0.75	0.75	0.75
Mechanical efficiency η_1	0.9	0.9	0.9	0.9
Motor capacity coefficient K	1.1	1.1	1.1	1.1
Pressure drop (Pa)	32	170	96	170
Fan power (W)	90	480	300	530

Figure 4 shows the electricity consumption of the two hybrid A/C systems with IEC and HRW throughout the whole year. The COP of the central air-conditioning system is assumed to be 4.5. Due to the less power consumption of the IEC, the hybrid A/C system with IEC consumed less energy than the one with the HRW, especially in winter and transition seasons. Although the HRW can reduce the energy consumption of AHU to a larger extent by recovering more heat from the exhaust air, it is less energy efficient than the RIEC due to the higher energy demand of itself. The annual total energy saving achieved by the A/C system combined with the IEC is 44.6 kWh/m^2, which is higher than that of the hybrid A/C system using HRW (28.9 kWh/m^2).

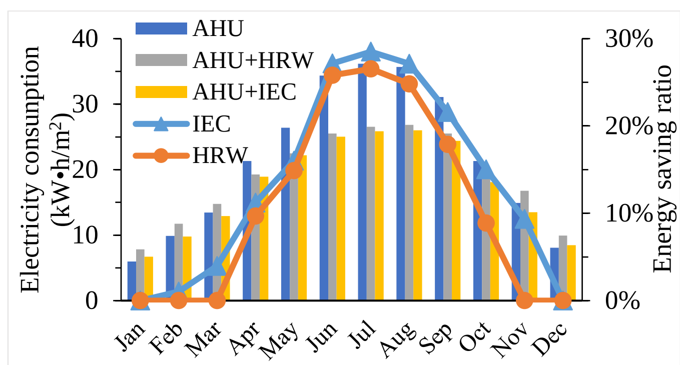

Fig. 4 Energy efficiency of the two A/C systems with IEC and HRW.

After comparing to the predicted electricity consumption of the A/C system without exhaust air heat recovery, the energy saving ratio of the IEC and HRW can be obtained, also shown in Figure 4. The energy-saving ratio of IEC was higher than that of HRW, especially in winter and transition seasons. The reason is that the IEC can achieve more heat recovery than the HRW during these periods and consume less energy. In summer, the heat recovered by HRW increases significantly and even overtakes that of IEC by a large amount. However, as the IEC has less energy consumption, there is little difference between the energy-saving ratio of the IEC and HRW even in summer. The annual energy saving ratio of the IEC and HRW are 13.4% and 10.7%, respectively. During the cooling season, the energy-saving ratio of the IEC and HRW are 27.6% and 25.7%, respectively.

5. CONCLUSIONS

As a highly energy-efficient solution for A/C systems, IEC has great application potential in Hong Kong or other similar hot and humid regions. Based on the year-round on-site testing in Hong Kong, the annual performance of the IEC and HRW used for exhaust air heat recovery was quantitatively analyzed. The comparative study was carried out on the heat recovery and energy efficiency between the IEC and HRW. Main conclusions are as follows:

- The dehumidification performance of the HRW is better than the IEC, while the IEC possesses greater sensible cooling performance than the HRW. The two systems can achieve a similar amount of total heat recovery during the whole year, in which the latent heat recovery accounts for 90% in the HRW and 40% in the IEC.
- The IEC can reduce the electricity consumption of the A/C system by 44.6kWh/m^2 per year, with an annual energy saving ratio (13.4%) higher than the HRW (10.7%). it is recommended that the IEC could be a better alternative of the HRW for the energy recovery of the all-fresh-air A/C systems.

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