https://doi.org/10.1016/j.apenergy.2018.05.046

Comparative study of on-off control and novel high-low control of regenerative indirect evaporative cooler (RIEC)

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Abstract

The main characteristic of an indirect evaporative cooler (IEC) is its dependency on ambient air conditions. To ensure stable indoor temperature and provide better thermal comfort for the occupants, proper control strategy is essential. However, very limited studies report the controller used in IEC. Therefore, two control schemes are comparatively studied for regenerative indirect evaporative cooler (RIEC) application, including conventional on-off control and newly proposed high-low (H-L) control. Under on-off control scheme, the fans are either in operation at constant rated speeds or turned off if the indoor temperature is satisfied. While under H-L control scheme, the fans would be switched between high speed and low speed rather than completely turned off. The annual performance of RIEC was simulated under the two control schemes based on the RIEC model and dynamic indoor heat and mass balance model. The results show that the H-L control is superior to on-off control by providing better thermal comfort, better indoor air quality and 11.3% less energy consumption annually. The advantages of H-L control are mainly reflected in transition seasons with smaller indoor temperature variation range, lower switch frequency of the fan speed, smaller predicted mean vote (PMV) variation and longer fresh air guarantee.

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Keywords: Indirect evaporative cooler; Comparative study; Controller; Thermal comfort; Energy efficiency

1. Introduction

Indirect evaporative cooler (IEC), a sustainable cooling device, has received intensive attentions worldwide in recent decades for its energy efficient, low energy consumption and environmental friendly features [1]. Based on cooling the air by water evaporation, the energy intensive compressor and environmentally harmful Chlorofluorocarbon (CFC) in the conventional mechanical vapor compression refrigeration (MVCR) system are unnecessary. The air passing through an IEC can be sensibly cooled by the walls with the aid of water evaporation in the adjacent channels. Unlike the MVCR system that highly replies on energy-intensive vapor compression process, an IEC equipped with only two air fans and a circulating pump is characterized by low energy consumption. In theory, the lower limit outlet air temperature of an IEC is the wet-bulb temperature of ambient air. However, in recent decade, a more advanced IEC named regenerative IEC (RIEC) was proposed and intensively studied, with the ability to cool the fresh air to its dew-point temperature [2].

The evaporative cooling is proved to have huge energy saving potential in hot and arid regions because of large evaporation driving force [3-5]. However, the main shortcoming of this technology is its high dependency on ambient weather conditions. The supply air temperature is greatly influenced by the variation of outdoor temperature, humidity and internal cooling load from season to season and even from minute to minute [6]. To ensure stable indoor temperature and provide better thermal comfort to the occupants, proper control strategy is essential.

However, current research on IEC focuses on heat and mass transfer modeling [7-10], performance evaluation [11, 12] and configuration optimization [13-15], very limited research work can be found reporting the control strategy in open literatures. The most simple and widely used control scheme is on-off control, in which the fans are either operated at a constant speed or turned off if indoor temperature is lower than the setting point. The on-off control is simple, stable and easy to implement, but two shortcomings can be identified. Firstly, no ventilation is provided when an IEC is at ‘off’ state. Satisfactory indoor air quality (IAQ) cannot be guaranteed, leading to building sick syndrome (BSS) or even outbreak of infectious diseases. Secondly, frequently switching on and off of a fan in transition season is inevitable. It will reduce the life span of the fan and increase its maintenance cost. Although on-off control is widely used in current IEC product, its actual performance has not been reported in detail in open literatures.

To overcome the weaknesses of on-off control, the development and availability of variable speed fan could provide an alternative solution. The fan speed is continuously adjustable under different cooling load. Maximum flow rate is provided at peak cooling load and smaller flow rate is supplied under lower cooling load. The variable speed fan and pump have been successfully implemented in many HVAC equipment and water distribution systems with considerable energy saved [16, 17]. New standards of variable speed air conditioning system in China have also been issued as GB21455-2013 and CEL 010-2016, providing minimum allowable values and energy efficiency grade for air-cooled condenser, fully enclosed speed-controlled compressor and speed-controllable air conditioner in climate type T1 [18, 19]. However, its most significant disadvantages are high cost and complexity in control algorithm [20, 21].

The disadvantages of on-off control and variable speed technology motivate us to develop a novel control strategy that balances the control performance and complexity. There are multi-speed fans available in the market to overcome the pricy and complexity of variable speed technology. The high-low (H-L) control is therefore proposed for IEC. The operation states of the fan include high speed, low speed and shutdown. The high speed is designed to meet the peak cooling load and the low speed meet the minimum fresh air demand of the occupants. The fan operates at high speed when the indoor air temperature is higher than the setting value and at low speed if the indoor air temperature is satisfied. The H-L control scheme combines the advantages of on-off control and variable speed fan for the following reasons. Firstly, no ventilation at ‘off’ state in on-off control is avoided. Secondly, the proposed H-L control can be realized using multi-speed fans without inverter. Therefore, it is much simpler and less costly than variable speed fan. Thirdly, usage of multi-speed fans is expected to provide energy saving potentials under low speed operation based on affinity laws. In sum, the successful carrying out of the novel control scheme of IEC would help achieve improved indoor air quality for occupants and reduced energy consumption.

Actually, the H-L control had been initially proposed by Xu et al [22] and applied into direct expansion air-conditioning system. Extensive experiment has been conducted to quantitatively compare the performance of H-L control and traditional on-off control in term of energy efficiency and fluctuation of indoor air parameters. The results show that improved humidity level and higher energy efficiency can be achieved by H-L control. Besides, hardware cost is much lower than that of variable speed technology, contributing to more potential marketoriented applications. Yan et al [23, 24] conducted further experimental and theoretical studies on the H-L control by expanding its application to multi-evaporator air conditioning (MEAC) system.

Although H-L control has been theoretical and experimentally investigated in MVCR system, it has not ever been proposed and quantitatively analysed for IEC. There are huge differences between MVCR system and IEC system. Firstly, the heat and mass transfer process in MVCR system is complex. It involves with refrigerant, metal walls and air in the evaporator, condenser, electronic expansion valve and compressor. However, the heat and mass transfer process in IEC takes place in primary air channel and secondary air channel with water, air and plate wall involved. Secondly, the MVCR system relies on vapour refrigerant compression process, which is greatly influenced by compressor speed and supply air fan speed. However, the IEC, relying on water evaporation process, is mainly influenced by ambient air temperature and humidity. Thirdly, previous H-L control in MVCR system is used for compressor and indoor supply fan. While the H-L control in IEC is used for primary air fan and secondary air fan.

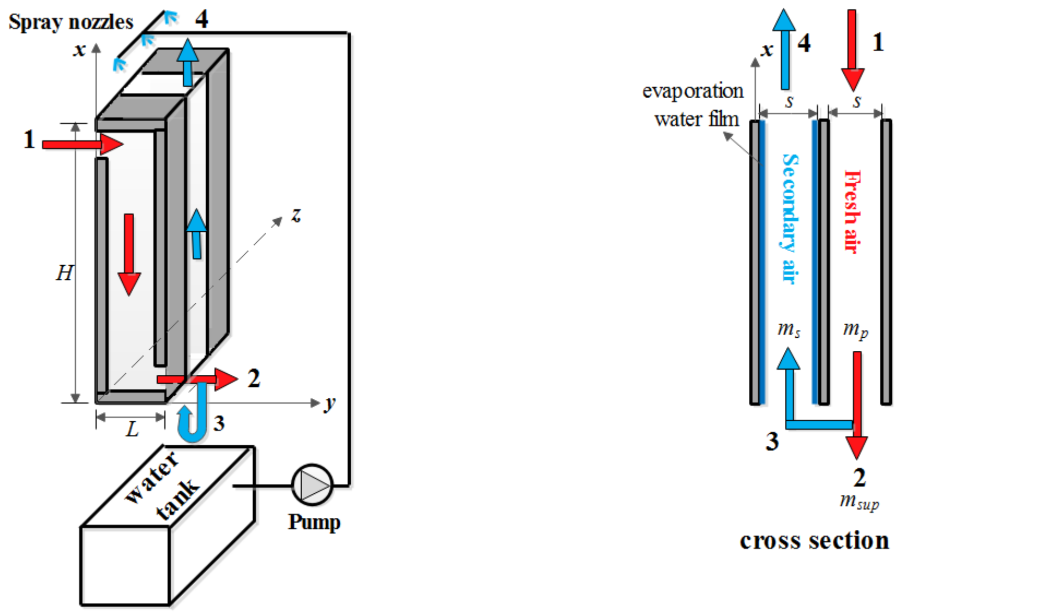
Considering the working principle and operational characteristics of MVCR system are very different from ambient sensitive IEC, a feasible study is needed to investigate whether H-L control is still effective for IEC, a promising alternative to MVCR system in the future. Although it can be seen from previous literature review that the multi-speed technology and H-L control have been widely discussed in MVCR system, very limited related studied can be found in the field of IEC. The only related research was conducted by Sohani et al in 2018 [25]. It is reported that a smart control system can provide a capability for 85% occupants with thermal comfort by switching the IEC fan under high speed, low speed and shutdown. It implies the H-L control strategy proposed in this paper, but the research focuses on evaluating the IEC performance, the detailed implementation and control effect of the controller have not been discussed.

From previous successful experience of applying H-L control in MVCR system, comparative study was conducted to IEC by using conventional on-off control and H-L control, respectively. This study aims, on one hand, to fill the research gap of very limited study regarding IEC control, and on the other hand, to investigate the suitability of applying H-L control in IEC and quantitatively measure its advantages over on-off control in terms of parameter variation, thermal comfort and energy efficiency.

The annual performances of a RIEC system were simulated under both on-off control and H-L control in this paper. The RIEC model and dynamic indoor heat and mass balance model are firstly established. Detailed control algorithms are introduced thereafter followed by a case study in Xi'an, a typical hot and arid region in western China. Comparison analyses have been conducted between the two control schemes in terms of indoor air temperature variation, thermal comfort, fan speed variation and energy consumption.

2. RIEC system description and model development

The most commonly used plate-type IEC consists of alternative wet and dry channels separated by thin plates. The water sprayed into the wet channels forms a water film and cools the separating wall with the aid of water evaporation under the reversed secondary air flow. The primary/ fresh air in the adjacent wall is then sensibly cooled without moisture added. The schematic diagram of a counter flow RIEC is shown in Fig.1. In RIEC, the wet channel extracts a part of fresh air from the outlet of the dry channel to form a secondary air flow.



1	Inlet primary/fresh air	$t_{p,in}, \omega_{p,in}$	3	Regenerative secondary air inlet	$t_{s,in}, \omega_{p,in}$
2	Supply air	$t_{sup}, \omega_{p,in}$	4	Secondary air outlet	$t_{s,out}, \omega_{s,out}$

Fig.1 schematic diagram of RIEC

A mathematical model describing the heat and mass transfer process inside an IEC needs to be established to facilitate the simulation under certain control algorithm. The RIEC is modeled and used for case study for its superior cooling capacity over conventional IEC. Several assumptions were made to simplify the complexity of the heat and mass transfer process of RIEC: (1) heat and mass transfer is perpendicular to the wall; (2) thermal resistance of liquid film and wall conduction are neglected; (3) air-liquid interface temperature is equal to the bulk liquid temperature. The model based on the energy and mass balance in the two channels is briefly introduced as Eq.(1) to Eq.(5). The detailed descriptions and heat and mass transfer coefficients can refer to the previous publication [26].

$$h_s(t_w - t_s)dA = c_{pa} m_s dt_s \quad (1)$$

$$h_{ms}(\omega_{sat} - \omega_s)dA = m_s d\omega_s \quad (2)$$

$$h_p(t_p - t_w)dA = c_{pa} m_p dt_p \quad (3)$$

$$dm_{ew} = m_s d\omega_s \quad (4)$$

$$m_s di_s - c_{pa} m_p dt_p = d(c_{pw} t_{ew} m_{ew}) \quad (5)$$

The mass flow rates of secondary air and primary air satisfy the relationship:

$$m_s = r \cdot m_p \quad (6)$$

The fresh air flow rate supplied to an indoor space is expressed as:

$$m_{\mathrm{sup}} = (1 - r) \cdot m_p \quad (7)$$

For counter flow RIEC, the boundary conditions are described as: x=H, t_{p}=$t_{\mathrm{p,in}}$; x=0, $t_{\mathrm{s,in}}$=$t_{\mathrm{p,out}}$; x=0, $\omega_{\mathrm{s,in}}$=$\omega_{\mathrm{p,in}}$; x=H, m_{ew}=$m_{\mathrm{ew,in}}$. The above one-dimensional ordinary equations are discrete by finite difference method and solved by Runge-Kutta iteration method. The RIEC model was validated by the experimental data derived from literature [27]. The largest discrepancy between the simulated outlet air temperature and experimental data is found to be 3% under various inlet air conditions, indicating the reliability of the simulation model.

The outlet fresh air from RIEC is supplied to indoor space to eliminate the cooling load. The variations of indoor air temperature (t_{N}) and humidity (ω_{N}) are constantly changing according to the cooling capacity provided by RIEC, cooling load and previous indoor air conditions, which are calculated as follows.

$$\rho c_{pa} V_{room} \frac{dt_{\mathrm{N}}}{dT} = Q_{sen} / 3600 - m_{\mathrm{sup}} \cdot c_{pa} \cdot \left(t_{\mathrm{N}} - t_{p,out}\right) \quad (8)$$

$$\rho V_{room} \frac{d\omega_N}{dT} = Q_{lat} / 3600 / h_{fg} - m_{\sup} \cdot \left(\omega_N - \omega_{amb}\right) \tag{9}$$

where, Q_{sen} and Q_{lat} are the sensible and latent cooling load at current moment, kJ/h. $t_{p,out}$ and ω_{amb} are the outlet air temperature of RIEC and ambient air moisture content, respectively. The differential terms in Eq.(8) and Eq.(9) were expanded into algebraic equations by Euler approach. The time step for numerical simulation is set to be 60 seconds in this paper, i.e, the indoor temperature signal is sent and fan speed adjustment are made every 60 seconds. The supply air flow rate m_{sup} is decided by the control algorithm.

Although the RIEC is designed mainly to remove sensible cooling, supply air humidity is also exported to be ambient humidity for evaluating indoor Predicted Mean Vote (PMV), a widely recognized thermal comfort index [28]. The PMV can be calculated as Eq.(10) according to two inputs (t_N and ω_N) and four assumptions for clothing, air velocity, activity level and mean radiant temperature.

$$\begin{aligned} PMV &= [0.303e^{-0.036M} + 0.028]\{M - 3.96e^{-8}\left(1.05 + 0.1I_{cl}\right)[(t_{cl} + 273)^4 - (t_r + 273)^4] \\ &-\left(1.05 + 0.1I_{cl}\right)\times 12.1(V_a)^{1/2}(t_{cl} - t_N) - 3.05[5.73 - 0.007M - p_a] - 0.42\left(M - 58.15\right) \\ &-0.0173M(5.87 - p_a) - 0.0014M(34 - t_N)\} \end{aligned} \tag{10}$$

where,

M - metabolic rate, assumed as 58.15 W/m^2;

I_{cl} - clothing insulation, assumed as 0.7 clo in summer and 1.0 clo in transition seasons;

t_r - mean radiant temperature, assumed as t_r=t_N;

V_a - local air velocity, assumed as 0.15 m/s；

p_a - vapor pressure of the air, kPa, available by giving t_N and humidity;

t_{cl} – surface temperature of clothing, ℃, calculated as

$$t_{cl} = 35.7 - 0.0275M - 0.155I_{cl}\{M - 3.05\left(5.73 - 0.007M - p_a\right) - 0.42(M - 58.15)$$
$$-0.0173M(5.87 - p_a) - 0.0014M(34 - t_N)\} \tag{11}$$

3. Development of two control schemes

Highly depends on ambient air conditions, a RIEC needs suitable control schemes to ensure stable indoor air temperature and thermal comfort for occupants. Comparative study is made between the two control schemes in this paper: conventional on-off control and novel developed H-L control, introduced respectively as follows. The control schemes and RIEC model are programmed by MATLAB to perform the simulation.

3.1 On-off control scheme

On-off control is the most widely used control scheme in current RIEC product. The RIEC is equipped with two constant speed fans: primary air fan and secondary air fan. The two fans are either in operation under the rated flow rate or shutdown simultaneously according to the variations of indoor temperature. The rated flow rate is usually designed to meet the peak load or the majority of cooling demand in a project.. They are turned on if the indoor air temperature is higher than the setting point and turned off otherwise. The control algorithm is expressed as:

$$\begin{aligned}
&If\ \ t_N\left(T\right) \le t_{set} - \Delta t_1, && m_p\left(T\right) = 0 \\
&If\ \ t_{set} - \Delta t_1 \le t_N\left(T\right) \le t_{set} + \Delta t_2, && m_p\left(T\right) = m_p(T-1) \\
&If\ \ t_N\left(T\right) > t_{set} + \Delta t_2, && m_p\left(T\right) = m_{pH}
\end{aligned} \tag{12}$$

where, T is the present time point and (T-1) is the last time point. Δt_1 is the lower dead band, set as 1.5℃. t_{set} is the setting temperature, which is 25.5℃ and Δt_2 is the upper dead band, set as 0.5℃. Therefore, the fans would be turned off if the indoor air temperature $t_N(T)$ is lower than

24℃, turned on if $t_N(T)$ is higher than 26℃ and remain the original state or the current operation state if $t_N(T)$ is between 24℃ to 26℃.

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3.2 High-low control scheme

H-L control is proposed as a novel control scheme for RIEC. A RIEC is equipped with a primary air fan and a secondary air fan. H-L control is adopted for both of the fans with multi-speed technology. The two fans either operate at their respective high speed or low speed or shutdown simultaneously. Besides, the ratio of secondary air flow rate to primary air flow rate should be kept at 30%. When the indoor air temperature is higher than the upper boundary of setting point, the fans would operate at high speed. Otherwise, the fans would operate at low speed instead of completely shutdown to meet the part load. However, to avoid overcooling in the early morning of transition seasons, the RIEC would not be active until the indoor air temperature increases to the lower boundary of the setting point.

$$\begin{array}{ll} If\ t_N(T) \le t_{set} - \Delta t_1, & m_p(T) = 0 \\ If\ t_{set} - \Delta t_1 < t_N(T) < t_{set} - \Delta t_2, & m_p(T) = m_{pL} \\ If\ t_{set} - \Delta t_2 \le t_N(T) \le t_{set} + \Delta t_2, & m_p(T) = m_p(T-1) \\ If\ t_N(T) > t_{set} + \Delta t_2, & m_p(T) = m_{pH} \end{array} \quad (13)$$

where, m_{pH} and m_{pL} are the primary air flow rate at high speed and low speed of the fan, kg/s, respectively. For comparative study, Δt_1, Δt_2 and t_{set} are kept identical as that of on-off control. Therefore, the fans would be turned off if the indoor air temperature $t_N(T)$ is lower than 24℃, operated at low speed if $t_N(T)$ is between 24℃ to 25℃, operated at high speed if $t_N(T)$ is higher than 26℃ and maintain the current operation state if $t_N(T)$ is between 25℃ to 26℃.

4. Simulation case

A case study is conducted to evaluate the annual performance of RIEC by using on-off control and H-L control, respectively. In this case, a RIEC is used to cool a small clinic in Xi'an, a typical hot and arid city in western China. The annual ambient temperature and moisture content in Xi'an is shown in Fig.2. The temperature and humidity varies greatly in a year. The cooling season is from 15th May to 30th September, including the hottest months of July and August and transition months of May and September. The maximum temperature and maximum moisture content are 39.9 ℃ and 19.6 g/kg, respectively.

The main parameters of the simulation case are listed in Table 1. The room is functioned as a small clinic. There are two exterior walls facing outside and two internal walls facing other room/corridor. The U-values of the building envelopes and window to wall ratio refer to the 'Design standard for energy conservation of residential buildings in hot summer and cold winter area' [29]. The annual cooling load on hourly base is simulated by Type 56 - TRNBuild multi-zone building module in Trnsys, a kind of powerful software used for building energy simulation. The simulation result of the annual sensible cooling load is shown in Fig.3. The maximum sensible cooling load is around 6000 kJ/h.

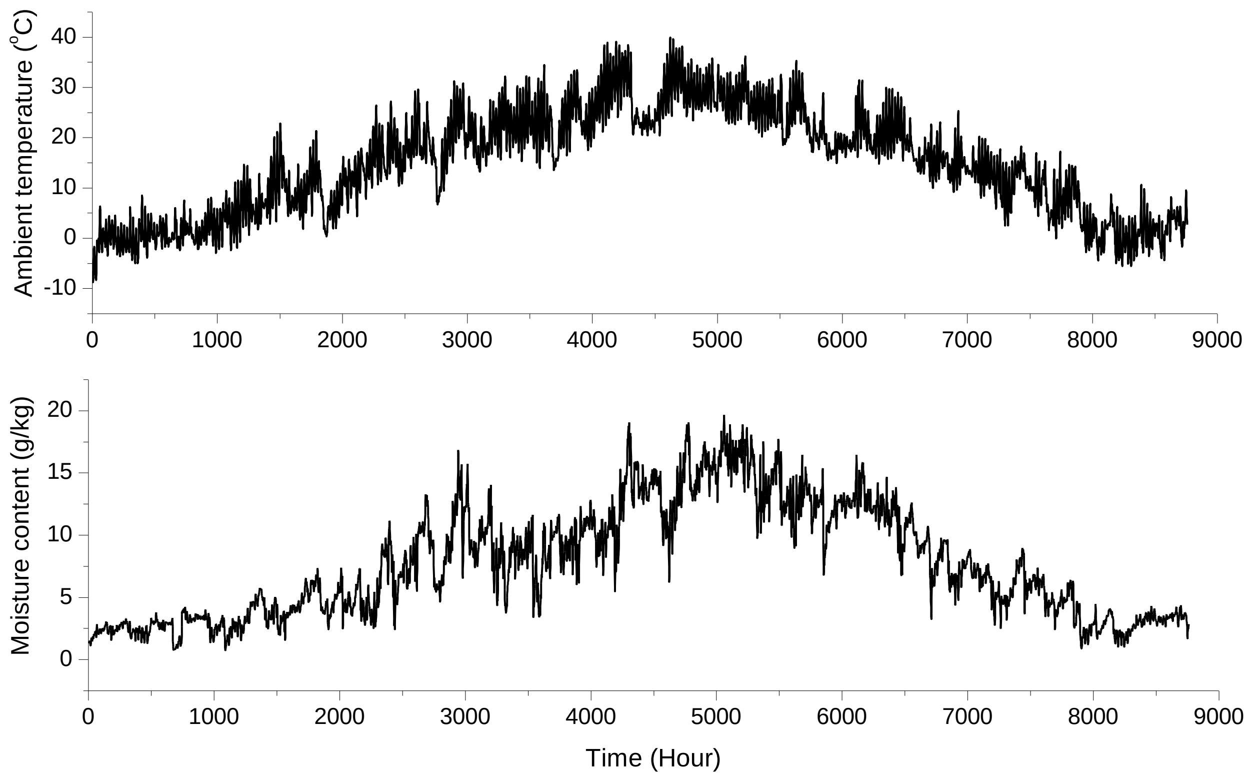

Fig.2 annual weather conditions in Xi'an

Table 1 Main parameters of the simulation case

Location	Xi'an (latitude 34°16′N, longitude 108°54′E)
Room dimensions	4.0m (L)× 8.0m (W) × 2.6 m (H)
Orientation	One exterior wall facing the south and the other facing the east
U-value	
Exterior wall ($W/m^2 \cdot K$)	0.5
Window ($W/m^2 \cdot K$)	2.2
Window to wall ratio	0.5
Heat gain	
Occupants	4 people/room (two doctors and two patient), light work
Lights	13 W/m^2
Computer	460 W/room (two computers with color monitor)
Schedule	8:00 to 20:00 every day, lunch break 13:00 to 14:00
Cooling season	15^{th} May to 30^{th} September

A RIEC is used to supply the cooled fresh air to the room. The rated cooling capacity of the RIEC is designed to meet the peak cooling load in a year. In on-off control, the rated supply air flow rate is 0.4 kg/s when the fan is turned on; while in H-L control, the supply air flow rate is 0.4 kg/s under high speed and 0.1 kg/s under low speed. In RIEC, a part of the primary air would be sacrificed as the secondary air so that 30% additional flow rate is needed for the inlet primary air in this case. The structure and operational parameters of RIEC are listed in Table 2.

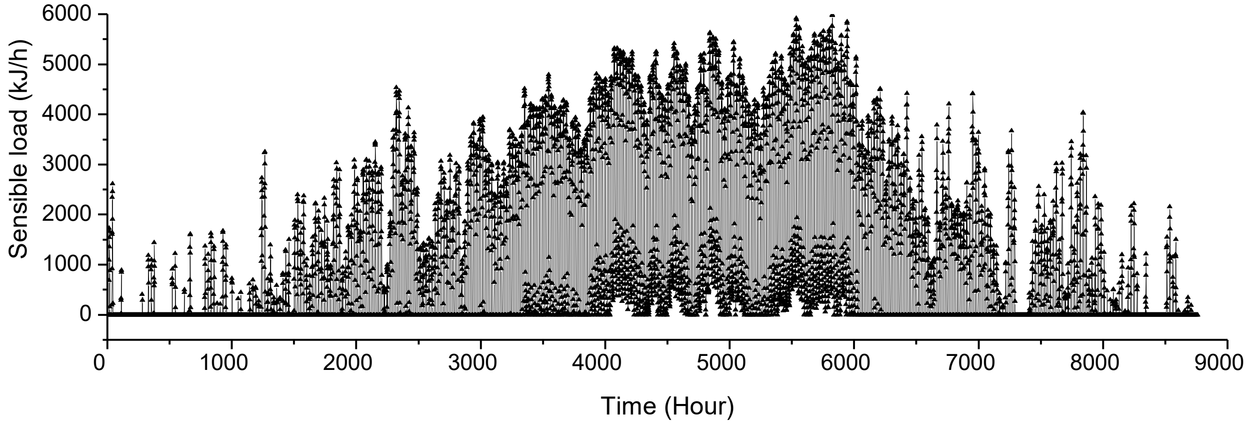

Fig.3 annual sensible cooling load

Table 2 Structure and operational parameters of RIEC

Parameter	Control scheme	Symbol	Value
Channel pairs		n	55
Height × width		$H \times W$	1.0 m×1.0 m
Channel gap		d_e	4 mm
Extraction ratio		r	0.3
Flow rate of supply air	On-off	m_{sup}	0.4 kg/s (on) 0 (off)
	H-L	m_{sup}	0.4 kg/s (high) 0.1 kg/s (low)
Fan speed of primary air	On-off	m_{p}	0.571 kg/s (on) 0 (off)
	H-L	m_{p}	0.571 kg/s (high) 0.143 kg/s (low)

5. Results and analysis

The annual performance of the RIEC is analyzed based on one minute step, i.e., the time step of the controller. The indoor temperature variation and PMV are selected as the indicators for evaluating the thermal comfort of occupants. To further elaborate the control effect, the variations of indoor temperature, fan speed, supply air temperature and PMV are analyzed under a typical summer day and a typical transition day.

5.1 Annual performance

The indoor air temperature variation under two control schemes of RIEC in cooling season (15th May to 30th September) is shown in Fig.4. Low temperature can be often observed in the early morning during transition months for both H-L control and on-off control. It owns to the low ambient temperature even though the RIEC is shutdown. However, the indoor temperature remains relatively steady in summer under both control schemes. Most indoor air temperature varies between 24.0 ℃ to 26.3 ℃ under H-L control (see Fig.4a), which shows good controllability of this algorithm. The maximum indoor temperature is 28.4 ℃, a little higher than the thermal comfort limit. Throughout the cooling seasons, the indoor temperature ranging from 26 ℃ to 27 ℃ accounts for 10.9% of the operation time, 25 ℃ to 26 ℃ accounts for 44.9%, 24 ℃ to 25 ℃ accounts for 25.5% and 23℃ to 24 ℃ accounts for 9.2%. The high indoor temperature (>27 ℃) and low indoor temperature (<23 ℃) only make up for 1.3% and 8.2%, respectively.

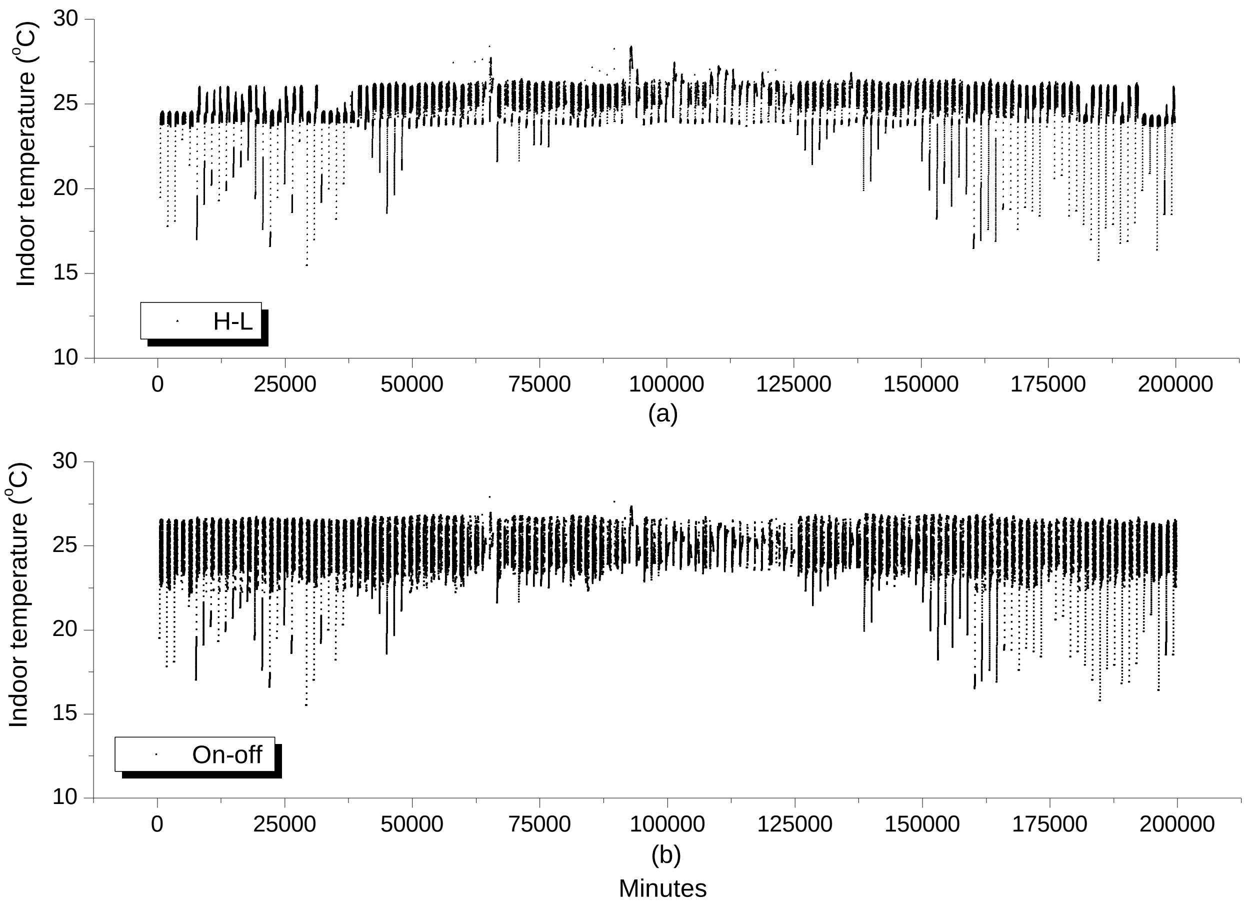

Fig.4 indoor air temperature variation under two control schemes in cooling season

Larger indoor temperature fluctuation can be observed under on-off control as shown in Fig. 4b. Daily indoor temperature range, i.e, maximum temperature minus minimum temperature, under the two control schemes is plotted as Fig.5. It can be seen that the temperature range of on-off control is significantly larger than that of H-L control, especially in transition months when frequent switch of fan speed is needed. Throughout the cooling seasons, the indoor temperature ranging from 26 ℃ to 27 ℃ accounts for 11.1% of the operation time, 25 ℃ to 26 ℃ accounts for 27.3%, 24 ℃ to 25 ℃ accounts for 35.2% and 23 ℃ to 24 ℃ accounts for 16.1%. The high indoor temperature (>27 ℃) and low indoor temperature (<23 ℃) only make up for 0.2% and 10%, respectively. In general, the average indoor temperature under on-off control is a little lower than that of H-L control, and the indoor temperature variation is larger than that of H-L control.

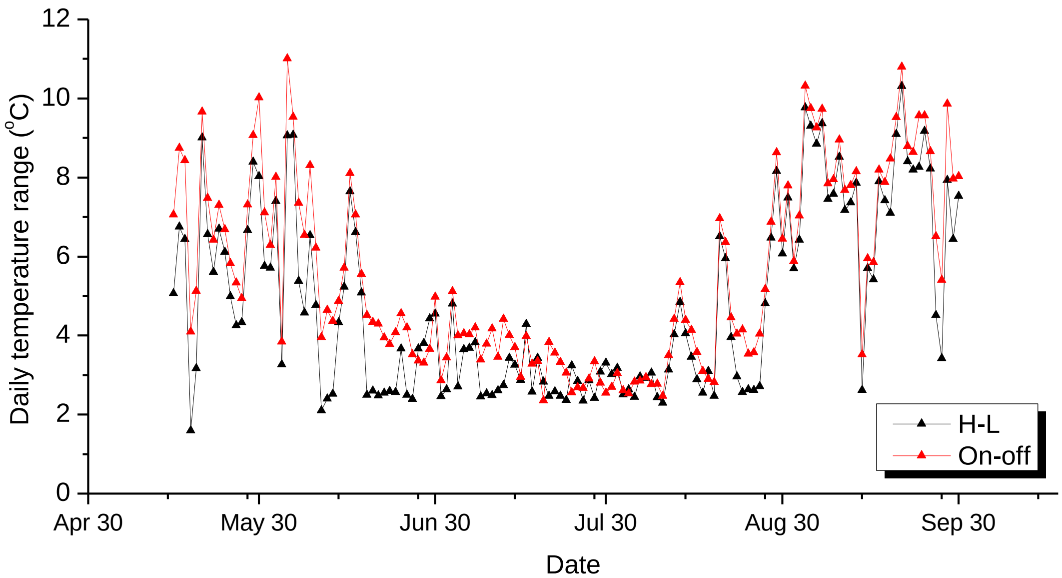

Fig.5 daily temperature range under two control schemes

The annual PMV variation is also comparatively discussed to evaluate the level of thermal comfort provided by RIEC. Fig.6 shows the PMV distribution under the two control schemes in cooling seasons. The PMV ranging from -0.5 and 0.5 accounts for 80.5% and 79.3% for H-L control and on-off control, respectively, indicating satisfactory thermal comfort can be achieved. It can be also noticed that on-off control trends to provide more ‘slightly cold feeling’ than that of H-L control.

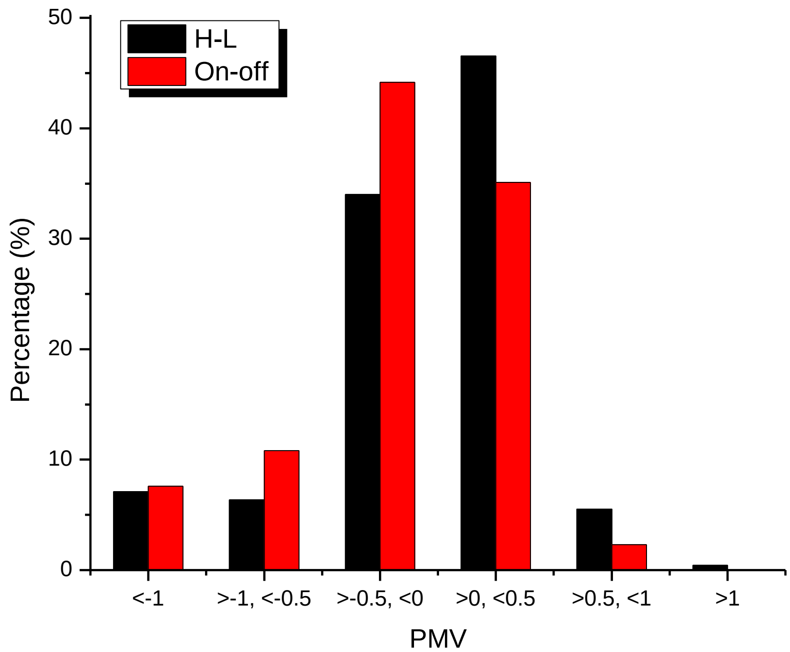

Fig.6 PMV distribution under two control schemes in cooling seasons

5.2 Typical day performance – summer

A typical summer day (28th July) is selected for comprehensively analyzing the fluctuation of various operational parameters under on-off control and H-L control. The operational parameters include the indoor temperature, fan speed, supply air temperature and PMV. The hourly ambient temperature, humidity and cooling load is shown in Fig.7. The temperature varies from 25.3 ℃ to 34.5 ℃ and moisture content varies from 12.61 g/kg to 15.76 g/kg. The maximum cooling load is 4800 kJ/h at 16:00. The operation schedule of RIEC is from 8:00 to 20:00 every day.

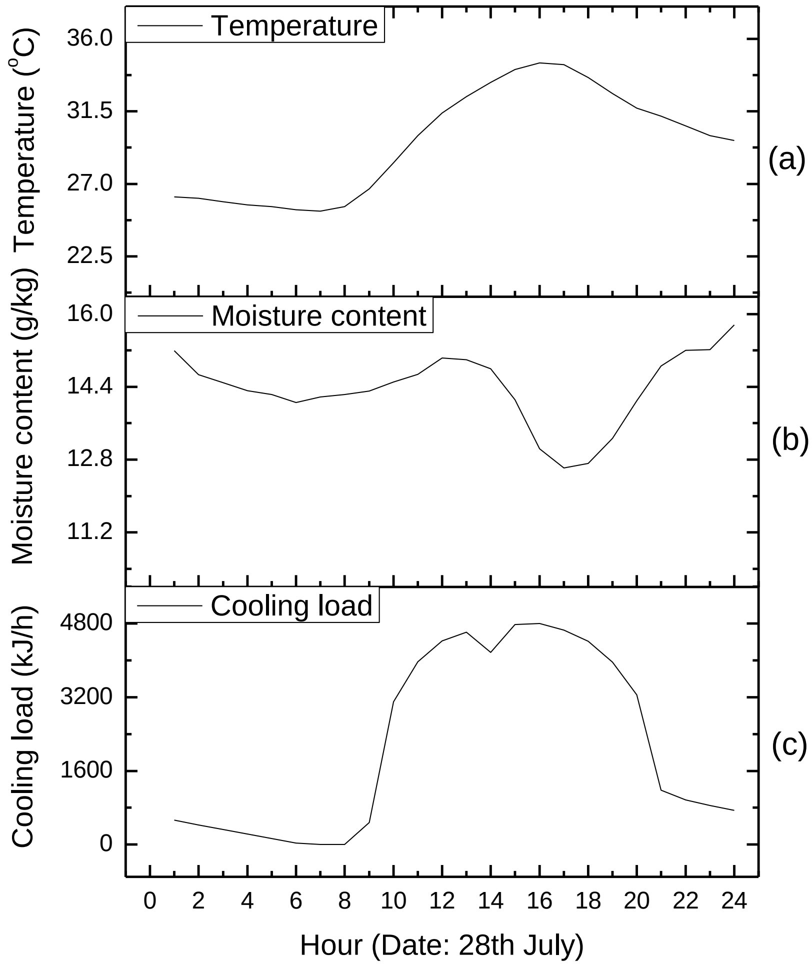

Fig.7 Hourly ambient temperature, humidity and cooling load in a typical summer day

The indoor temperature variation is compared under two control schemes, as shown in Fig.8. It can be seen that the indoor temperature fluctuates within a reasonable range for maintaining the thermal comfort under both on-off control and H-L control, although the ambient weather conditions varies greatly. Therefore, the two control methods are proved to be effectively for IEC application. However, much larger variation can be observed in on-off control compared with H-L control. The indoor temperature varies between 23.3 ℃ to 26.7 ℃ under on-off control. While it varies only between 23.9 ℃ to 26.3 ℃ under H-L control, creating a more thermally-comfort environment.

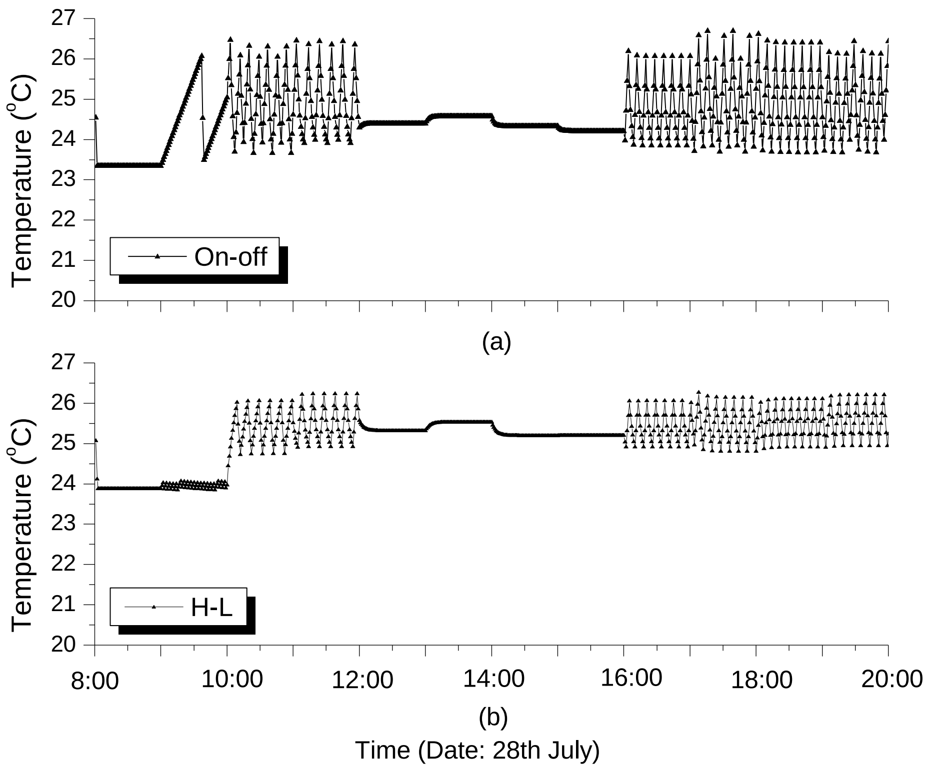

Fig.8 indoor temperature variation under two control schemes in a typical summer day

Fig.9 shows the fan speed variation under the two control schemes. Under on-off control, the air flow rate periodically switches between the rated flow rate (m_{pH}) and zero, except for the high load demand from 12:00 to 16:00. Under H-L control, the air flow rate mostly periodically switches between the rated flow rate (m_{pH}) and small flow rate (m_{pL}), apart from the moment when there is extremely low cooling load in the morning. The switch frequency of the fan speed is around 4 minutes for both of the control schemes. The H-L control is superior to the on-off control in term of fresh air guarantee. At lower indoor temperature, the fan operates at low speed under H-L control which is designed to meet the minimum fresh air demand (30 m^3/h/person) rather than completely shut down. Besides, H-L control avoids damage of the motor brought by frequent start and stop of the fan, but enjoys much simple control procedure and lower investment than the infinitely variable speed fan.

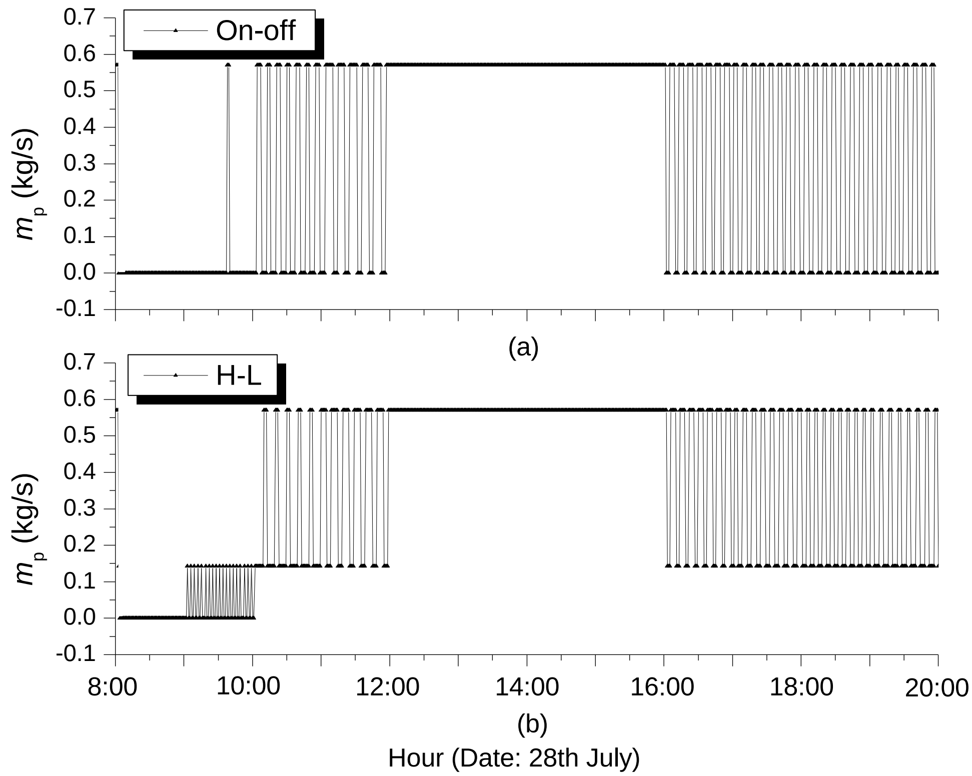

Fig.9 fan speed variation under two control schemes in a typical summer day

The supply air temperature variation under the two control schemes is shown in Fig.10. Since the RIEC performance highly depends on the ambient temperature and humidity, the supply air temperature varies from 20.8 ℃ to 22.3 ℃ under on-off control but varies from 19.9 ℃ to 22.3 ℃ under H-L control. It can be seen that the supply air temperature is more steady under on-off control for the reason that constant air flow rate is provided under on-off control, while changeable air flow rate provided under H-L control. In general, lower supply air temperature can be achieved when the primary air flow rate decreases and vice versa. Thus, periodic changes of the supply air temperature keep the same pace with the switch frequency of the fan. As the supply air temperature is relatively high than that of MVCR system, no draft feeling would take place even though there is continuous change of supply air temperature under H-L control.

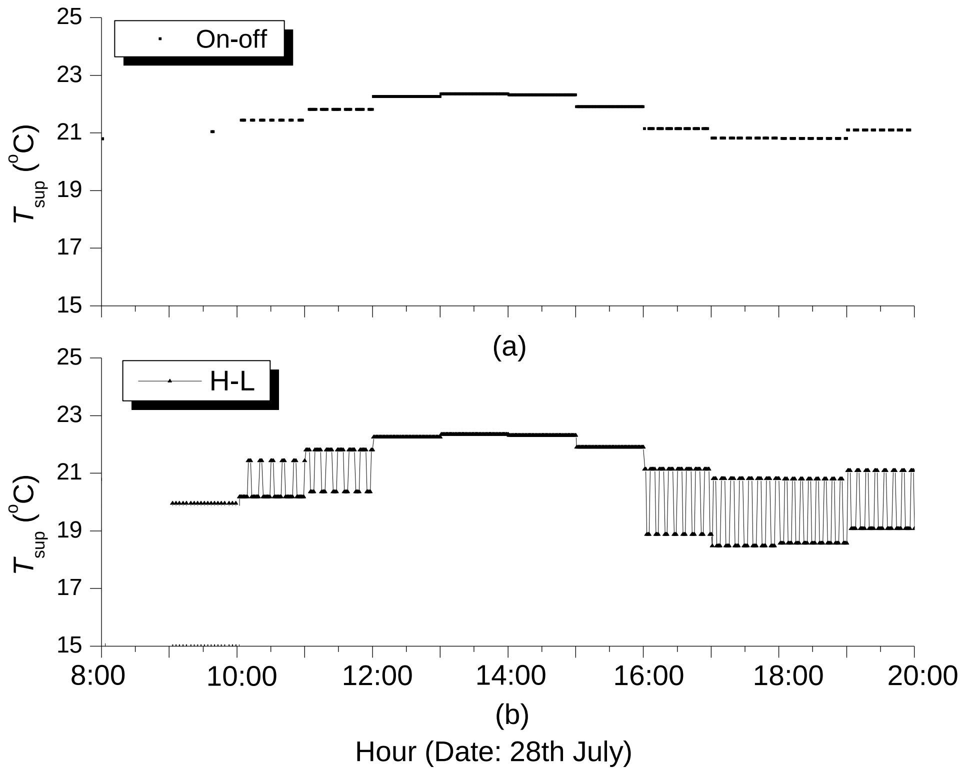

Fig.10 supply air temperature variation under two control schemes in a typical summer day

The PMV variation under two control schemes is shown in Fig.11. It can be seen that the PMV fluctuates within reasonable thermally-comfort zones under both on-off control and H-L control. Similar with indoor air temperature, the PMV fluctuates much more greatly under on-off control. The variation range of PMV under on-off control is -0.43 to 0.54. While it varies only between -0.26 to 0.46 under H-L control, indicating a much more comfort environment can be provided.

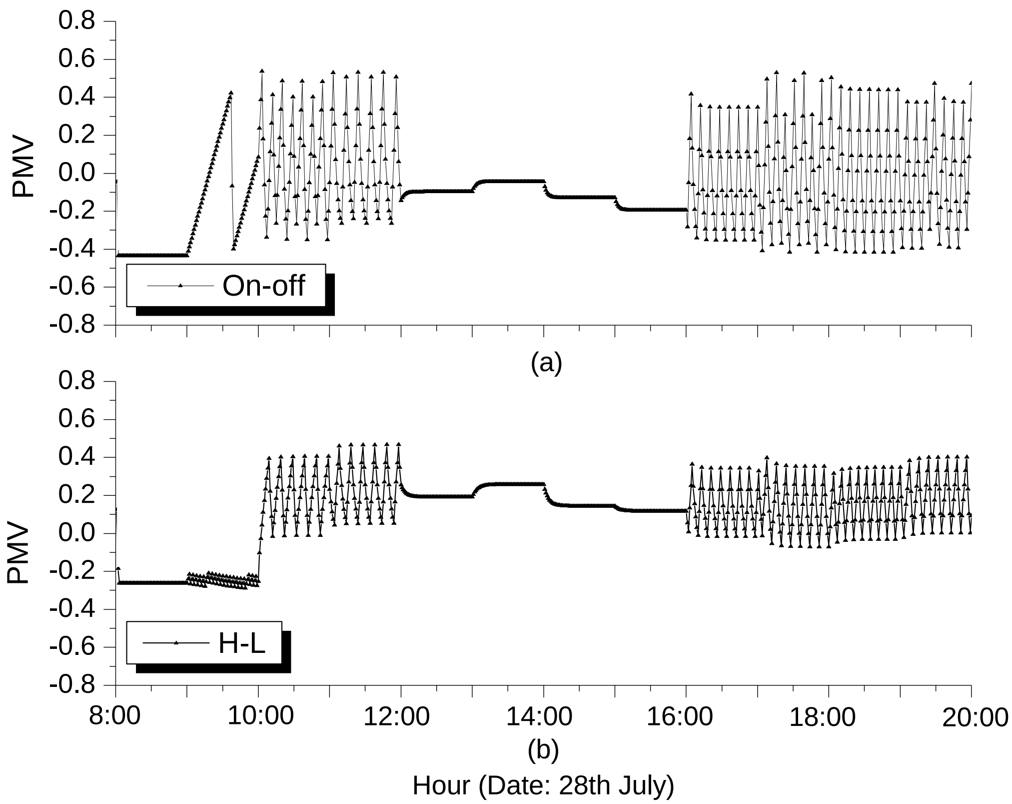

Fig.11 PMV variation under two control schemes in a typical summer day

5.3 Typical day performance - transitional season

A typical day in transitional season (11th September) is also selected for comprehensively analyzing the fluctuation of various operational parameters under the two control schemes. The hourly ambient temperature, humidity and cooling load is shown in Fig.12. In transition season, the ambient air temperature is significantly lower than that in summer. The temperature varies from 17.7 ℃ to 21.1 ℃ and moisture content varies from 12.1 g/kg to 13.4 g/kg. The maximum cooling load is 3290 kJ/h at 16:00.

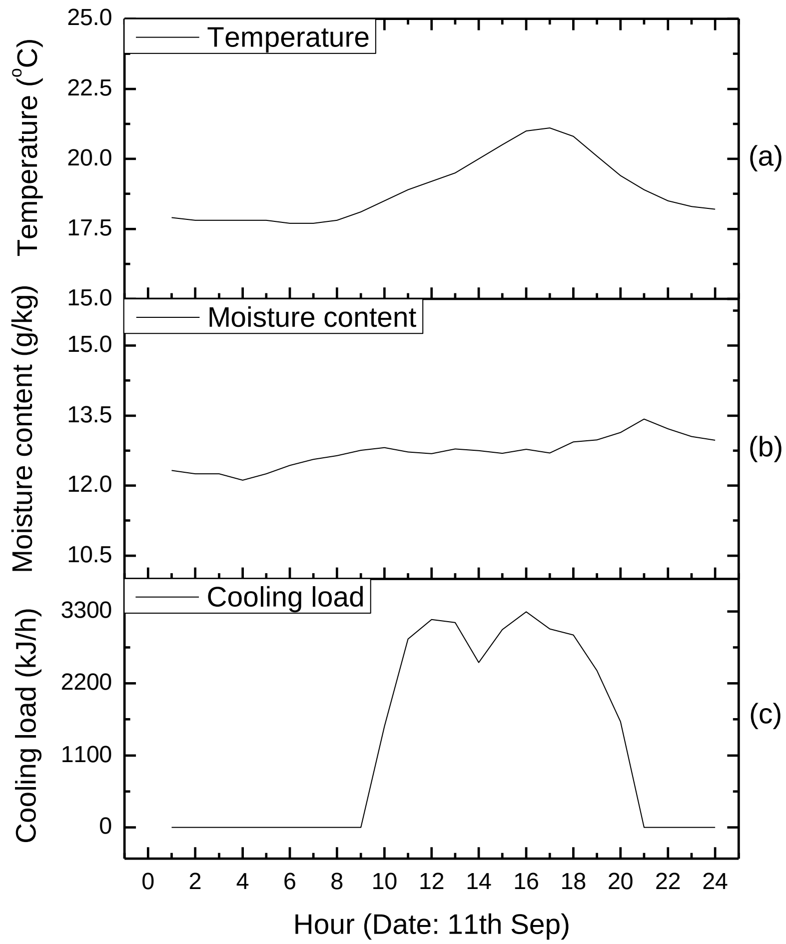

Fig.12 Hourly ambient temperature, humidity and cooling load in typical transitional season

The indoor temperature variation under the two control schemes is shown as Fig.13. The temperature is low in the first two hours even though the RIEC is not in operation. Then the temperature begins to increase as the heat accumulation until it fluctuates periodically within a thermally-comfort range from 24.7 ℃ to 26.0 ℃ under H-L control and 22.6 ℃ to 26.3 ℃ under on-off control. However, the variation of indoor temperature under H-L control is significantly smaller than that of on-off control, indicating that better thermal comfort can be provided.

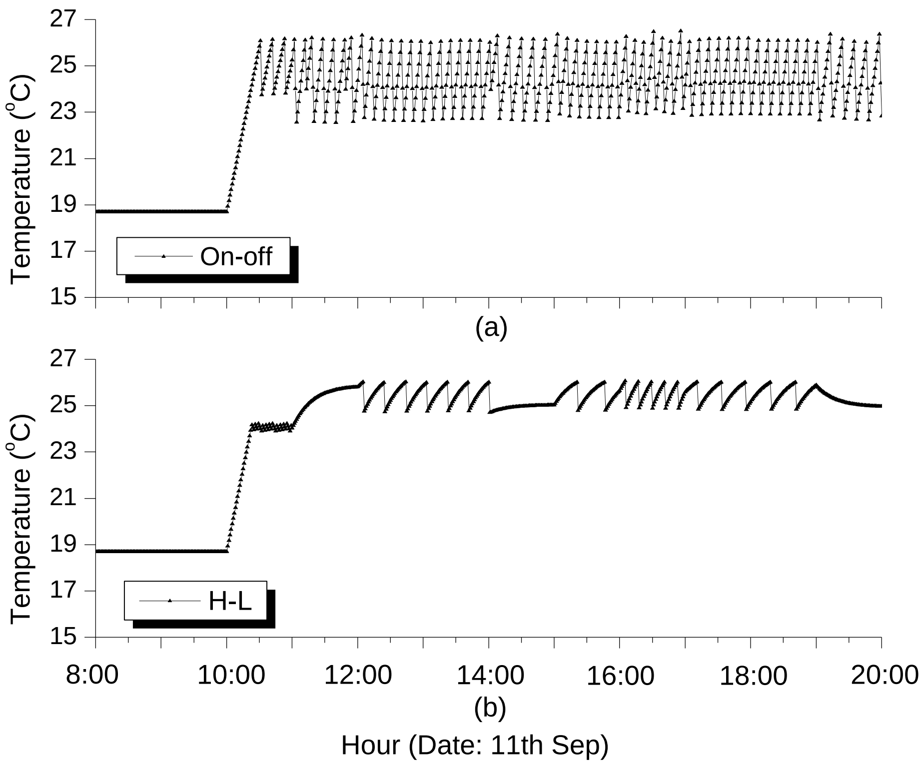

Fig.13 indoor temperature variation under two control schemes in typical transitional season

The fan speed variation under the two control schemes is shown in Fig.14. It can be seen that the fan switches frequently from 'on' state to 'off' state under on-off control. This is contributing to the relatively small cooling load in transitional season, which can be removed rapidly when the fan operates at rated value. However, the switch frequency is much less under H-L control. The fan operates at low speed accounts for the majority of time, with occasionally switches to the high speed. It can be speculated that the cooling capacity provided under low speed can basically meet the cooling demand in transition seasons. Therefore, the rated cooling capacity may lead to overcooling and frequent switch between 'on' and 'off' is inevitable under on-off control. In sum, the H-L control is superior to on-off control in terms of fan speed variation, which avoids frequent switch and provides smaller indoor temperature variation.

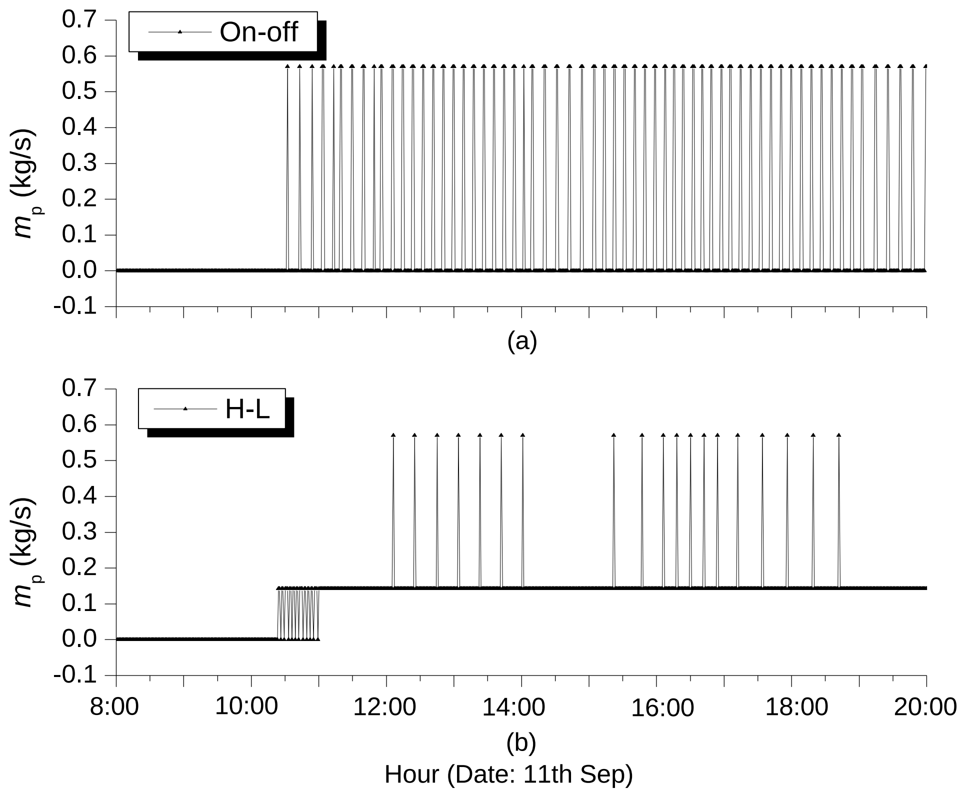

Fig.14 fan speed variation under two control schemes in typical transitional season

Fig.15 shows the supply air temperature variation under the two control schemes. The supply air temperature varies around 18.0 ℃ to 18.7 ℃ under both control schemes but the supply air temperature is more steady under on-off control. It is because changeable air flow rate provided under H-L control. In general, lower supply air temperature can be achieved when fan operates at low speed and vice versa. Thus, periodic changes of the supply air temperature keep the same pace with the switch frequency of the fan. The larger variation of supply air temperature is not an important consideration for RIEC because higher supply temperature would not lead to draft feeling.

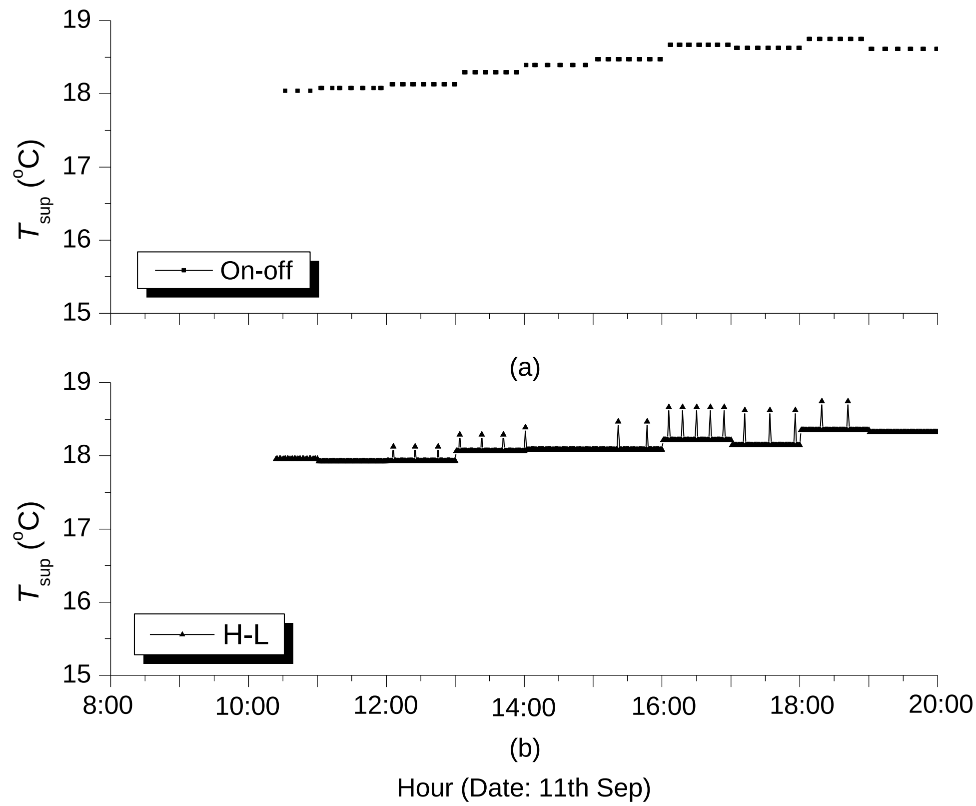

Fig.15 supply air temperature variation under two control schemes in typical transitional season

Fig.16 presents PMV variation under two control schemes. Apart from the low PMV values in the first two hours, the PMV fluctuates within a thermally satisfied range from -0.08 to 0.32 under H-L control. However, much larger variation can be observed for on-off control with the PMV value varies from -0.76 to 0.42. Thus, more cold feeling would be sensed when on-off control is used in transition month. Besides, the PMV is changed much more rapidly under on-off control, leading to discomfort for the occupants. In sum, compared with the RIEC performance in summer, the advantage of H-L control is more significant in transition seasons in terms of thermal comfort.

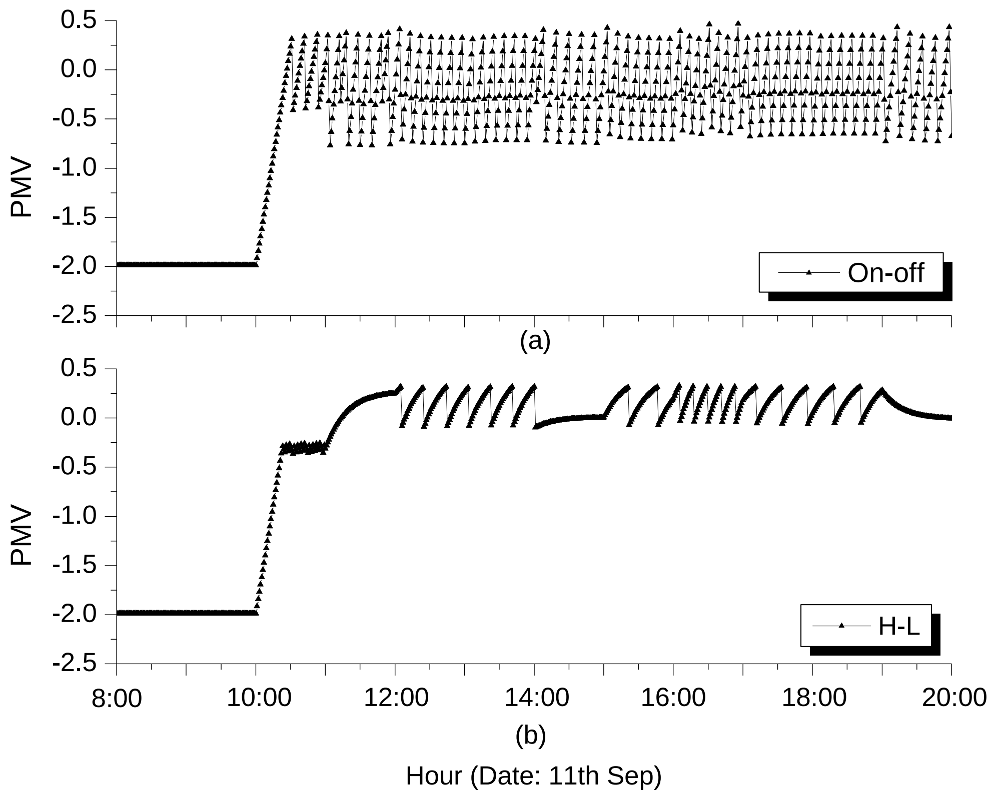

Fig.16 PMV variation under two control schemes in typical transitional season

5.4 Energy consumption analysis

The energy consumption is comparatively analyzed. The energy consumption of RIEC includes primary air fan, secondary air fan and pump. The energy consumption of the pump is the same for both control schemes, thus only the two fans are considered for energy saving evaluation, calculated as:

$$W_{fan} = \frac{V \times \Delta P}{3600 \times 1000 \times \eta_0 \times \eta_1} \tag{14}$$

where, ΔP is pressure drop, calculated to be 100 pa under m_p=0.571 kg/s and 25 Pa under m_p =0.143 kg/s according the reference [30]; η_0 is the internal efficiency of the fan; η_1 is the mechanical efficiency which determined by the connection method between the motor and fan. In this study, η_0 and η_1 are assumed as 0.82 and 0.97, respectively.

Under on-off control, the power of the fan is either the rated power or zero. However, the fans under H-L control are switched between the high speed and low speed. Based on the affinity laws, power is proportional to the cube of shaft speed, i.e, the power would reduce to 1/64 of rated power if the fan speed is reduced to ¼ of rated speed. This law provides huge energy saving potential of applying H-L control. However, as the pressure is proportional to the square of shaft speed, i.e., the pressure would also reduce to 1/16 of rated pressure if the fan speed is reduced to ¼ of rated speed. In order to ensure sufficient pressure to overcome the RIEC's resistance, another linkage fan with 25 Pa pressure would operate under low speed state.

Table 3 breakdown of annual energy consumption of H-L control in cooling seasons

Fan	Fan speed	m_{sup} (kg/s)	Running hours (h)	Power (W)	Energy consumption (kWh)
Primary air fan	High	0.571	477.5	55.3	26.4
	Low	0.143	899.8	4.3	3.9
	Off	0	1958.8	0	0
Secondary air fan	High	0.171	477.5	16.6	7.9
	Low	0.043	899.8	1.3	1.2
	Off	0	1958.8	0	0

Table 4 breakdown of annul energy consumption of on-off control in cooling seasons

Fan	Fan speed	m_{sup} (kg/s)	Running hours (h)	Power (W)	Energy consumption (kWh)
Primary air fan	On	0.571	617.3	55.3	34.2
	Off	0	2718.7	0	0
Secondary air fan	On	0.171	617.3	16.6	10.2
	Off	0	2718.7	0	0

The breakdowns of annual energy consumption of RIEC under H-L control and on-off control are calculated as Table 3 and Table 4, respectively. Under H-L control, the total energy consumptions of fresh air fan and secondary air fan are 30.3 kWh and 9.1 kWh, respectively, giving total energy consumption of 39.4 kWh. However, under on-off control, the total energy consumptions of fresh air fan and secondary air fan are 34.2 kWh and 10.2 kWh, respectively, giving total energy consumption of 44.4 kWh. Therefore, 11.3% energy can be saved by applying H-L control instead of on-off control.

It can be also noticed that the total running hours of the fans under H-L control are 1377.3 h, with 477.5 h for high-speed operation and 899.8 h for low-speed operation. However, the total running hours are only 617.3 h under on-off control, much less than that of H-L control. Even so, the energy consumption of H-L control is still less than that of on-off control because of the small energy consumption at low speed operation. More importantly, low speed operation instead of completely turning off enables fresh air supply and provides better indoor air quality.

6. Conclusions

Proper control strategy is essential in an indirect evaporative cooler (IEC) because its cooling performance is highly influenced by ambient air conditions. However, the controller development for IEC and IEC performance under certain control strategy had been rarely reported in open literatures. Therefore, a novel control scheme named high-low (H-L) control is proposed for IEC application. Unlike widely used on-off control at current IEC market, the fans would be switched between high speed and low speed rather than completely turned off under H-

L control. Quantitative data about RIEC performance under on-off control and H-L control are provided by simulation. The main conclusions are as follows.

1. Both the on-off control and H-L control can provide suitable indoor air temperature (23 ℃ to 27 ℃) for 90.5% of time in the cooling seasons. However, the temperature variation range under on-off control is significantly larger than that of H-L control, especially in transition months. Compared with H-L control, on-off control tends to provide a slightly cold feeling.
2. The switch frequency of fan speed is almost the same in summer under the two control schemes. However, the switch frequency is much higher in transition month when adopting on-off control, resulting in high potential of breakdown and higher cost of maintenance.
3. The PMV fluctuates within reasonable thermally-comfort zones (-0.5 to 0.5) under both on-off control and H-L control for 80% of time. However, the PMV fluctuates much more greatly under on-off control, especially in transition month.
4. The energy saving ratio of applying H-L control instead of on-off control is 11.3% because of utilization of multi-speed technology. The operation of fan under H-L control is much longer than that of on-off control, providing better indoor air quality.

In sum, the newly proposed H-L control is superior to on-off control for providing better thermal comfort, better indoor air quality and less energy consumption. The H-L controller has a high potential of commercialization, which can promote the development of IEC and advance the applications of similar sustainable cooling technology, such as multi-stage IEC and M-cycle IEC and some any HVAC devices. The H-L control benefits the IEC manufacturer, engineers and industry in producing higher efficient product, designing and operating more thermally-comfort IEC system.

Nomenclatures

A	heat and mass transfer area, m^2	h_m	mass transfer coefficient, $kg/m^2 \cdot s$
H	cooler height, m	h_{fg}	latent heat of vaporization of water, J/kg
Q	cooling load, W	i	enthalpy of air, J/kg
T	time interval	m	mass flow rate, kg/s
V	volume, m^3	r	extraction air ratio of RIEC
c_{pa}	specific heat of air, J/kg·℃	s	channel gap, m
c_{pw}	specific heat of water, J/kg·℃	t	celsius temperature, ℃
h	heat transfer coefficient, $W/m^2 \cdot$℃		
Greek symbols			
ω	moisture content of air, kg/kg	ρ	air density, kg/m^3
Subscripts			
H	high speed	ew	evaporation water
L	low speed	in	inlet
N	indoor air	out	outlet
p	primary air	sup	supply air
s	secondary air	sen	sensible heat
w	wall/water	lat	latent heat
Abbreviation			
IEC	indirect evaporative cooler	RIEC	regenerative indirect evaporative cooler
H-L	high-low control	HVAC	heating, ventilation and air-conditioning
PMV	predicted mean vote		
MVCR	mechanical vapor compression refrigeration system		

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