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Development and optimization of a novel controller for regenerative indirect evaporative cooler

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Abstract

The main characteristic of an indirect evaporative cooler (IEC) is the high dependency on ambient air conditions. To ensure stable indoor temperature and provide better thermal comfort, proper control strategy is essential. However, very limited studies report the controller used in IEC. In this paper, a novel control scheme named high-low (H-L) is proposed for regenerative indirect evaporative cooler (RIEC). Under H-L control scheme, the fans would be switched between high speed and low speed rather than completely turned off. The H-L control adopts the multi-speed technology, providing energy saving potential compared with conventional on-off control and overcome the complexity and costly of variable speed technology. The annual performance of RIEC was simulated under H-L control based on the RIEC model and dynamic indoor heat and mass balance model. The influence of low speed to high speed ratio (L/H) is discussed in order to propose an optimal L/H by considering both the thermal comfort and annual energy consumption. The results show that the H-L control can provide stable indoor temperature and satisfactory thermal comfort with Predicted Mean Vote (PMV) in the range of -0.5 to 0.5 for 76.2% of time. The optimal L/H is found to be 0.25 to 0.33 because of high thermal comfort provided and lowest energy consumption.

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Keywords: Indirect evaporative cooler; Controller; Thermal comfort; Energy consumption; Optimization

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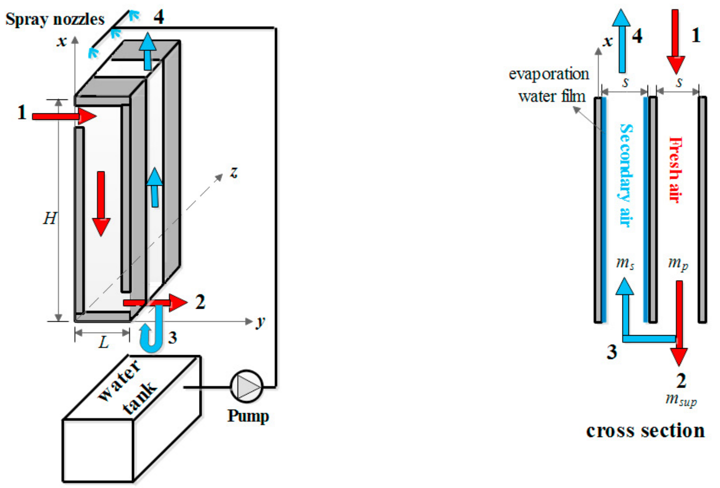
1. Introduction

Indirect evaporative cooler (IEC) is a sustainable cooling device which cools the air by water evaporation. 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. 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, as shown in Fig.1.

The evaporative cooling is proved to have huge energy saving potential in hot and arid regions because of large evaporation driving force. 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. To ensure stable indoor temperature and provide better thermal comfort to the occupants, proper control strategy is essential.

However, very limited research work can be found reporting the control strategy in open literatures. In this paper, a novel control scheme named high-low (H-L) is proposed for RIEC. Under H-L control scheme, the fans would be switched between high speed and low speed rather than completely turned off. The H-L control adopts the multi-speed technology, providing energy saving potential compared with conventional on-off control and overcome the complexity and costly of variable speed technology [1,2].

This study aims, on one hand, to investigate the feasibility of using H-L control for RIEC. On one hand, it fills the research gap of very limited study regarding IEC control. The controller discussed has a high potential of commercialization, which can promote the development of IEC to achieve better living environment with less energy consumption.



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

Nomenclatures			
A	heat and mass transfer area, m^2	h	heat transfer coefficient, $W/m^2 \cdot °C$
Q	cooling load, W	h_m	mass transfer coefficient, $kg/m^2 \cdot s$
T	time interval	i	enthalpy of air, J/kg
V	volume, m^3	m	mass flow rate, kg/s

c_{pa}	specific heat of air, J/kg·℃	r	extraction air ratio of RIEC
c_{pw}	specific heat of water, J/kg·℃	t	celsius temperature, ℃
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	PMV	predicted mean vote

2. RIEC model development and control scheme

2.1. RIEC model

A mathematical model describing the heat and mass transfer process inside a RIEC needs to be established to facilitate the simulation under certain control algorithm. The detailed descriptions and heat and mass transfer coefficients can refer to the previous publication [3].

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

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

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

$$dm_{ew} = m_s d\omega_s \tag{4}$$

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

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

$$m_s = r \cdot m_p \tag{6}$$

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

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

For counter flow RIEC, the boundary conditions are described as: x=H, t_p=$t_{p,in}$; x=0, $t_{s,in}$=$t_{p,out}$; x=0, $\omega_{s,in}$=$\omega_{p,in}$; x=H, m_{ew}=$m_{ew,in}$. The above one-dimensional ordinary equations are discrete by finite difference method and solved by Runge-Kutta iteration method.

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.

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

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

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.

2.2. Control scheme

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% [4]. 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. The detail control algorithm is as follows.

$$\begin{aligned}
&\textit{If } t_N(T) \le t_{set} - \Delta t_1, && m_p(T) = 0 \\
&\textit{If } t_{set} - \Delta t_1 < t_N(T) < t_{set} - \Delta t_2, && m_p(T) = m_{pL} \\
&\textit{If } t_{set} - \Delta t_2 \le t_N(T) \le t_{set} + \Delta t_2, && m_p(T) = m_p(T-1) \\
&\textit{If } t_N(T) > t_{set} + \Delta t_2, && m_p(T) = m_{pH}
\end{aligned} \tag{10}$$

where, m_{pH} and m_{pL} are the primary air flow rate at high speed and low speed of the fan, kg/s, respectively. Δt_1, Δt_2 and t_{set} are set as 1.5°C, 0.5°C and 25.5°C, respectively. Therefore, the fans would be turned off if the indoor air temperature $t_N(T)$ is lower than 24°C, operated at low speed if $t_N(T)$ is between 24°C to 25°C, operated at high speed if $t_N(T)$ is higher than 26°C and maintain the current operation state if $t_N(T)$ is between 25°C to 26°C.

3. Simulation case

A case study is conducted to evaluate the annual performance of RIEC by using H-L control. 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 cooling load is simulated by Trnsys, Type 56 module. The main parameters of the simulation case are listed in Table 1. According to the simulation results, the maximum sensible cooling load is around 6000 kJ/h.

Table 1. Simulation parameters of the case

Location	Xi'an (latitude 34°16′N, longitude 108°54′E)
Room dimensions	4.0m (L)× 8.0m (W) × 2.6 m (H)
U-value	
Exterior wall (W/m^2·K)	0.5
Window (W/m^2·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	10:00 to 20:00 every day, lunch break 13:00 to 14:00

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. 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. Therefore, the fan speed of primary air should be 0.571 kg/s under high speed and 0.143 kg/s under low speed. The simulation parameters of RIEC are listed in Table 2.

Table 2 Simulation parameters of RIEC

Parameter	Symbol	Value
Channel pairs	n	55
Height × width	H×W	1.0 m×1.0 m
Channel gap	d_e	4 mm

Extraction ratio	r	0.3
Fan speed of primary air	m_p	0.571 kg/s (high speed) 0.143 kg/s (low speed)

4. Results and discussion

4.1. Annual performance

The indoor air temperature variation under H-L control in the cooling season (15th May to 30th September) is shown in Fig.2. Low temperature can be often observed in the early morning during transition months because of low ambient temperature. However, the indoor temperature remains relatively steady in summer. Most indoor air temperature varies between 24.0 ℃ to 26.3 ℃, which shows good controllability of this algorithm. The maximum indoor temperature is 28.4 ℃. Throughout the cooling seasons, the indoor temperature ranging from 26 ℃ to 27 ℃ accounts for 11.5% of the operation time, 25 ℃ to 26 ℃ accounts for 42.0%, 24 ℃ to 25 ℃ accounts for 23.5% and 23℃ to 24 ℃ accounts for 9.9%. The Predicted Mean Vote (PMV), a widely recognized thermal comfort index, in the range of -0.5 to 0.5 accounts for 76.2% of time and in the range of -1.0 to 1.0 accounts for 90.5%. In sum, H-L control can provide stable indoor temperature and satisfactory thermal comfort for the majority time of a year.

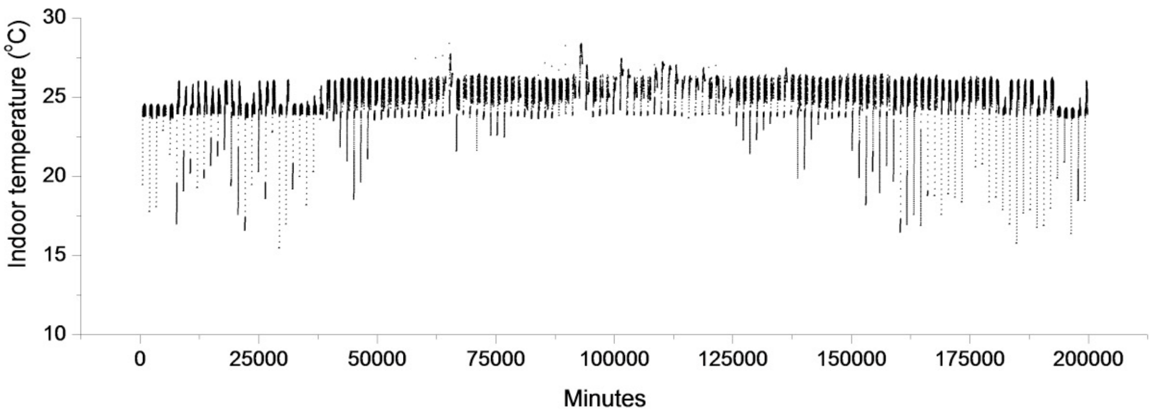


Fig. 2. Indoor air temperature variation under H-L control in cooling season

4.2. Optimization of H-L control

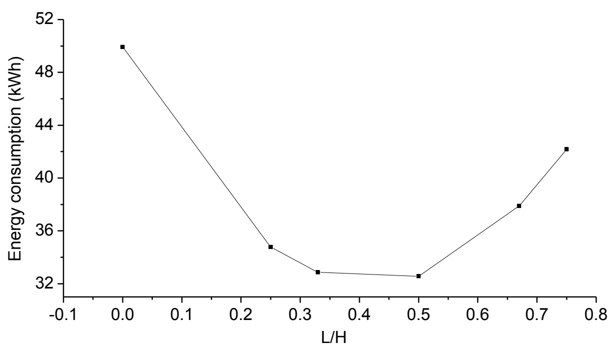


Fig. 3. Annual energy consumption of RIEC under different L/H

The high speed is designed to meet the peak cooling load and the low speed meet the minimum fresh air demand of the occupants. In order to optimize H-L control in an representative city considering the total energy consumption and indoor thermal comfort, different low speed to high speed ratio (L/H) are simulated at fixed high speed. As it presented in Fig. 3, six sets of L/H ratio were used, including 0, ¼, 1/3, ½, 2/3 and ¾, while 0 means that the fans would not be operated. As L/H increased from 0, the annually energy consumption was suddenly dropped revealing the priority of H-L control in energy saving. It continued to decline until reaching a low point at around 33 kWh between 1/3 and ½. After that, the energy consumption increased when increasing L/H ratio. Therefore, ¼ to ½ L/H ratio are recommended in terms of annual energy consumption.

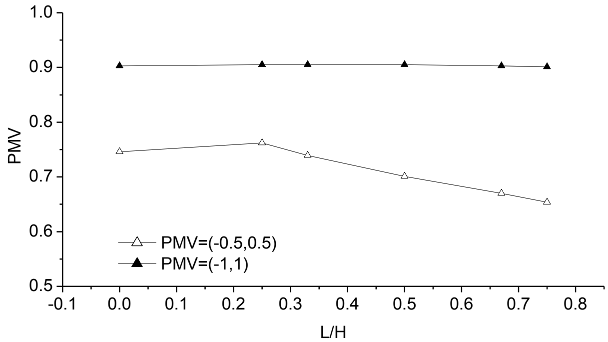


Fig. 4. Annual PMV ratio under different L/H

Predicted Mean Vote (PMV) was chosen as the index to evaluate the indoor thermal comfort of the RICE with the H-L controller. It can be seen from Fig. 4 that, 90% of the year around PMV were within -1 and 1 under all the L/H ratios, while all the satisfying data were reduced when compared to the PMV range of (-0.5, 0.5). At 0 L/H ratio, around 75% PMV values were within (-0.5, 0.5). The satisfactory data was increased as 0.25 L/H and peaked at 76.2% before it dropped at increasing L/H ratio. The optimal L/H is found to be 0.25 to 0.33 when considering both thermal comfort provided and energy consumption.

5. Conclusions

A novel control scheme named high-low (H-L) is proposed for regenerative indirect evaporative cooler (RIEC). Under H-L control, the fans would be switched between high speed and low speed rather than completely turned off. The H-L control adopts the multi-speed technology, providing energy saving potential compared with conventional on-off control and overcome the complexity and costly of variable speed technology. The main conclusions are:

1. H-L control can provide stable indoor temperature and satisfactory thermal comfort with Predicted Mean Vote (PMV) in the range of -0.5 to 0.5 for 76.2% of time and in the range of -1.0 to 1.0 for 90.5%.
2. The low speed to high speed ratio (L/H) is an important consideration for H-L control. The optimal L/H is found to be 0.25 to 0.33 because of high thermal comfort provided and lowest energy consumption.

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