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A proportional–integral (PI) law based variable speed technology for temperature control in indirect evaporative cooling system

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Abstract

The operation of indirect evaporative cooler (IEC) largely depends on the ambient temperature and humidity. To maintain stable indoor temperature, proper controller is essential. On-off control is a mature and stable control method used on constant speed fans. However, large fluctuation of indoor temperature can be observed because of limited control precision. To achieve better thermal comfort, a proportional–integral (PI) law based variable speed technology is proposed for accurate temperature control in an IEC system. This technology had been proved highly effective in central air-conditioning systems and direct expansion air-conditioners in terms of control precision and energy saving, but its techno-economic feasibility in IEC has not been investigated. In this study, annual dynamic simulation has been conducted to an IEC system based on the IEC model and control algorithm. Results show that indoor temperature can be controlled within ±0.5 °C around the setting point for 81.9% of time, while it is only 30.5% under on-off control. The PI based controller is well adapted to cooling loads in all seasons with good control precision, fast response speed and small overshoots. Response time of PI control is only 10 minutes in a disturbance rejection test, which is much shorter than 30 minutes under the on-off control. Annually, IEC with variable speed fans consume 50.0% less energy than that of on-off fans. At last, economic analysis

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shows that this technology is economically feasible only when the power of primary air fan is larger than 1.75 kW.

Keywords: Indirect evaporative cooler; variable speed; PI control; energy consumption; economic analysis

1. Introduction

With the improvement of living standard, indoor thermal comfort becomes a basic requirement of life. Mechanical vapor compression refrigeration system is a dominate cooling system worldwide for its stable performance and mature technology in maintaining proper indoor temperature and humidity. However, its shortcomings gradually emerge under current circumstance of energy crisis and environment pollution because of its high dependency on energy-intensive compressor and chlorofluorocarbons (CFCs) refrigerant. Therefore, sustainable cooling technology is being developed rapidly, of which indirect evaporative cooler (IEC) stands out for its high efficient, pollution free and simple configuration [1]. An IEC can sensibly cools the fresh air relying on water film evaporation in the adjacent secondary air channels. The operation of an IEC depends on two fans and a circulating pump only, consuming much less energy than a mechanical refrigeration system [2,3].

However, the main shortcoming of IEC is that the supply air condition is largely influenced by ambient air temperature and humidity [4]. Indoor temperature will deviate from the comfort zone if the cooling load varies greatly or outdoor weather condition fluctuates largely. Therefore, a controller is essential in an IEC for maintaining a stable indoor thermal environment under constant internal and external disturbances.

Recent research regarding IEC focuses heat and mass transfer modeling [5,6], performance evaluation [7], hybrid system simulation [8] and new material development [9]. However, the controller development of IEC system received less attention. The limited studies reporting the controller used in an IEC system include a smart control system proposed by Sohani et al. [10]. It reports that the control system can provide a capability for 85% occupants with thermal comfort by switching the IEC fan among high speed, low speed and shutdown. Another similar study has conducted by Chen et al. [11]. A high-low controller is proposed for regenerative indirect evaporative cooler (RIEC). The results show that high-low control is superior to on-off control by providing better thermal comfort, better indoor air quality and 11.3% less energy consumption annually. However, it is found that the control precision of high-low control is still unsatisfactory. In addition, there are some control logics and devices patented to be applied in evaporative cooling system, such as Programmable Logic Control (PLC), Direct Digital Control (DDC) and Distributed Control System (DCS) [12,13]. However, the dynamic performance of evaporative cooler, such as indoor temperature fluctuation and fan speed variation have not been discussed. Besides, detail parameter settings and control algorithm are not reported.

The advantages of variable speed technology motivate us to conduct a feasibility study by incorporating it into an IEC system. It is not a new idea to incorporate variable speed technology in mechanical equipment. The variable speed of fan, pump and compressor relies on an inverter, which can operate stepless at different speeds generating a modulated flow and cooling output. About 10 years ago, the variable speed technology had been proved to be effective in pumping system [14], HVAC system [15], industrial aerial coolers [16] and air compressor system [17] for its competitive advantages such as avoid system oversizing, reduce electricity bill, increase comfort and soft start up and over speed capability.

Later, extensive further studies can be found on the variable speed technology used in some advanced HVAC systems and equipment in recent years. Schibuola et al. [18] presents a detailed assessment of applying variable speed drive (VSD) to HVAC components in a public building based on long-term data collection. The investigation shows that a global annual energy saving of 38.9% is achieved by VSD in comparison with the alternative constant speed HVAC system in terms of electricity consumption of pumps and fans. Chuang et al. [19] proposed a stepless variable speed driving technology applied to the Air Cooled Packaged Water Chiller Unit (ACH) to realize energy saving. The experimental results indicate at least 20% of energy saved if the pressure sensor combined with Stepless Variable Refrigerant Output (SVRO) technique was used. Attracted by 30-50% considerable energy saving of distributed variable-speed-pumps, Wang et al. [20] proposed a new hydraulic regulation method to achieve on-site hydraulic balance for the district heating systems with distributed variable-speed-pumps. In recent years, the energy saving technology of packaged rooftop units (RTU) is one of the research hotspots because of its large market occupancy rate in small commercial buildings in the United States. The variable speed technology becomes the first choice to embrace the technology revolution. Cai and Braun [21] presents relatively comprehensive assessment results for three RTU variable-speed retrofit options by replacing existing fixed-speed RTUs with variable-speed fans for different building types and locations in the U.S. Similar research has also been conducted by Wang et al. [22]. They evaluates the energy performance of a packaged unit with all variable-speed components, including the supply fan, the compressor, and the condenser fan by both field tests and simulation. Simulation results showed that energy saving ratio depending on the climate ranging from 45% to 54%. Apart from HVAC system, the variable speed technology in pumping system received intensive attentions, such as using variable-speed drives in photovoltaic pumping systems for irrigation [23] and using variable speed drive pumps to enhance the ability of a water distribution network to provide demand response energy to the grid [24, 25].

It can be seen that although variable speed technology has been developed for many years, existing research focusing on certain HVAC components including fan, pump, compressor and condenser. The technical feasibility of variable speed fans used in IEC has not been investigated. The IEC is an environmental-sensitive cooling technology, whose supply air temperature is greatly influenced by the inlet air temperature and humidity [26]. Therefore, the system characteristics of IEC are very different from the mechanical refrigeration system which is less affected by the outdoor air conditions. Moreover, existing research focuses on evaluating the energy saving potential of variable speed technology, the thermal comfort improvement (temperature fluctuation and control precision) has seldom been reported from year-around perspective. Unlike the mechanical cooling system which experienced long-term verification of performance stability, the thermal comfort of an IEC system under annual continuously internal and external disturbances is questionable to some extent and worth investigation. Lastly, existing evaluation of variable speed technology are more focusing on technology aspect rather than techno-economic aspect.

The variable speed can be realized by many control algorithms include most commonly used PID/PI/PD control, fuzzy logic control, artificial neural network (ANN) based control and system identification based control. The PID/PI/PD control is easy-to-use and feasible to implement by simulation tools, but overshoot can hardly be avoided. Fuzzy logic control depends on expert knowledge [27, 28]. ANN control relies on large amount of experimental dada to train a semi-empirical model for a fixed system [29].

In this paper, a proportional–integral (PI) law based variable speed technology is proposed for accurate temperature control in an IEC system. The objectives of this study include~~: 1. Develop an IEC system model under~~ PI control development with proper tuning parameters,~~; 2. Quantitatively~~quantitatively evaluation~~e the advantages of PI control over on-off control~~ of control performance in an IEC~~ in terms of temperature variation, control precision, response time and energy consumption; 3. Analyze the~~ and economic feasibility analysis of PI-based variable speed technology used in an IEC system. The paper is organized as follows. Firstly, the IEC is modelled and control algorithm introduced. Secondly, a case is selected for annual simulation. Control performance in an IEC under both the PI control and on-off control are compared in terms of temperature variation, control precision, response time and energy consumption. Lastly, quantitative techno-economic analysis results are presented.

2. RIEC system description and model development

In this section, the working principle of IEC is firstly introduced. Then, the heat and mass transfer model of IEC is established and validated. Lastly, the energy consumption model of IEC is presented.

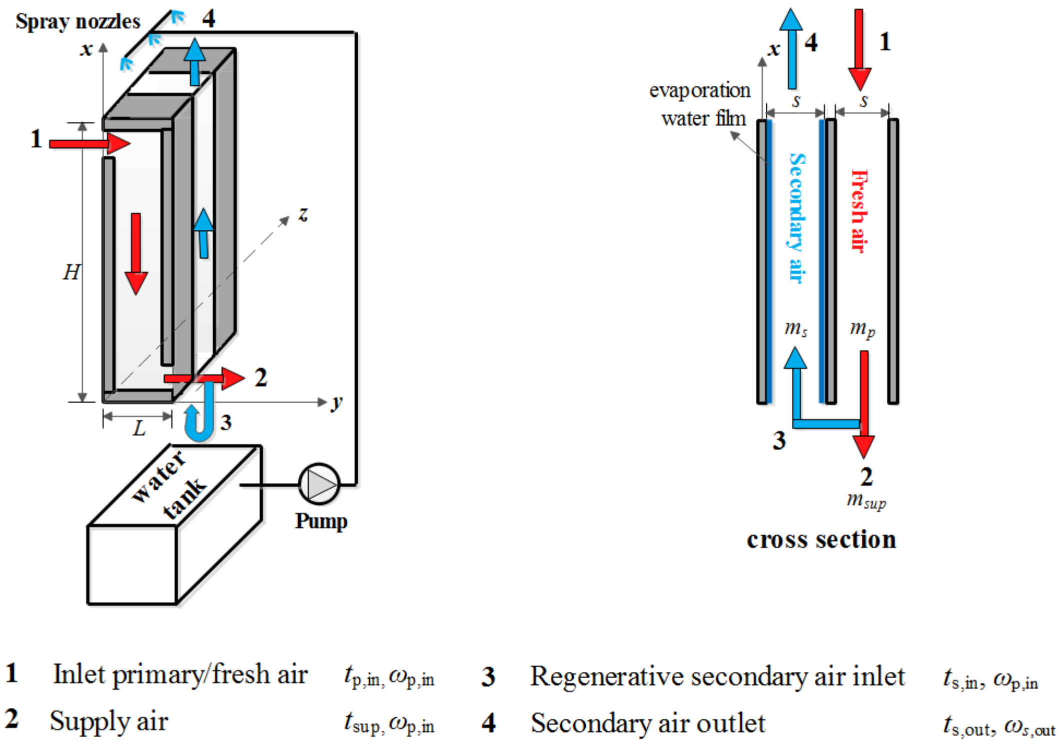

Fig.1 schematic diagram of RIEC

Plate-type IEC is the most commonly used IEC. It is consisted of a series of wet and dry channels arranged alternately and separated by thin metal wall. Water film are formed on the wall surfaces facing the wet channels due to the water spray. The metal wall is therefore cooled along with water evaporation under the reversed secondary air flow. In the adjacent channels, the primary/fresh air is indirectly cooled by evaporation without change in moisture content. Recently, great research efforts have been put on Regenerative IEC (RIEC), a more advanced IEC, which can cool the primary air to its dew-point temperature. In a RIEC, a portion of fresh air at the exit of dry channel is extracted to form the secondary air flow, as shown in Fig.1 [30].

A heat and mass transfer model of RIEC is required to predict its thermal performance under certain control scheme. There is an existing RIEC model available derived in our previous publication [31]. The model is based on the conservation of two air channels as described by Eq.(1) to Eq.(5). To avoid duplicate contents, the detailed descriptions of heat and mass transfer process, assumptions and solving method can refer to a previous work [31].

$$h_s(t_w - t_s)dA = c_{pa}\rho\dot{V}_s dt_s \tag{1}$$

$$h_{ms}(\omega_{sat} - \omega_s)dA = \rho\dot{V}_s d\omega_s \tag{2}$$

$$h_p(t_p - t_w)dA = c_{pa}\rho\dot{V}_p dt_p \tag{3}$$

$$dm_{ew} = \rho\dot{V}_s d\omega_s \tag{4}$$

$$\rho\dot{V}_s di_s - c_{pa}\rho\dot{V}_p dt_p = d(c_{pw}t_{ew}m_{ew}) \tag{5}$$

The relationship between the volume flow rate of secondary fan and primary fan is:

$$\dot{V}_s = r \cdot \dot{V}_p \tag{6}$$

After extraction, the remaining fresh air is directed supplied to the room, which can be calculated as:

$$\dot{V}_{\mathrm{sup}} = (1 - r) \cdot \dot{V}_p \tag{7}$$

Boundary conditions in a counter flow RIEC are given as follows: $x=H$, $t_{p}=t_{p,in}$; $x=0$, $t_{s,in}=t_{p,out}$; $x=0$, $\omega_{s,in}=\omega_{p,in}$; $x=H$, $m_{ew}=m_{ew,in}$. To solve the above one-dimensional ordinary equations, Runge-Kutta iteration method is used after discretion.

The RIEC model was validated by comparing the numerical simulation results with those experimental data obtained from a counter-flow RIEC [32]. The simulations were conducted by setting the same geometry and inlet air conditions as given in the literature. The inlet air temperature varies from 25℃ to 45℃ and moisture content varies from 6.9g/kg to 26.4g/kg, which covers the weather conditions in Xi’an as describe in Fig.3. It can be seen that the simulation results agree well with the experimental data with maximum discrepancy of 3.4% in predicting supply air temperature. Therefore, the RIEC model is regarded as reliable for further system-based simulation.

The indoor air temperature (t_{N}) and moisture content (ω_{N}) can be derived from indoor heat and mass balance models, as described in Eq. (8) and (9). Their fluctuations are determined upon the dynamic cooling capacity provided by RIEC, current cooling load and previous indoor air conditions.

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

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

where, Q_{sen} and Q_{lat} are the current sensible and latent cooling load, kJ/h. $t_{p,out}$ is the supply air temperature of RIEC, ºC. ω_{amb} is the moisture content of ambient air, g/kg. The differential terms in Eq.(8) and Eq.(9) can be solved by algebraic equations using Euler method. Considering the operability of the control system, 1-minute time interval is adopted during the simulation. Namely, the control signal is logged and fan speeds adjusted every 60 seconds.

Energy-consumed components in RIEC include the circulation pump and primary fan and the secondary fan. Energy consumed by the pump is not considered in this study since it is the same for both control schemes. Energy consumption of a fan is given as:

$$W_{fan} = \frac{\dot{V} \times \Delta P}{3600 \times 1000 \times \eta_0 \times \eta_1} \tag{10}$$

where, ΔP represents pressure drop, determined as 100 Pa when $\dot{V}_p$ =0.5 m^3/s [33, 34]. η_0 is the internal efficiency of the fan, set as 0.82. η_1 is the mechanical efficiency, assumed to be 0.97. According to the affinity laws, power is proportional to the cube of shaft speed, i.e, the energy consumption is only 1/8 of rated power if the fan speed is 1/2 of rated speed. Therefore, potential energy saving is expected when the PI control is used. Nevertheless, the pressure is also proportional to the square of shaft speed, an additional linkage fan with 25 Pa pressure is installed. It is controlled to operate along with the primary fan when $\dot{V}_p$ is smaller than 0.375 m^3/s to ensure sufficient pressure.

3. Control schemes

In this section, the control algorithm of the two controllers, namely on-off control and PI control, are described. The control algorithm was programmed by MATLAB to facilitate the annual simulation of IEC system under constantly changing cooling load and inlet air conditions.

3.1 On-off control

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. 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:

$$\begin{array}{lll} \text{If} & t_N(T) \le t_{set}(T) - \Delta t_1, & \dot{V}_p(T+1) = 0 \\ \text{If} & t_{set}(T) - \Delta t_1 \le t_N(T) \le t_{set}(T) + \Delta t_2, & \dot{V}_p(T+1) = \dot{V}_p(T) \\ \text{If} & t_N(T) > t_{set}(T) + \Delta t_2, & \dot{V}_p(T+1) = \dot{V}_p \end{array}$$

where T is the present time point and (T+1) is the next time point. Δt_1 is the lower dead band, set as 1.5 ℃. t_{set} is the setting temperature and Δt_2 is the upper dead band, set as 0.5 ℃. If indoor temperature is set as 25.5 ℃, the fans would be turned off if $t_{\mathrm{N}}(T)$ is lower than 24 ℃. They would be turned on if $t_{\mathrm{N}}(T)$ is higher than 26 ℃ and remain the original state or the current operation state if $t_{\mathrm{N}}(T)$ is between 24 ℃ and 26 ℃.

3.2 PI control scheme

PI control is realized by calculating the error value $e(T)$ as the temperature difference between a preset $t_{set}(T)$ and a recorded process variable, namely, $t_N(T)$. To simplify the calculation, incremental PI is adopted in this paper. Formulas (11) are applied based on two terms, i.e., the proportional and integral. To minimize the temperature error over time, the controller updates the control variable $\dot{V}_p$ to a new value, $\dot{V}_p\left(T+1\right)$, determined by the sum of the previous fan speed and the two control terms, as shown in Fig.2.

$$
\begin{aligned}
& e(T)=t_{set}(T)-t_N(T) \\
& m_p(T+1)=m_p(T)+k_p[e(T)-e(T-1)]+k_i e(T) \\
& \dot{V}_p(T+1)=m_p(T+1)/\rho \\
& \text{If} \quad t_N(T)\le t_{set}(T)-\Delta t_1,\ \dot{V}_p(T+1)=0
\end{aligned} \tag{11}
$$

where $e(T)$ is the temperature error, k_p is the proportional gain, k_i is the integral gain. k_p and k_i are manually tuned as -0.2 and -0.5, followed the Ziegler-Nichols Tuning Rule [35].

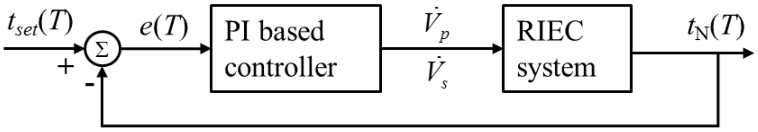

Fig.2 Feedback loop of PI based controller applied in RIEC system

4. Simulation case

A case is selected to investigate the annual performance of RIEC system equipped with variable speed fans based on PI control. For comparative study and quantitatively evaluation of the advantages of PI control over on-off control, the annual performance of RIEC system under on-off control is also simulated under the same setting conditions. The studied case is a small clinic located in Xi’an, a hot and dry city in China. The hourly weather condition in a year is shown in Fig. 3. Details of major parameters used in the simulation case are given in Table 1.

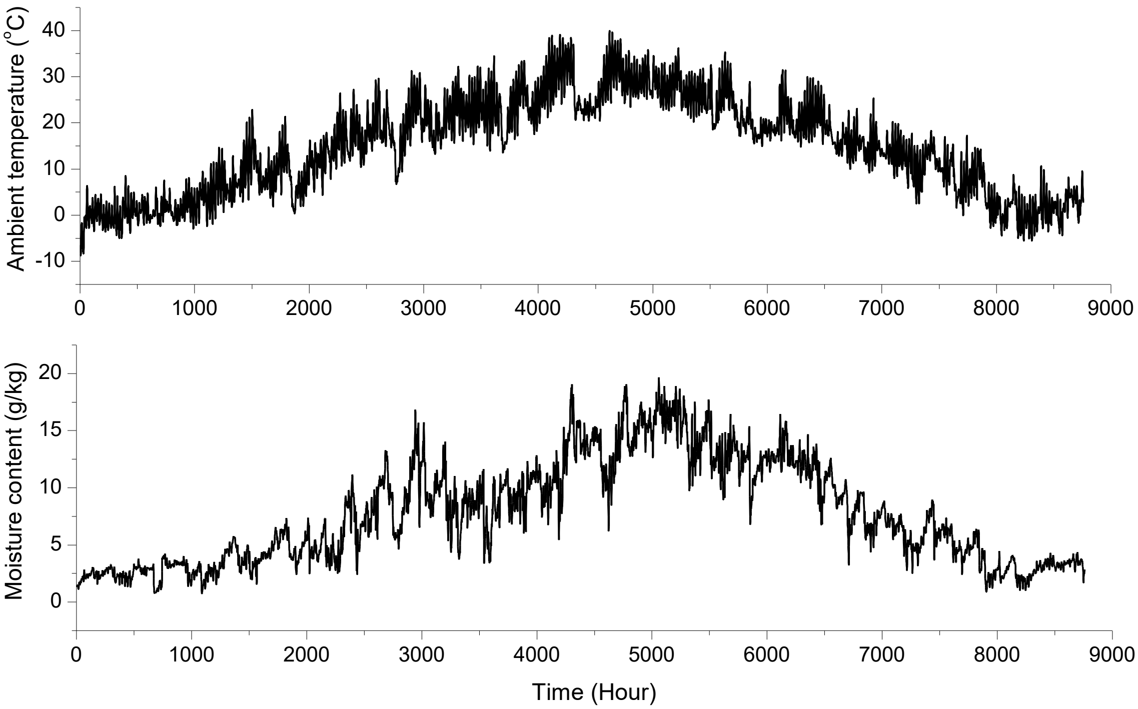

Fig.3 Year round weather condition in Xi'an

Table 1 Major parameters used in the simulation case

Location	Xi'an
Room dimensions	4.0 m (L)× 6.0 m (W) × 2.6 m (H)
Orientation	Two exterior walls facing the south and east
U-value	
Exterior wall (W/m^2·K)	0.5
Window (W/m^2·K)	2.83
Window to wall ratio	0.3
Heat gain	
Occupants	4 people/room (two doctors and two patients), light work
Lights	10 W/m^2
Computer	280 W/room (two computers with monitor)
Schedule	9:00 to 20:00 every day, lunch break 12:00 to 13:00
Cooling season	1st June to 15th September

TRNBuild multi-zone building module in Trnsys software was used to simulate the year-round cooling load of the studied case. The peak sensible cooling load is 6082 kJ/h, taking place in

August. The average sensible heat ratio (SHR) is around 0.8 to 0.9 in cooling season, indicating the suitability of applying evaporative cooling technology as sensible load dominates.

5. Results and discussion

In this section, firstly, comparison between RIEC performance under PI control and on-off control is made on annual basis in terms of indoor temperature distribution. Secondly, the indoor temperature and fan speed fluctuations in two typical days are comparatively discussed. Thirdly, disturbance rejection test is conducted to evaluate the robustness of both the controllers. Then, the annual energy consumption of RIEC system is analyzed for evaluating the energy saving potential of PI based controller. Lastly, the economic analysis is conducted by considering the additional investment of PI controller over on-off controller.

5.1 Annual performance

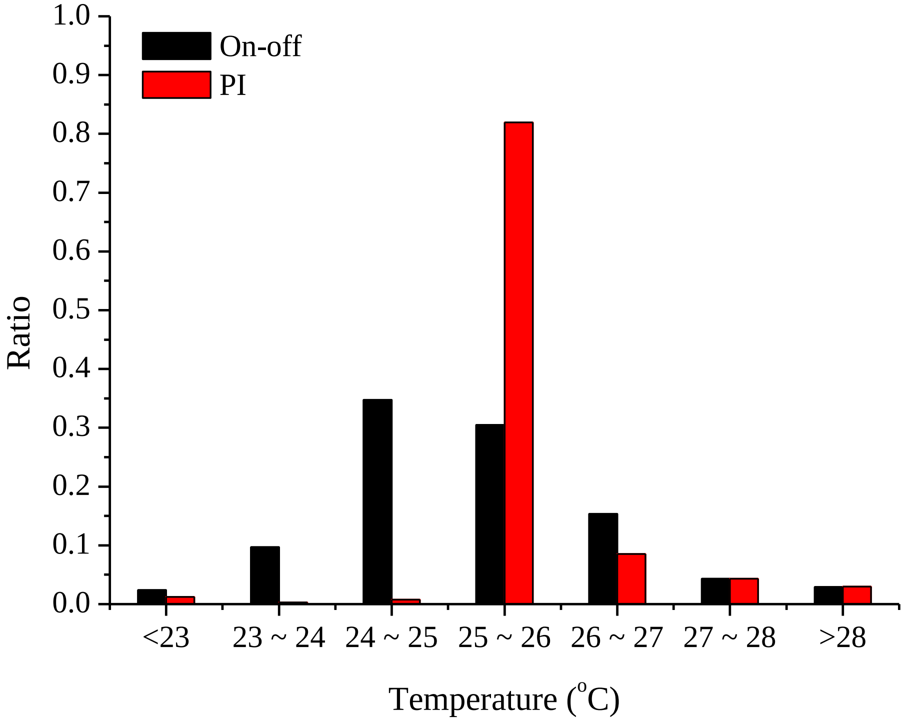

Fig.4 Annual temperature distribution under PI control and on-off control

Fig.4 shows the annual temperature distributions under PI based control and on-off control, with the same target indoor temperature setting as 25.5 ℃. It can be seen that PI based controller can provide much more comfortable thermal environment with indoor temperature ranging from 25 ℃ to 26 ℃ for 81.9% of operation time. The control precision of on-off is much worse than that of PI based controller. The indoor temperature fluctuating around the setting value between 25 ℃ to 26℃ only accounts for 30.5% of operation time under on-off control. The indoor temperature is more widely distributed with 15.4% of operation time varying between 27 ℃ to 28 ℃, 30.5% of operation time varying between 26℃ to 27 ℃ and 34.7% of operation time varying between 24 ℃ to 25 ℃. It is found that much lower indoor temperature that deviates from the setting point is commonly seen in on-off control. In other words, insufficient precision of on-off control tend to bring more cold feeling to occupants. However, the proportion of higher indoor temperature (>27 ℃) is the same for both on-off control and PI based control because of the limited cooling capacity of the RIEC under extremely hot days.

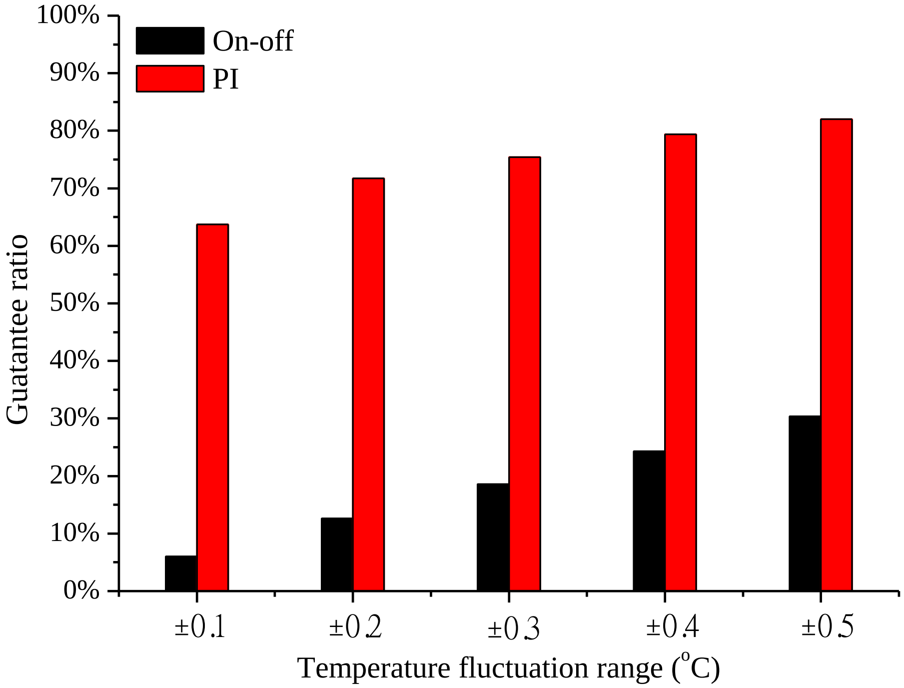

Fig.5 Annual temperature fluctuation range under PI control and on-off control

To further elaborate the control precision, the annual temperature fluctuation range deviating from the setting value under PI based control and on-off control are shown in Fig.5. It can be seen that 63.7% of indoor temperature fluctuates only within ±0.1 ℃ around the setting value under PI based control, while only 6% under on-off control. With the temperature fluctuation range increases from ±0.1 ℃ to ± 0.5 ℃, the guarantee ratio keeps increasing from 63.7% to 82.0% under PI based control and from 6.0% to 30.4% under on-off control. It indicates that the PI control is much superior to on-off control in terms of control precision from a year-round perspective.

5.2 Performance in typical days

The thermal performance of RIEC is highly influenced by the weather conditions. Two typical days, including a typical summer day (28-July) and a typical day of transition season (02-

September), have been selected to comparatively investigate the RIEC performance under the two controllers.

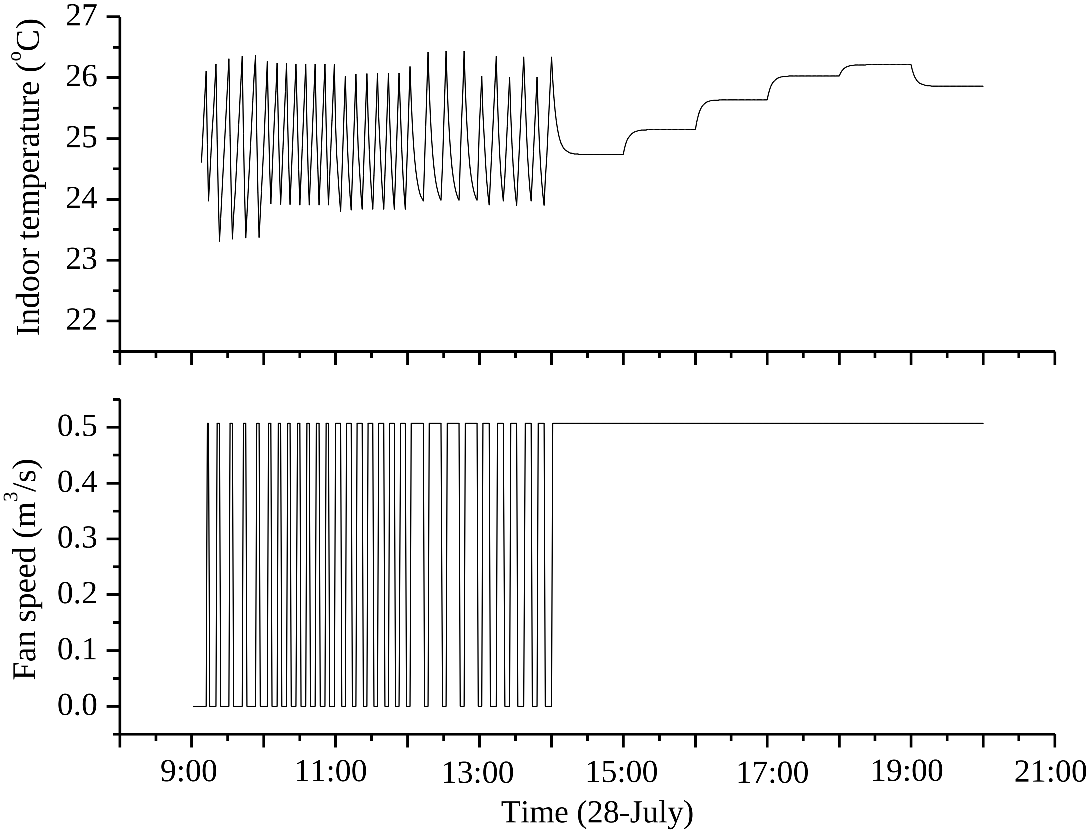

Fig.6 Indoor temperature and fan speed variation under on-off control on 28-July

Fig.6 shows the indoor temperature and fan speed variation under on-off control in a typical summer day. The indoor temperature fluctuates between 23.3 ℃ and 26.4 ℃ in operation hours, which is out of the control range of 24 ℃ to 26 ℃. This is mainly caused by the setting of 1 minute's control interval. For example, indoor temperature is as low as 24.03 ℃ at 09:22. However, fans will continue ~~operating~~ operate at the rated speed according to the on-off control scheme, resulting in space overcooling to 23.30 ℃ at 09:23. Rapid, frequent and large temperature variation can be observed from 9:00 to 14:00, unavoidably creating uncomfortable thermal environment to occupants. During the period, the hourly cooling load gradually increases from 3002 kJ/h to 4513 kJ/h. Correspondingly, the fan speed ~~periodically~~ switches between rated speed and off state periodically and frequently. When the cooling load increases to near the peak, the primary fan speed remains constant at the maximum speed, i.e., 0.5 m^3/s after 14:00. However, the indoor temperature still gradually increases from 24.7 ℃ to 26.2 ℃ because the peak cooling load of 5000 kJ/h during 16:00 to 18:00 is beyond the cooling capacity of RIEC. The average indoor temperature during the operation hours is 25.2 ℃, a little lower than the setting value of 25.5 ℃. In sum, the simulation results indicate that the on-off control is effective, but some shortcomings, such as large temperature fluctuation and unsatisfied control precision, can be identified.

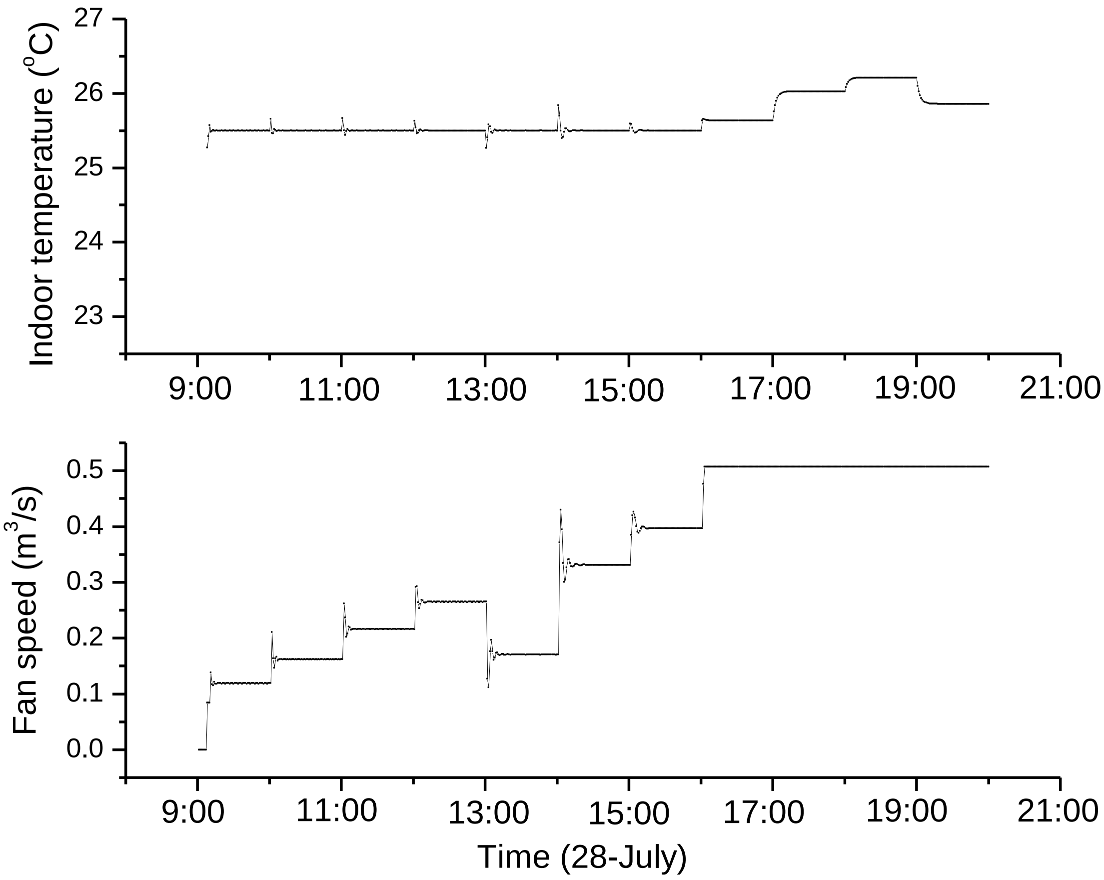

Fig.7 Indoor temperature and fan speed variation under PI control on 28-July

Fig.7 shows the indoor temperature and fan speed variation under PI based control in the same typical summer day. It can be seen that the indoor temperature mostly controlled at the setting value of 25.5 ℃ precisely. There is inconspicuous temperature fluctuation during the operation hours apart from the disturbances caused by hourly changed cooling load and weather conditions. These disturbances are inevitable since 100% fresh air is treated by the RIEC, making it sensitive to the ambient temperature. Disturbances caused by ambient condition variations can be reduced if a shorter control interval is used. The maximum indoor temperature fluctuation of 0.42 ℃ occurs at 14:00 where ambient temperature increases by 0.53 ℃ and cooling load increases form 4513 kJ/h to 4904 kJ/h, respectively. Under current tuning parameters (k_p=-0.2, k_i=-0.5) setting, indoor temperature can be quickly adjusted to the setting value within 7 minutes under large disturbance. Slightly overshoot or undershoot of temperature can be observed. All the overshoots are within 0.1 ℃. They decay and become invisible in one oscillation period. It indicates that the PI based controller is well adapted to the changing of cooling load and ambient conditions in terms of response time and control precision.

Correspondingly, the fan speed is automatically adjusted to adapt the cooling load. Overall, fan operates at higher speed under higher cooling load and vice versa. The primary fan speed suddenly reduces to 0.15 m^3/s owing to cooling load reduction during lunch break between 13:00 to 14:00. Stable operation of fans can be achieved under the PI based control as shown in Fig. 7. As the cooling load varies greatly in a day, varying a fan's speed allows it to match changing load requirements more closely under PI control. Full load operation at constant rated speed under on-off control is unnecessary and largely reduces the lifetime of fan by frequent start and stop. In addition, part load operation provides considerable energy saving because fan power draw is proportional to the cube of its speed.

Same as the on-off control, the indoor temperature under PI based control is out of the control range in the afternoon because of the limited cooling capacity of RIEC. In sum, as an ambient sensitive cooling device, the RIEC assisted by PI based controller can create better thermal environment compared with on-off control for its control precision and cooling load adaptability.

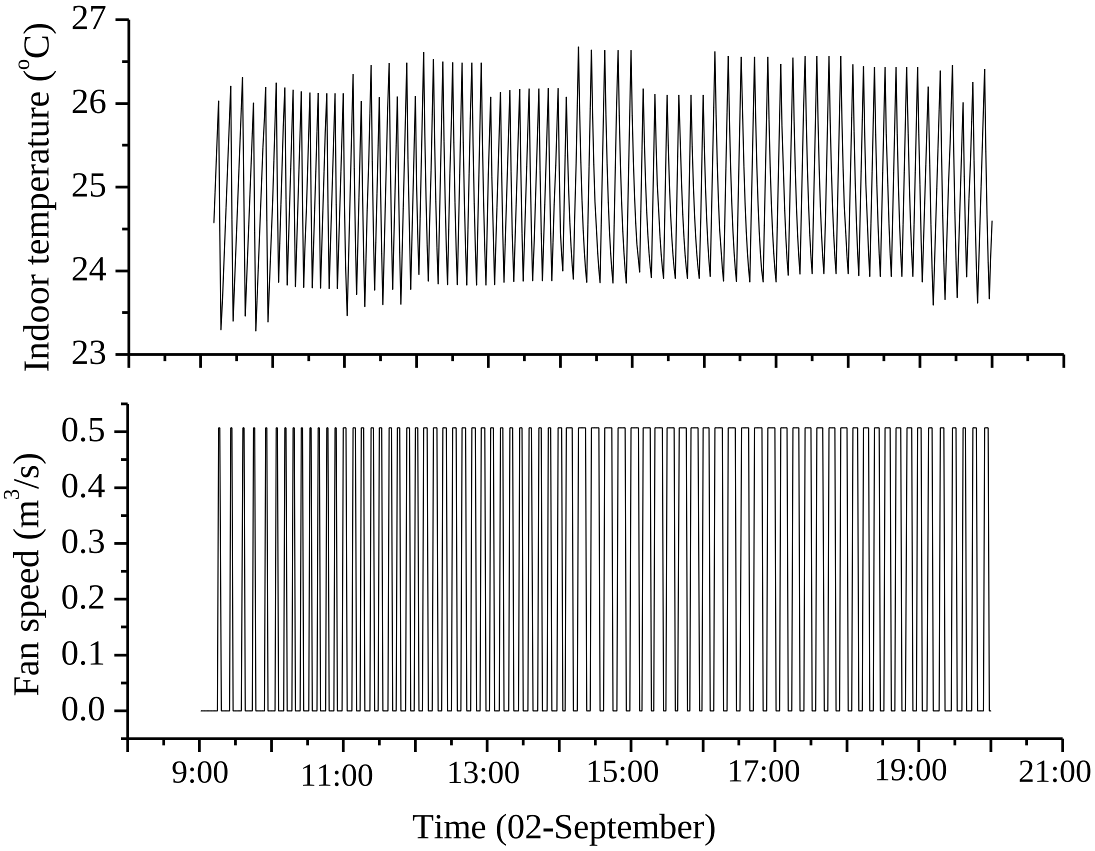

Fig.8 Indoor temperature and fan speed variation under on-off control on 02-September

Fig.8 shows the indoor temperature and fan speed variation under on-off control in a typical day of transition season. It can be seen that the indoor temperature fluctuates greatly between 23.3 ℃ to 26.4 ℃ from minute to minute when setting temperature is 25.5 ℃. In transition season, the cooling load is smaller than the rated capacity of the RIEC. Space cooling load can be easily eliminated and therefore, the indoor temperature decreases rapidly once the fan operates at rated speed. In this simulation case, the fan speed switches every 3 to 7 minutes to maintain the preset temperature. The frequent switching would shorten the lifetime of the fan. Moreover, the indoor air quality can not be guaranteed when the RIEC is at off state. In sum, the thermal performance of RIEC under on-off is unsatisfactory in transition season because of large indoor temperature fluctuation, frequent switching of fan speed and unguaranteed indoor air quality.

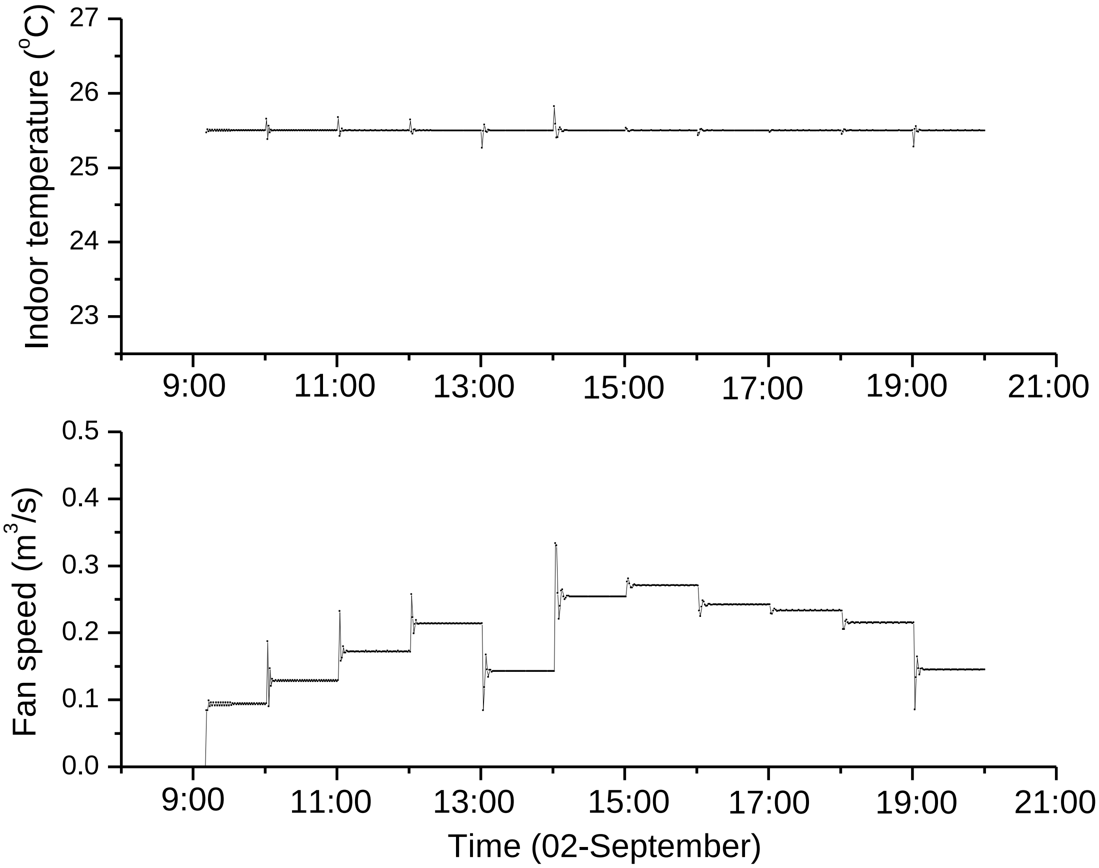

Fig.9 Indoor temperature and fan speed variation under PI control on 02-September

Fig.9 shows the indoor temperature and fan speed variations under PI based control in a typical day in transition season. It can be seen that the indoor temperature can be controlled at the setting value of 25.5 ℃ precisely apart from some disturbances caused by hourly changing cooling load and weather conditions. The disturbances are all within ±0.30 ℃, which are slightly smaller than that in a typical day. Fan speed can be perfectly adjusted every 2 to 6 minutes to meet the changing cooling load and suppress the disturbances. Under the PI control, small overshoot or undershoot of indoor temperature can be observed when dealing with each disturbance. The maximum undershoot is detected at 10:02 as 0.12 ℃. The amplitude of the overshoot damped to 0.04 ℃ two minutes later. After that, indoor temperature can be precisely controlled owing to the small adjustment of fan speeds. No overshoot or undershoot can be found between 15:00 and 18:00 because of the small cooling load variation during the period.

The superiority of PI control is more evident in the transition season. The primary fan operates at partial speed ranging between 0.08 m^3/s and 0.27 m^3/s, which perfectly matching the low changing cooling load. In sum, the PI based controller is well adapted to both full load and part load cases in all seasons with good control precision and fast response speed.

5.3 Disturbance rejection test

One disturbance rejection test has been conducted under two control schemes to investigate the RIEC performance when the setting temperature suddenly changes.

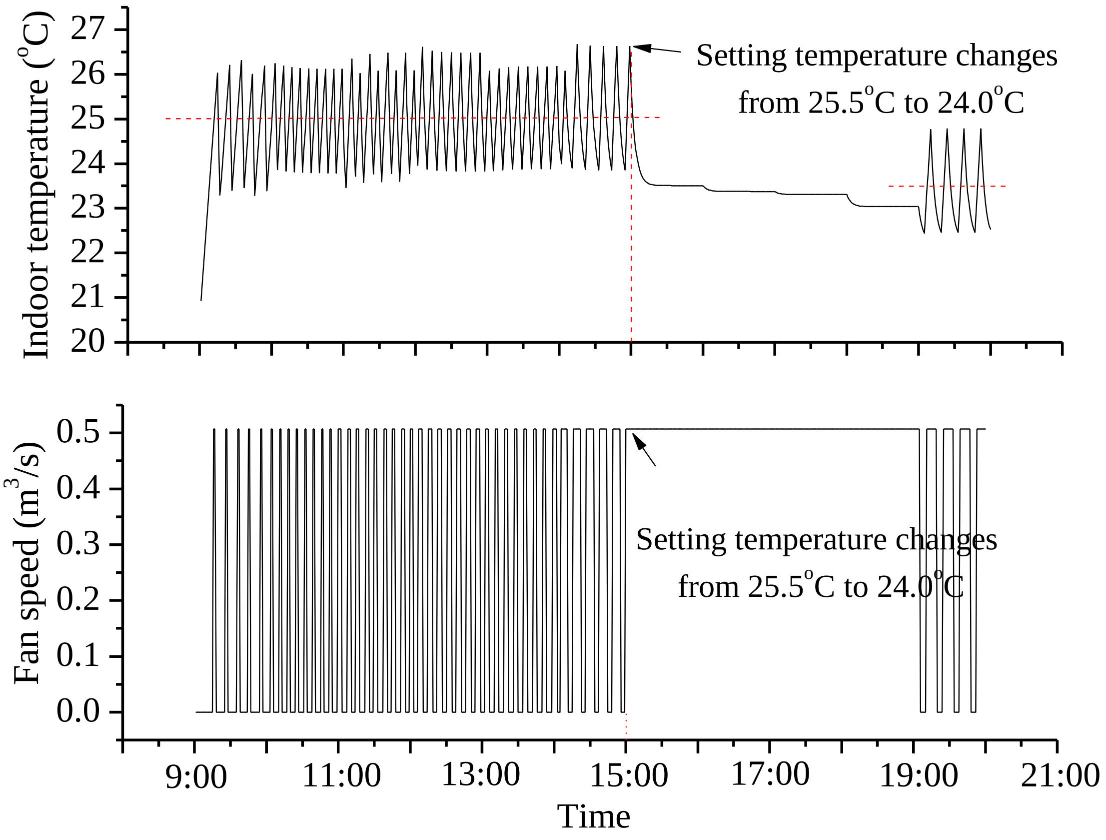

Fig.10 Indoor temperature and fan speed variation when setting temperature changes under on-off control

Fig.10 shows the indoor temperature and fan speed variation when setting temperature changes under on-off control. In the simulation case, the initial indoor temperature is set to be 25.5 ℃ and the actual temperature fluctuates around 25.0 ℃. The setting temperature is suddenly changed to 24.0 ℃ at 15:00. Then, the fan is operated at rated speed from 15:00 to 19:00 continuously. Two problems can be identified through the disturbance rejection test. Firstly, the control precision is unsatisfied. The steady temperatures before and after the change of setting are 25 ℃ and 23.5 ℃, respectively, rather than the setting value of 25.5 ℃ and 24.0 ℃, respectively. Secondly, the long response time is observed. In this case, it takes 6 minutes for the system to adjust from 25 °C to 24.0 °C. However, indoor temperature cannot be maintained at 24.0 °C due to 1.5 °C lower dead band in the on-off control scheme. Therefore, excessive regulation can be observed. Indoor temperature is continued to be cooled to 23.5 °C around 15:30 and further to 23.04 °C between 18:00 and 19:00. Therefore, the fan keeps operating at rated speed for almost 4 hours, resulting in over-cooled of the space to 22.5 °C. The response time is 30 minutes when indoor temperature decreases from 25°C to 23.5°C for the first time. The two shortcomings would cause uncomfortable feelings to occupants because of poor regulation characteristics and large temperature fluctuation.

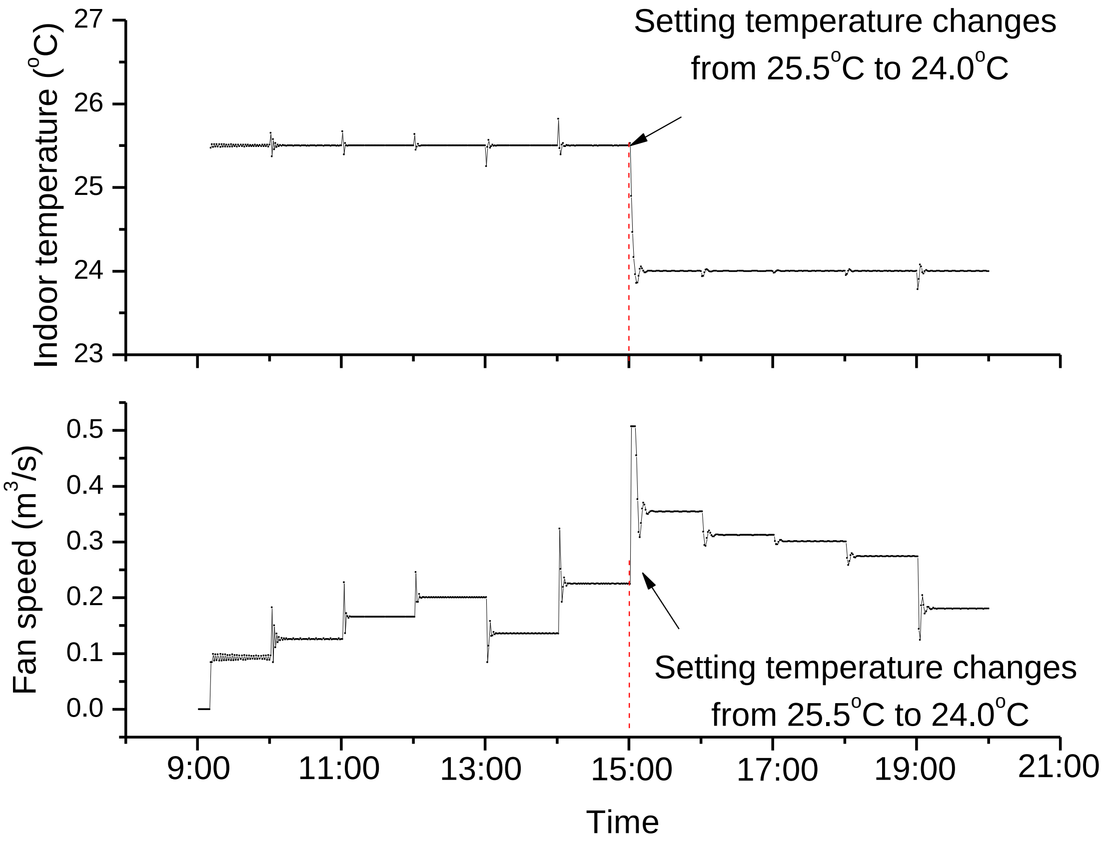

Fig.11 Indoor temperature and fan speed variation when setting temperature changes under PI control

Fig.11 shows the indoor temperature and fan speed variation when setting temperature changes under PI based control. The initial indoor temperature is set to be 25.5 ℃ and the setting temperature is suddenly changed to 24.0 ℃ at 15:00. It can be seen that the PI control responses immediately to operate fans at the rated speed. As indoor temperature approaching the new setting, fan speed reduces accordingly. After one period of oscillation, the primary fan runs smoothly at around 0.35 m^3/s for the rest of 45 minutes. The actual indoor temperature changes from 25.5 ℃ to 24.0 ℃ promptly within only 10 minutes. The temperature fluctuations before and after the disturbance test are very small. A maximum undershoot of 0.14 ℃ can be observed at 15:06. It attenuates and becomes invisible in one oscillation period. Therefore, in terms of control precision and response speed, the PI based control is much superior to on-off control. In addition, fans are stably operated below the rated speed during each operation hour. The operation hours of the fan at high speed is much shorter under PI based control compared with that of on-off control, providing consideration energy saving of RIEC system.

5.4 Energy consumption analysis

The annual energy consumptions of the RIEC under both controllers are analyzed. The energy-consumed components of a RIEC include a primary air fan, a secondary air fan, a linkage fan if necessary and a circulation pump. As the energy consumption of circulation pump is the same for two control strategies, the comparison of energy consumption between the two controllers only takes account of the primary air fan and secondary air fan.

Table 2 Energy consumption of RIEC under on-off control

	Fan speed (m^3/s)	Power (W)	Operating hours (h)	Energy consumption (kWh)
Primary air	0.5	58.14	708	41.2
	0	0	1860	0
Secondary air	0.15	17.44	708	12.4
	0	0	1860	0
Total				53.5

Table 2 lists out the energy consumption of RIEC under on-off control in the whole cooling season. The total operation time in the cooling season from 1st June to 15th September is 708 hours, while non-operation time is 1860 hours. Therefore, the total energy consumption is calculated to be 53.5 kWh.

Table 3 lists out the energy consumption of RIEC under PI based control in the whole cooling season. Unlike the on-off control in which the RIEC operates either at rated load or off mode, the RIEC under PI based control is equipped with variable speed fans. The fan speed is automatically regulated between 0 and 0.5 m^3/s every minute based on current indoor temperature. According to the statistics, the fans mostly operate between 0.42 ~ 0.5 m^3/s and 0.08 ~ 0.25 m^3/s. The non-operation hours of RIEC is only 1447 hours, much shorter than that of 1860 hours in on-off control. Longer operation hours enable better indoor air quality by ventilation. Unsurprisingly, the annual energy consumption using the PI control is only 26.8 kWh, 50% less than that of on-off control. It is attributed to the much lower energy consumption under part load. According to the affinity laws, power is proportional to the cube of shaft speed. In the simulation case, the energy consumption is 15.8 kWh when primary fan speed ranges from 0.42 ~ 0.5 m^3/s for 278.8 hours. However, it is only 0.7 kWh when the fan speed ranges from 0.08 ~ 0.17 m^3/s for 281.6 hours. In sum, RIEC equipped with PI based variable speed fans consume 50.0% less energy than that of on-off controlled fans.

Table 3 Energy consumption of RIEC under PI based control

	Fan speed (m^3/s)	Operating hours (h)	Energy consumption (kWh)
Primary air	0.42~0.5	278.8	15.8
	0.34~0.42	64.6	1.6
	0.25~0.34	105.0	1.2
	0.17 ~ 0.25	256.9	1.0
	0.08 ~ 0.17	281.6	0.7
	0.08	133.7	0.4
	0	1447	0
Secondary air	0.127 ~ 0.152	278.8	4.7
	0.101 ~ 0.127	64.6	0.5
	0.076 ~ 0.101	105.0	0.4
	0.050 ~ 0.076	256.9	0.3
	0.025 ~ 0.050	281.6	0.2
	0.025	133.7	0.1
	0	1447	0
Total		1121	26.8

5.5 Economic analysis

The above results show that PI based control can provide better thermal comfort and energy saving at the same time. However, the PI based control can only be realized with the assistance of an additional variable frequency driver (VFD), which increases its investment compared with on-off control. To investigate if this technology is cost-effective, economic analysis is conducted by retrofitting an on-off based RIEC into a variable speed based RIEC considering the trade-off between the investment increase and energy saving.

The investment increase comes from the capital cost of VFD. A market survey has been conducted to find out the relationship between the power of VFD and price as shown in Fig.12 based on 86 quotations from RS Hong Kong, a world leading distributor of electronics, automation and control components, tools and consumables [36]. It can be seen that the average price of VFD is almost proportional to the power of VFD.

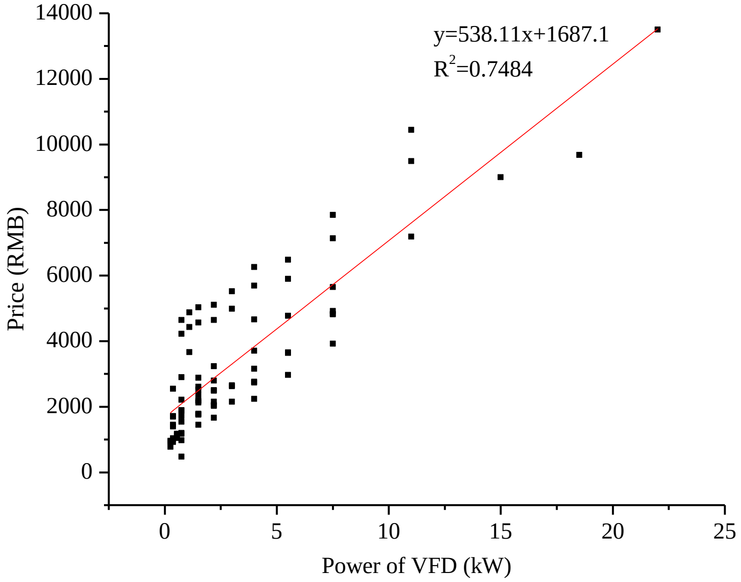

Fig.12 The relationship between power of VFD

The dynamic economic analysis considering the time value of money is adopted to measure how long it takes for retrofitting to 'pay for itself'. The cash flow was used in economic analysis, where outflows are recorded as negative and inflows are positive. The net cash flow value (*NCF*) refers to the difference between cash inflow value (*CIV*) and cash outflow value (*COV*).

$$NCF = CIV - COV \tag{12}$$

Because of the time value of money, the *NCF* (RMB/year) can be converted into net present value (*NPV*) as:

$$NPV = \frac{NCF}{(1+i)^n} \tag{13}$$

Where *n* is the equipment lifetime (years); *i* is the discount rate.

The payback period can be calculated as:

$$PBT = (N-1) + \frac{|\sum_{0}^{n-1} NPV_n|}{NPV_n} \tag{14}$$

Where, N represents the year when NPV becomes positive.

Table 4 Key assumptions used in discounted cash flow calculation

Factor	Value
VFD lifetime	10 years
Discount rate	5%
Electricity price	0.8 RMB/kWh

According to the reference [37], the typical lifetime of a VFD is 5-10 years depending on the manufacturer and during that time virtually no maintenance is required. Therefore, the VFD lifetime is assumed to be 10 years in this study considering the VFD technology had developed fast since the market survey completed in 2011. Table 4 lists out the key assumptions used in discounted cash flow calculation. By adopting the payback period calculation methods above, the summary of economic analysis result is shown as Table 5. The investment includes capital cost of VFD equipped on primary air fan (VFD_P) and capital cost of VFD equipped on secondary air fan (VFD_S), depending on fan power. The price of VFD listed in Table 5 is estimated by the correlation derived by regression analysis in Fig.12. According to previous simulation, the annual total operation time of RIEC under on-off control is 708 hours, therefore, the annual consumption of fans can be calculated based on their power and operation hours. Considering the energy saving ratio is 50% if constant speed fan based on on-off control is replaced by variable speed fan based on PI control, the annual total energy consumption of PI control based RIEC can be estimated. Assuming that the electricity price is 0.8 RMB/kWh in annual monetary saving calculation. It can be seen from Table 5 that payback period is shortened with the increase of fan power. Considering the lifetime of VFD is 10 years, the investment is economically infeasible if the payback period is longer than 10 years. Thus, the RIEC equipped with variable speed fan based on PI control is economically feasible only when the power of primary air fan is larger than 1.75 kW. The payback period is about 3 ~ 4 years if the power of primary air fan is between 3.25 kW to 4.75 kW.

Table 5 Payback calculation of RIEC retrofitting

P_p (kW)	0.25	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75
Price of VFD_p (RMB)	1822	2091	2360	2629	2898	3167	3436	3705	3974	4243
P_s (kW)	0.08	0.25	0.41	0.58	0.74	0.91	1.07	1.24	1.40	1.57
Price of secondary fan (RMB)	1731	1820	1909	1998	2087	2175	2264	2353	2442	2531
Total price (RMB)	3553	3911	4269	4627	4984	5342	5700	6058	6416	6774
Operation hours (h)	708									
E_{tot} under on-off control (kWh)	235	706	1177	1648	2119	2590	3060	3531	4002	4473
E_{tot} under PI control (kWh)	118	353	589	824	1059	1295	1530	1766	2001	2236
Monetary saving (RMB/year)	94	282	471	659	847	1036	1224	1412	1601	1789
Payback (years)	>10	>10	>10	7.3	5.7	4.8	4.1	3.7	3.3	3.1

6. Conclusions

To achieve better thermal comfort, a proportional–integral (PI) law based variable speed technology is proposed for accurate temperature control in an indirect evaporative cooling system. To quantitatively evaluate the PI based controller applied in an indirect evaporative cooler (IEC), comparative study has been conducted between the cooler equipped with on-off based constant speed fans and PI based variable speed fans. The year around simulation is conducted for investigation of indoor temperature fluctuation and energy consumption. Economic analysis is also conducted by considering the trade-off between the energy saving and cost increase. The main conclusions are summarized as follows:

1. The control precision PI based control is much higher than on-off control in IEC application. The indoor temperature can be controlled within ±0.5 ℃ around the setting point for 81.9% of time, while it is only 30.5% under on-off control.
2. As an ambient sensitive cooling device, the IEC assisted by PI based controller can create satisfactory thermal environment for its small temperature fluctuation, low switch frequency of fan speed, long fresh air guarantee hours and good control precision under continuously internal and external disturbances in both summer and transition season.
3. The PI based control is much superior to on-off control in terms of response speed when setting temperature changes. In the simulation case, it takes 30 minutes for the RIEC system to adjust from 25 ℃ to the new setting temperature under on-off control, while it only takes 10 minutes under PI based control. Excessive regulation can be observed in on-off control.
4. The annual energy consumption of RIEC under PI based control is 50% less than that of on-off control.
5. A RIEC equipped with variable speed fans is economically feasible only when the power of primary air fan is larger than 1.75 kW. The payback period is about 3 ~ 4 years if the power of primary air fan is between 3.25 kW to 4.75 kW.

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Nomenclatures			
A	heat and mass transfer area, m^2	h	heat transfer coefficient, W/m^2·℃
E_{tot}	Total energy consumption, kWh	h_m	mass transfer coefficient, kg/m^2·s
P	power of fan, kW	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, ℃
$\dot{V}$	volume flow rate, m^3/s		
Greek symbols			
ω	moisture content of air, kg/kg	ρ	air density, kg/m^3
Subscripts			
N	indoor air	in	inlet
p	primary air	out	outlet
s	secondary air	sup	supply air
w	wall/water	sen	sensible heat
ew	evaporation water	lat	latent heat
Abbreviation			
IEC	indirect evaporative cooler	RIEC	regenerative indirect evaporative cooler

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