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Dynamic Performance of Indoor Environment and Energy Consumption of Air Conditioning System under Intermittent Mode

Xiaofang SHAN [a,*], Wei-Zhen LU [a,*],Shichang HUI [b]

[a]*Department of Architecture and Civil Engineering, City University of Hong Kong, Tat Chee Road, Hong Kong, 999077, China*
[b]*Guangxi Fangchenggang Nuclear Power Co.,Ltd, Fangchenggang, Guangxi Province, 538000, China*

Abstract

Nowadays, energy efficiency and indoor thermal comfort have become two main issues in heating, ventilation and air conditioning (HVAC) systems. However, the balance between these two issues is difficult as the improvement of one is generally accompanied with trade-off the other. Hence, to achieve energy efficiency and thermal comfort simultaneously is of great significance to actual applications. This study proposes an optimal, intermittent operation mode for individual air conditioning system to achieve two goals concurrently. Firstly, the transient CFD approach is applied to explore the changing patterns of temperature profiles under on and off mode of the air conditioner. Secondly, the experimental test is implemented to validate the simulation results, which indicates that the indoor air temperature follows the exponential distribution via curve regression method. Based on the fitting curves of temperature under on/off patterns, the optimal intermittent operation mode can then be proposed involving 18 minutes switching-on and 8 minutes switching-off cycles. The energy consumption evaluation of such intermittent mode indicates that the 11% reduction of cooling power consumptions achieved comparing to the traditional operation mode.

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Keywords: Transient CFD simulation; Intermittent operation mode; Air conditioning system; Energy Performance; Thermal Comfort;

* Corresponding author. Tel.: +852-3442-4316; fax: +852-3442-0427.
E-mail Address: xiaofang.shan@yahoo.com; bcwzl@cityu.edu.hk.

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1. Introduction

Buildings generally account for 40% of total energy consumptions [1], and the energy-consuming terminals within the buildings consists of heating/cooling systems, electric appliances, and hot water equipment. In tropical and subtropical areas, cooling energy is the main composition of building energy due to the long operation period of cooling systems, which basically occupies 60% of total building energy. Therefore, effective reduction of cooling energy can significantly improve the energy performance of buildings in such areas. The available ways to reduce energy consumptions can be classified into two categories: improving the thermal performance of buildings materials and optimizing operation modes of HVAC systems. The second method is widely adopted via controlling the cooling or heating equipment to enhance the energy performance of HVAC systems [2]. Many control methodologies are proposed to reduce the energy consumptions of air conditioning systems, such as VAV (variable air volume) methods and the intermittent operation mode. The performance of intermittent modes which are applied in radiant floor heating system and ground source heat pump system is evaluated in [3]. Compared to the continuous operation mode, the intermittent operation mode can possess better energy performance. Besides the building efficiency, thermal comfort which relates to the health and working productivity of occupants is also drawn numerous attentions. Researchers have performed lots of studies on indoor environment of air-conditioned space through CFD simulations, and the distributions of velocity, temperature and the pollutant concentration are obtained and analyzed [4]. However, among current research, CFD simulations are generally steady without considerations of dynamic properties of internal and external conditions [5]. Therefore, transient CFD simulations can be used to investigate dynamic properties of indoor environmental parameters under different operation modes of air conditioning systems.

This study proposed an optimal, intermittent operation mode of air conditioning systems to achieve the energy efficiency and thermal comfort concurrently via transient CFD simulations and full-scale experiments. The paper includes four sections. The CFD model for the air-conditioned room is established in Section 2. Section 3 illustrates the dynamic boundary settings of enclosures and air inlet. In Section 4, the simulation results and experimental measurements are analyzed, and the changing patterns of indoor air temperature are presented under the running and suspension of air conditioner, from which the temperature profiles can be obtained. Based on the dynamic characteristics of temperatures, the optimal intermittent operation mode is generalized to meet the thermal comfort of occupants as well as the energy saving of operation concurrently. Finally, the conclusions are drawn in Section 5.

2. CFD models for the air-conditioned room

The office room with a ceiling-hanging air conditioner is located at Hong Kong, with the dimension of 5.2×2.7×2.85m, one external solid wall without windows, and three internal walls mounted with four internal windows. The physical model and mesh scheme of the air-conditioned room are established, as shown in Fig. 1. To achieve good simulation accuracy with reasonable computational cost, the mesh scheme is constructed with the Hexa-structured grid consisting of 500,000 hexahedral cells, presented in Fig. 1. The grid is refined at the air inlet, return vent, and the exhaust vent where the flow patterns are relatively complex and sensitive to the mesh scheme. The ventilation room is supposed to be of good air tightness without concerning the air leakages from door and windows.

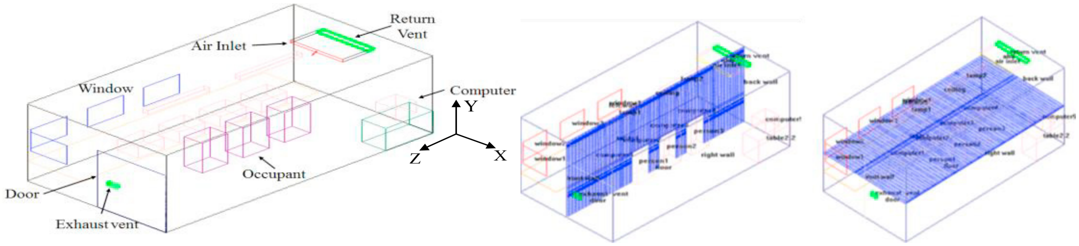


Fig. 1 The geometry and mesh scheme of the air-conditioned office room

The RNG k-ε turbulence model is adopted to estimate the indoor airflow. Besides the turbulent model, the convection model, heat conduction model and thermal radiation model are adopted to obtain the thermal effects of occupants, electric equipment and enclosures. When running the calculation, it is assumed that the airflow in the room is incompressible, and the buoyancy effect of the body force is therefore ignored. The residual convergence criterion for continuity, momentum, turbulent kinetic energy and turbulent dissipation rate is 10^{-3}, and for energy is 10^{-6}. The time step of the transient simulation is 1s and the maximum iteration number is 20 for each time step.

3. Dynamic boundary conditions

3.1. Supply air temperature

Once the air conditioner is switched on, the supply air temperature tends to gradually decrease with the operation time. In order to obtain the changing patterns of supply air temperature, the experimental test is conducted using wireless sensor to measure the inlet temperature once the air conditioner is on. The experiment takes about 30 min to cover the whole fluctuating process of supply air temperature. The wireless sensor records the temperatures every 3 seconds, and the measured data shown in Fig. 2. Through the figure, it can be observed that the supply air temperature presents a rapid slump in first 6 min and then decrease slowly. When the air conditioner runs about 15 min, the supply air temperature tends to be steady at 14.5°C. According to the data, a fitting cure can be obtained with two exponential functions expressed in Eq. (1). The fitting function can be interpreted by UDF file to depict the dynamic characters of supply air temperature under actual operation of the air conditioner. Besides the external wall and supply inlet, the other relevant boundary conditions, are listed in Table 1.

$$T_s = 1.91 * EXP(-\tau * 0.00533 + 1.559) + 1.18 * EXP(-\tau * 0.00138 + 1.122) + 14.6 \quad (1)$$

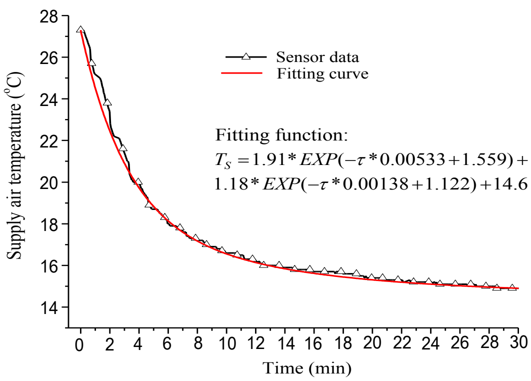


Fig. 2 The dynamic characteristics of supply air temperature

Table 1. Settings of boundary conditions.

Geometry	5.2m (length)×2.7m(width)×2.85m(height)
Supply air inlet/outlet dimension	1.01m×0.1m, rectangle grille
Supply airflow rate	0.3m^3/s
Windows	0.7m×0.7m, heat flux rate: 20W/m^2
Door	1.33m×2.1m, constant heat flux rate: 10W/m^2
Internal walls	Constant heat flux rate: 10W/m^2
Occupants	0.4m×0.2m×1.2m, calorific value: 3×100W/per person
Computers	0.4m×0.4m×0.5m, calorific value: 4×60W/each
Monitor	1.0m×0.5m×0.1m, calorific value: 50W

4. Simulation results

4.1. Dynamic temperature characteristics

The indoor air temperature is affected by internal and external conditions, and thus the energy conservation equation of the space can be described by Eq. (2):

$$C\frac{dt_R}{dt} = Q_{\text{int}} + Q_{enclo} + Q_{\text{inf}} - Q_{ex} \tag{2}$$

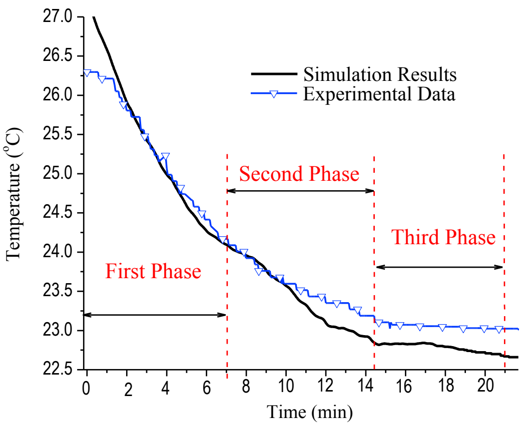
where C is the thermal capacitance of the room, t_R is the indoor air temperature, Q_{int} represents the internal heat gains, Q_{enclo} is the heat transfer through the walls and fenestrations, Q_{inf} is the heat gains through the infiltration air, and Q_{ex} is the heat offset by air conditioners.

Based on the thermodynamics model of the air-conditioned room, the indoor air temperature can be estimated using Eq. (3) to describe the effects of internal and external factors, where t_R is the room air temperature, °C; t_∞ is the characteristic temperature under steady state when the time reaches to infinity, °C; t_{in} is the initial temperature of the considered room, °C; B is the time constant of the room, which reflects the changing speeds of room air temperature; τ represents the time, s:

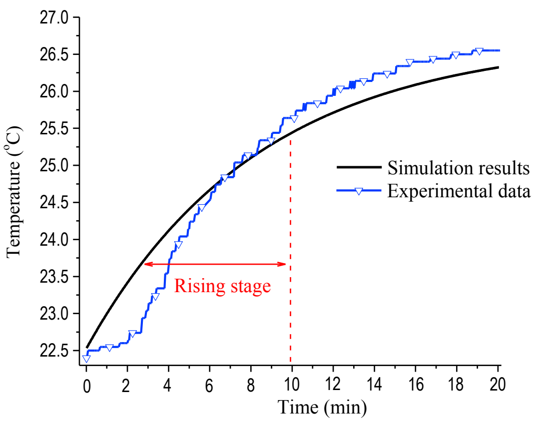
$$t_R = t_\infty - (t_\infty - t_{in})e^{-B\tau} \tag{3}$$

4.2. Distributions of temperature files under optimal intermittent mode

Base on the boundary conditions, the transient CFD simulation runs about 20 min to simulate the operation and suspension process of air conditioner. The changing patterns of mean temperature profiles under on/off modes of the are presented in Fig. 3.



a. Temperature files under on mode



b. Temperature files under off mode

Fig. 3. The dynamic changing pattern of temperature files under off mode

As shown in Fig.3.*a*, it can be observed that the cooling process is typically divided into three phases. The initial temperature is 27.2°C, and then the room temperature is decreasing due to the cold air supplied via the air conditioner. In the first phase, the cold air primarily cools the room air down, and thus the room air temperature drops rapidly in the first 8 min. During the second stage, the cold air mainly offset the heat power generated by the occupants and electric equipment to reduce the surface temperature of those facilities, and thus the room air temperature goes down gradually from 8 min to 16 min. Because the equality between the cooling power and the cooling loads of the room, the room air temperature keeps constant as 22.5°C in the final stage, which involves the last 4 min. Furthermore, the comparison between the simulation results and experimental data is conducted. From the figure, the simulations are generally in consistent with the experimental data with the maximum temperature deviation is 0.2°C. Based on the simulation results and measurements, the dynamic pattern of temperature under operation mode can be described by exponential function through the curve regression method, as expressed by Eq. (4):

$$t_R = 22.5 + 4.78e^{-0.00255\tau} \tag{4}$$

Fig.3.*b* presents the dynamic characters of room air temperature between simulation and measurement when the air conditioner is turned off. Base on the figure, the off-mode process can be divided into two stages i.e., rising stage with 10 min and stable stage with 10 min. During the first 3 min (within rising stage), the indoor air temperature climbs up rapidly from 22.5°C to 26°C. Within the stable stage, the room temperature fluctuates around 26.5°C afterwards. The changing laws of temperature under off-mode can be described as Eq. (5):

$$t_R = 26.7 - 4.2e^{-0.002\tau} \tag{5}$$

4.3. Performance of the optimal intermittent operation mode

The determination of the on and off mode of the air conditioner is based on the occupants' requirement on thermal comfort, which can be justified in terms of the temperature level in occupied zone. In general, the return temperature level is utilized to regulate the control of air conditioning systems. However, the temperature differences exist between the return air temperature and the occupied zone due to the temperature profiles vary spatially. In our study, the temperature in occupied zone is used to determine the operation of the air conditioning system. Concerning seating occupancy, the heal level is selected as the determination criterion of intermittent operation. The plane of Y=1.1m is a typical one corresponding to the heal level of seating occupants, and thus mean temperature of this plane can realistically reflect the thermal sensations of occupants. Based on the thermal standards, the comfortable temperature ranges from 23.5°C to 25°C. The dynamic temperature curves under intermittent mode are demonstrated in Fig. 5.

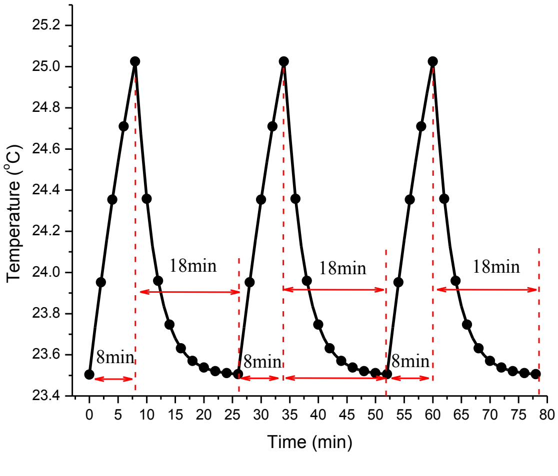


Fig. 4 The changing pattern of temperature under optimal intermittent operation mode

The optimization time periods for intermittent mode are 18 min and 8 min respectively, which means the air conditioner runs for 18min and then switches off for 8 min. While the traditional intermittent mode is 35 min switching-on and 10 min switching-off. The electric power consumed under two intermittent operation modes is calculated by Eq. (6). Comparing with the traditional operation mode, the optimized intermittent operation mode can achieve the reduction of 11.1% cooling power consumption.

$$\text{Traditional intermittent operation mode: } P_t = \frac{35\times1200}{45} = 934W$$
$$\text{Optimal intermittent operation mode: } P_o = \frac{18\times1200}{18+8} = 830W \quad (6)$$
$$\text{Energy saving percentage: } r = \frac{|830-934|}{934} = 11.1\%$$

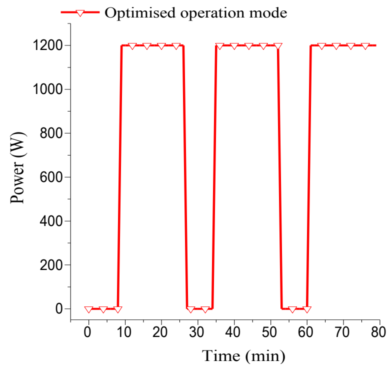


Fig. 5 The energy consumptions of optimal intermittent operation cycle

5. Conclusions

This study conducts the transient CFD simulations considering the dynamic boundary conditions of supply air temperature to detect the changing laws of the indoor air temperature when the air conditioner is running and suspending. The simulation results are validated by the experimental data using wireless sensor, in which good agreements with the measured data are observed. According to the dynamic characteristics of temperature profiles, both the reliable fitting model and the optimized intermittent operation mode are proposed. The optimal operation mode produces 18 min switching-on and 8 min switching-off of air conditioner system to maintain the air temperature in occupied zone ranging from 23.5°C to 25°C in terms of the thermal comfort standards. Moreover, the energy performance of such optimal intermittent mode presents superior to the traditional operation mode with an extra saving of 11% cooling power consumption.

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