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Study on the effects of air conditioners under intermittent operation conditions on residential demand response

Weilin Li[a,]*, Liu Yang[b]

[a]*Zhengzhou University, No. 100 Science Avenue, Zhengzhou and 450001*
[b]*The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

Abstract

This paper studies the applicability of the intermittent operation of air-conditioners in residential building demand response (DR). Firstly, the thermal inertial model of the building is established based on the dynamic heat transfer theory and verified by the experimental platform; then, based on the validated thermal inertial model of the building, the power demand change of intermittent operation of a residential air conditioner is simulated; because intermittent operation of an air-conditioner cannot achieve a smooth reduction of power demand, this article studies a group of residential building further and evaluates the DR effect of multiple air-conditioners interacting with each other. The study found that by use of the thermal inertia of the building, intermittent operation of air conditioners can maintain the indoor temperature within a certain range while achieving temporary reduction in electricity demand; through the cooperation between multiple air conditioners, the long-term stable reduction can be achieved under the premise of guaranteeing the temperature of the air-conditioned rooms.

Keywords: Demand response (DR); air-conditioner; intermittent operation; residential building;

Nomenclature

A	area, m^2
$A_{fur,cal}$	calculated area of furniture, m^2

* Weilin Li. Tel.: +86-183-3631-3933.
E-mail address: weilinli@zzu.edu.cn

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$A_{fur,eff}$	effective area of furniture, m^2
$C_{fur,cal}$	calculated heat capacity of furniture, kW/K
c	specific heat, kJ/kg·K
L	size dimension, m
m	mass, m
Q	heat quantity, kW
T	temperature, K
T_{ave}	average temperature of indoor partition surfaces, K
$T_{out-solar}$	comprehensive temperature, K
t	time, s
V	volume,m3
α	heat transfer coefficient, kW/m^2·K
γ	ratio of absorbed heat to the whole solar radiation
θ	ratio of effective area to calculated area
κ	ratio of absorbed heat to the whole heat source radiation
λ	heat conductivity coefficient, kW/m·K
ρ	density, kg/m^3
σ	thickness, m
Subscripts	
AC	air conditioning
a	indoor air
conv	convention
env	envelop
fur	furniture
i	inside surface
IN	indoor heat source
o	outside surface
par	partition
rad	radiation

1. Introduction

With the steady growth of the national economy, the supply and demand of electricity in China is also increasing (Fig. 1) [1]. However, the utilization of power generation equipment is declining (Fig. 2) [2]. This shows that more and more power generation equipment is built to meet the needs of peak hours, and is idle in peacetime. And although the power generation equipment continues to be increased, the power shortage caused by high temperatures in the summer has always existed. As in the past 2017, affected by the continuous high temperature in the summer, power shortages have occurred in North China [3]. Obviously, expanding the supply side blindly will not only solve the contradiction between power supply and demand, but also cause more problems. Demand Response (DR) starts from the demand side and changes the user's power demand through regulation and control. In recent years, DR has attracted the attention of China and related policy support has been issued [4][5].

As one of the important users of DR, residences participated in pilot experiments in Shanghai, Beijing, and Suzhou [6]. The main energy-using equipment for residential buildings includes air conditioners, lighting, washing machines and water heaters [7]. This study focuses on the regulation of air-conditioning, because on the one hand the air-conditioning power consumption accounted for a large part in residential buildings power consumption, and air-conditioning power consumption speak caused by the high temperature in the summer is an important reason for the city's power shortage [8].

Research [9] pointed out that building thermal inertia has the effect of stabilizing room temperature. Therefore, a residential building can achieve intermittent operation of air conditioning by utilizing the thermal inertia of the building, and temporarily reduce the power demand without affecting the thermal comfort of the building. This article will study the changes in the power demand of individual air conditioners for intermittent operation, and evaluate the effect of the DR of multiple air conditioning intermittent operations.

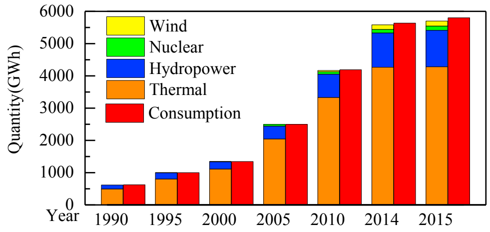


Fig. 1. Changes in China's electricity production and consumption

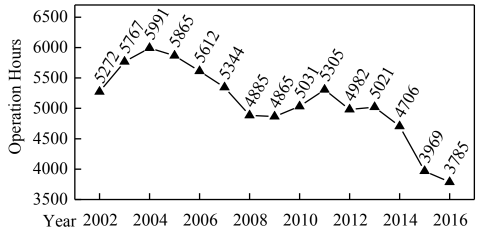


Fig. 2. Average utilization hours of national power generation equipment

2. Establishment and Validation of Buildings Thermal Inertial Models

2.1. The Build of Building Thermal Inertia Model

Controlling air-conditioning in the DR will cause changes in the amount of cooling to the room, and changes in the outdoor parameters will also cause changes in the heat transfer of the building envelope to the room (Fig. 3). The dynamic heat balance of indoor air is shown in Eq.(1).

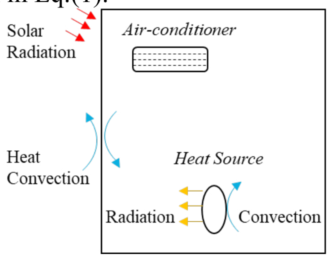


Fig. 3. Indoor air dynamic heat balance diagram

$$\rho_a V_a c_a \frac{\partial T_a(t)}{\partial t} = \sum_{env} Q_{env}(t) + \sum_{par} Q_{par}(t) + \sum_{fur} Q_{fur}(t) + \sum Q_{IN,conv}(t) + \sum Q_{AC}(t) \quad (1)$$

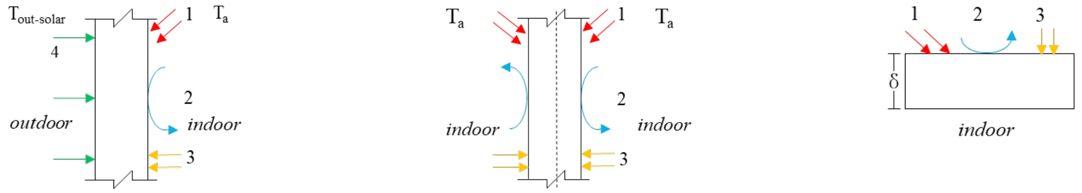
The dynamic heat transfer process and the equations of the thermal inertia model for the building envelope, internal structure, and furniture are shown in Table 1.

2.2. Experimental Validation of Building Thermal Inertia Model

The experimental platform for this study is shown in Fig. 4. Room 2 is the test room for this study. The envelope consists of colour steel plate and fireproof rock wool material. The net height of the room is 3.24m, the net length is 4.61m in the north-south direction, and the net length is 3.23 m in the east-west direction. In the experiment, a number of sofas, tables, chairs and other furniture were added to the room 2, and the building model was verified. The results are shown in Fig. 5. The maximum deviation of the predicted temperature was 0.48 °C, and the root mean square error (RMSE) was 0.35 °C. The results showed that the established building thermal inertia model has certain accuracy and can be used to predict the change of indoor air temperature when the internal and external disturbance changes (e.g. the DR period).

Table 1. Building Thermal Inertia Model

envelope	internal structure	furniture[10]



1- solar incident radiation 2- heat convection 3- indoor heat source radiation 4- total outdoor heat transfer

(a) envelope (b) internal structure (c) equivalent furnish

$Q_{env}=\sum\alpha_{env,i}\left(T_{env,i}-T_a\right)A_{env}$ (2)	$Q_{par}=\sum\alpha_{par}\left(T_{par,\frac{\sigma_{par}}{2}}-T_a\right)A_{par}$ (5)	$\gamma_{fur}Q_{solar,i}+\alpha_{fur,rad}\left(T_{fur}-T_{ave,i}\right)A_{fur,eff}+\kappa_{fur}Q_{IN,rad}=\alpha_{fur}\left(T_{fur}-T_{in}\right)A_{fur,eff}+C_{fur,cal}\frac{dT_{fur}}{dt}$ (8)
$-\lambda_{env,o}\left(\frac{\partial T_{env}}{\partial x_{env}}\right)_{x_{env}=0}=\alpha_{env}\left(T_{out-solar}-T_{env,o}\right)$ (3)	$-\lambda_{par,0}\left(\frac{\partial T_{par}}{\partial x_{par}}\right)_{x_{par}=0}=0$ (6)	$C_{fur,cal}=c_{fur}\times m_{fur}$ (9)
$-\lambda_{env,i}\left(\frac{\partial T_{env}}{\partial x_{env}}\right)_{x_{env}=\sigma_{env}}+\gamma_{env}Q_{solar,i}/A_{env}+\alpha_{env,rad,i}\left(T_{env,i}-T_{ave,i}\right)+\kappa_{env}Q_{IN,rad}/A_{env}=\alpha_{env,i}\left(T_{env,i}-T_a\right)$ (4)	$-\lambda_{par}\left(\frac{\partial T_{par}}{\partial x_{par}}\right)_{x_{par}=\frac{\sigma_{par}}{2}}+\gamma_{par}Q_{solar,i}/A_{par}+\alpha_{par,rad,i}\left(T_{par,\frac{\sigma_{par}}{2}}-T_{ave,i}\right)+\kappa_{par}Q_{IN,rad}/A_{par}=\alpha_{par}\left(T_{par,\frac{\sigma_{par}}{2}}-T_a\right)$ (7)	$A_{fur,eff}=A_{fur,cal}\times\theta$ (10)
		$A_{fur,cal}=\frac{m_{fur}}{\rho_{fur}\cdot L_{fur}}$ (11)

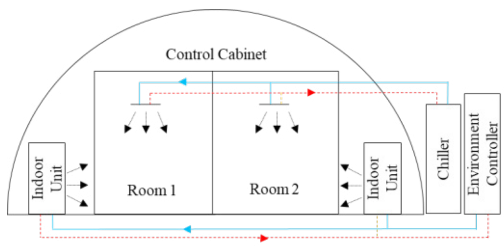


Fig.4. Platform

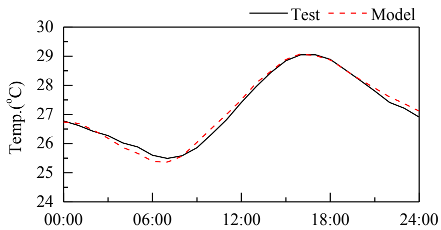


Fig.5. Experimental validation results

3. Analysis of DR Effect of Air Conditioning Intermittent Operation

3.1. Setting of model

Based on the thermal inertial model of the building, a simulation analysis of the DR of a residential living room air conditioner) was conducted (Fig. 6, Table 2). It is assumed that the air conditioner in the living room was running all the time, and a DR event occurred during 13:00–15:00. Room temperature is set at 25°C in normal time, and 28°C is the upper limit.

3.2. Simulation results

The room temperature simulation results (Fig. 7 (a)) showed that due to the thermal inertia of the building, when the air conditioning was switched off after 35 minutes, the room temperature became to 28.12°C which exceeded the upper limit and the air conditioning was turned on again. After air conditioner is shut down again at 14:30, the indoor temperature exceeds the upper limit set at 15:00 for the second time, reaching 28.01°C.

The air conditioning energy consumption simulation results (Fig. 7(b)) show that the air conditioner power drops to zero during the shutdown. However, because the air conditioner needs to be restarted when the room temperature exceeds the comfort upper limit, the building electricity consumption reduction is intermittent.

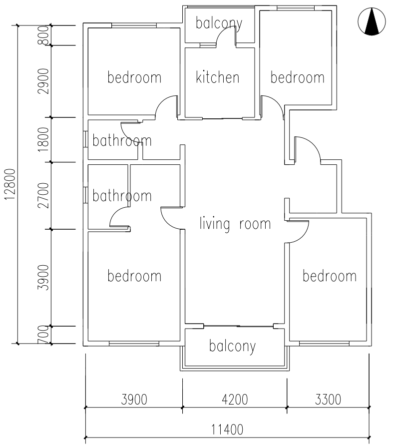
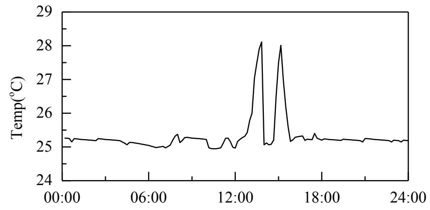
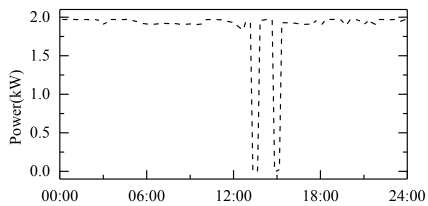


Fig.6. A house plan (layout A)



(a) room temperature



(b) air conditioner power

Fig.7. DR effect of intermittent operation of a single air conditioner

Table 2. Basic parameters of a residential living room-layout A/B

object	structure :material, thickness-mm，area m^2	furnish: material mass kg	Air-conditioner	Interior heat source
Living room	Exterior wall: cement mortar-20+ extruded polystyrene board-80+ aerated concrete block-200+ cement mortar-20 A:10 m^2 /B:7 m^2 Outer window: aluminum alloy low-emissivity insulating glass window-5+air-12+ low-emissivity insulating glass window -5 A: 4 m^2 /B:4 m^2 Interior wall: cement mortar-20+ aerated concrete block-200+ thermal insulation mortar-20 A: 65 m^2 /B:46 m^2 Floor: cement mortar-20.0+reinforced concrete-180+cement mortar-20 A: 38 m^2 /B:29 m^2	Sofa : wood A:250kg /B:180kg TV cabinet :wood A: 60kg /B:40kg Cabinets :plywood A: 40kg /B:30kg Tables and chairs :Rubber wood A: 80kg /B:60kg	Cooling capacity: 6500w/5000w EER: 3.3/3.3 Rated power:1970W/1515W	persons 2/1 TV 1/1 Refrigerator 1/1 Led light 6/3

4. DR effect of multi-residential cooperation

In the actual DR, the amount of reductions done by the user needs to maintain a certain degree of stability. A residential building is now used as an object to analyze the DR effect of multiple residential buildings

The residential building has 20 floors, with 4 houses per floor, divided into two types, A and B (Fig. 8, Table 2).

In order not to affect the thermal comfort of the room, a single air conditioner will be closed for 30 minutes in a single session. During the demand response period, the air conditioning with 4 (or multiples of 4) similar power is used as a group for wheel stop, and continuous reduction between 13:00–15:00 can be realized. At the same time, it is not necessary to repeat start-stop air-conditioning for individual houses. The condition in which all the residences of the building participate in the demand response is simulated. The effect of the demand response that can be achieved through the coordinated rotation between different residences is shown in Fig.9.

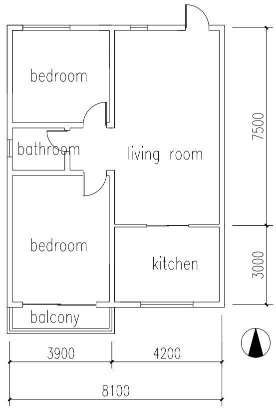


Fig. 8.The layout B plan

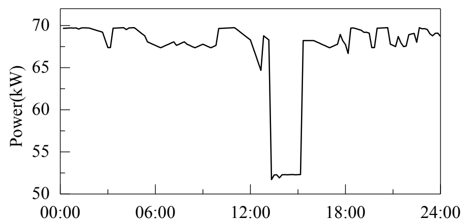


Fig. 9. Residential building

5. Conclusion

In this study, a dynamic model group describing the thermal inertia of buildings was established. The accuracy of the entire model was verified by building a test platform. The verification results show that the model can relatively accurately simulate the dynamic change of indoor temperature, and it can be used as the basis for analysis of DR of residential buildings.

Based on this model, the DR effect of one house air conditioning start-stop control was analyzed. The results show that by using the thermal inertia of the building, it can be ensured that the room temperature does not exceed the set upper limit within a short time after the air conditioner is turned off. And through the cooperation between multiple intermittent operations of air conditioners, it is possible to achieve stable reduction for a relative long period of time while ensuring the temperature of a single air-conditioned room.

Acknowledgements

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References

[1] National bureau of statistics of the people’s republic of china. Chinese statistic yearbook 2017. Beijing: China Statistic Press, 2017.10
[2] National Energy Administration. Average utilization hours of power generation equipment for power plants of 6000 kilowatts and above in China. 2017.01.26
[3] State Grid. 12 provincial grids have a new high electricity load. 2017.07.14
[4] Ministry of Finance of the People’s Republic of China, National Development and Reform Commission. Interim Measures for the Management of Central Financial Award Funds for City Comprehensive Pilot Work in Electricity Demand Side Management. 2012.07
[5] National Development and Reform Commission, Ministry of Finance of the People’s Republic of China. Notice of improving the power emergency response mechanism and doing well in power demand side management of the city's comprehensive pilot work . 2015.04
[6] Li W, Xu P, Lu X, et al. Electricity demand response in China: Status, feasible market schemes and pilots. Energy, 2016, 114:981-994
[7] Tang Y, Deng KY, Sun HD. Research on coordination Scheme for Smart Household Appliances Participating Underfrequency Load Shedding. Power System Technology, 2013(10):2861-2867.

[8] Hu M, Xiao F. Price-responsive model-based optimal demand response control of inverter air conditioners using genetic algorithm. Applied Energy, 2018:151–164
[9] Braun J, Montgomery K, NitinChaturvedi. Evaluating the Performance of Building Thermal Mass Control Strategies. Hvac & R Research, 2001, 7(4):403-428.
[10] Li W, Xu P, Wang H, et al. A new method for calculating the thermal effects of irregular internal mass in buildings under demand response. Energy & Buildings, 2016, 130:761-77.