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# The Equivalent Thermal Parameter Model and Simulation of Air Conditioner System in Demand Response Programs

Ligai Kang, Liangxu Liu, Qingsong An*, Junhong Yang, Jun Zhao, Hongjie Jia, Dan Wang

*Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, School of Mechanical Engineering, Tianjin University, Tianjin 300072*

**Abstract**

Estimating end-use energy consumption that accurately reflects the variance of the end-load is critical for the grid wise simulation and analysis work. In a house, the largest load with a thermal cycle is often the heating ventilation and air conditioning (HVAC) system. So the thermal dynamics of typical residential electric air conditioner is discussed, and then an equivalent thermal parameters (ETP) model is built by the thermal equilibrium in this paper. Based on this, the switch status, indoor air temperature and power consumption are simulated through control strategies of constant thermostat set point. The results show according the switch status, indoor air temperature can be calculated by the ETP model, thus give the desire status to the grid according the setting temperature. In summer, with the increasing of setting temperature, the frequency of on-off becomes lower, thus the power consumption also reduces from 1200 kW(26℃) to 970 kW(27℃). So if some control strategies are used, the model will play an important part on decreasing the peak-average rate of the power grid and also improving the load rate of grid.



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*Keywords:* residential air conditioner; equivalent thermal parameter; temperature simulation; power simulation; switch status

## 1. Introduction

Currently, the energy and environmental problems have become increasingly prominent, greenhouse effect become aggravating and global warming. After the worldwide energy crisis in 1970s, electric load control system was introduced from Europe to the United States to control intermittent load. In 1980s, the U.S. Electric Power Research Institute proposed demand side management (DSM)[1], that is combination of demand response and smart grid technologies, using the smart meters, communications and control systems and other load control technology to realize the interaction between user and smart grid. So the end-load (air conditioners, water heaters, heat storage systems, etc.) can be grouped in batches, controlled in turns to make the load management not affect the basic living and production[2]. However, in China, for the end load equipment, the air conditioner has been widely used in residential buildings. In addition it is used intensively, the heavy running will make the grid wise unstable especially at the peak load of electric,. Therefore, carrying out DSM is imperative and estimating end-use energy consumption that accurately reflects the variance of the end-load is critical for the grid wise simulation and analysis work.

To realize the dynamic interaction of the air conditioner and grid, Ning Lu proposed a simplified equivalent thermal parameters model of a residential HVAC unit to discuss the effect of a state queuing model[3,4], in which, there was no heat transfer from the internal surface and mass surface to the air. K.P.Schneider *et al.* studied the impact of time-variant multi-state models on a single family residence and 8500-node test system using ZIP models and physical models [5,6]. To analyze the benefits of demand

* Corresponding author. Tel.: +86 22 2740 7617; fax: +0-000-000-0000 .
*E-mail address:* anqingsong@tju.edu.cn (Qingsong An).


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response programs for the individual homeowner as well as a population of homes, S.Katipamula and N. Lu described the methodology used to develop the simulation model and the application to study the economic benefits and impacts on electric distribution feeder load shapes when applying different control strategies to HVAC systems [7]. Xinyi Peng *et al.* propose an approach that cooling load can be adjusted remotely through measuring indoor air temperature [8]. Based on above, according to standards and codes of HVAC and heat transfer calculation, this paper proposes a physical model. Through invoking meteorological parameters and switch states of air conditioner, the model can calculate the indoor air temperature, thus feedback to the grid at each time step to ensure smooth operation of the grid.

The paper is organized as follows: the simplified ETP model is presented in Section 2. The simulation of the model is discussed in Section 3. The conclusions and future work are summarized in Section 4.

## 2. ETP model of Household Appliance

There are three assumptions as follows: 1) The air temperature in the house is considered as the same. 2) The mass temperature is also considered to be the same. 3) The HVAC system is only in cooling mode.

According to the first law of thermodynamics, a physical model of the HVAC system is constructed using an equivalent thermal parameter (ETP) model. Fig.1 is a diagram showing the heat flow of a single residence. There are three sources of heat: solar radiation through glasses, internal gains from waste heat and the capacity of HVAC system, which constitute the total heat Q in the house. So Q is made up by convective heat and radiant heat. The convective heat forms the load immediately, while the radiant heat forms the load suffering from attenuation at a later time that means the heat firstly transfers to the interior surface, i.e., walls and furniture, when its temperature is higher than the indoor air, then transfers to the air. Therefore, heat Q is divided between the air and the mass in the house. Also, the indoorair temperature of the house is thermally coupled to the internal mass temperature, and is then thermally coupled to the outside air temperature through the thermal envelope.

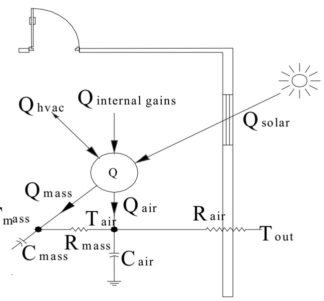


Fig. 1 The heat flow in a typical residence

For the thermal circuit, if heat transfer properties are represented by equivalent electrical components with associated parameters, according to the first law of thermodynamics a heat balance for the indoor air and mass temperature node can be written as:

$$m\%Q - \frac{T_{air} - T_{out}}{R_{eq}} - \frac{T_{air} - T_{mass}}{R_{mass}} = C_{air}\frac{dT_{air}}{dt}$$

$$(1 - m\%)Q - \frac{T_{mass} - T_{air}}{R_{mass}} = C_{mass}\frac{dT_{mass}}{dt}$$

Then the electric circuit control equation could be written as

$$\hat{T} = AT + BU \qquad y = CT + DU$$

$$\hat{T}=\begin{bmatrix}\hat{T}_{air}\\ \hat{T}_{mass}\end{bmatrix}\quad T=\begin{bmatrix}T_{air}\\ T_{mass}\end{bmatrix}\quad U=\begin{bmatrix}T_{out}\\ Q\end{bmatrix}\quad C=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\quad D=\begin{bmatrix}0\\ 0\end{bmatrix}$$

$$A=\begin{bmatrix}-(\frac{1}{R_{eq}C_{air}}+\frac{1}{R_{mass}C_{air}}) & \frac{1}{R_{mass}C_{air}}\\ \frac{1}{R_{mass}C_{mass}} & -\frac{1}{R_{mass}C_{mass}}\end{bmatrix}\quad B=\begin{bmatrix}\frac{1}{R_{air}C_{air}} & \frac{m\%}{C_{air}}\\ 0 & \frac{1-m\%}{C_{mass}}\end{bmatrix}$$

$C_{air}, C_{mass}$ — indoor air heat capacity, mass heat capacity, kJ/K; $A_{total}$ —the total area of envelope, m$^2$;

$T_{out}, T_{air}, T_{mass}$ —outdoor air temperature, indoor air temperature, mass temperature,℃;

$Q_{air}, Q_{mass}, Q_{internal\ gains}, Q_{solar}$ —heat to indoor air, heat to mass, internal heat gains, solar radiation,W;

$h_1 / h_2$ —the convection heat transfer coefficient of the inner surface/outer surface, W/(m$^2$ K).

$m\%$ — heat rate to air, $m\% = 50\%$; $R_{eq}$ —the total thermal resistance of envelope, K/W;

While the HVAC system is on, the cooling capacity $Q_{hvac}$ is injected, otherwise, $Q_{hvac}$=0. Therefore, through the grid give some control signal at each time step to the simulation model to control the air conditioner on or off, it will make great effect on load shifting and stable operation of the grid.

## 3. Simulation and Discussion

To verify the model, a room located on the top floor is selected in a building in Guangzhou. The length of the room is 12m, width is 7.2m, height is 3.9m. It only has one side of exterior wall in which there are three windows(1.8m×2.1m). The total thermal resistance of external wall, external glasses, roof are set to 53.5 K/W, 1223.4 K/W, 130 K/W, respectively, while $h_1$, $h_2$ are confirmed to 8.7 W/(m$^2$ K), 18.6 W/(m$^2$ K), respectively.

Based on the ambient parameters and characteristics of the building room, an air conditioner with cooling capacity 7kW is chosen. Fig 2 shows the diurnal variation of outdoor temperature (Fig. 2-A), the solar radiation (Fig. 2-B) and indoor air temperature (Fig. 2-C) when the air conditioner is set off or on all the simulating time. Because of the load characteristics in hot summer and warm winter zone and bad thermal insulation of chosen structure, there is little heat dissipating to out, the indoor temperature is even higher than the outside temperature when the air conditioner is off. On the contrary, when air conditioner is always on, the indoor temperature shows same trend but lower than the required temperature, power consumption is also very large.

To avoid the undesired comfort and huge power consumption above, control strategy of constant thermostat set point is adopted. The setting temperature is 26℃, dead band is set to 4℃; 26℃, 2℃ and 27℃, 4℃ make up the comparison groups. The control signals of switch status must last for 3 minutes at least to protect compressor. Through simulating, the indoor temperature and power are shown in Fig.2(D~F). From them, we can see that the indoor temperature is well controlled to ensure the comfort. The power is also shapely decreased while controlling the state on-off. With the increasing of setting temperature, the opening time of air conditioner is greatly reduced, even in the early morning, the air conditioner can stop for a longer time, the frequency of on-off becomes lower, thus the power consumption also reduces from 1200kW to 970kW, reduced rate is about 19.17%. On the other hand, with the decreasing of dead band, the opening time of air conditioner is shorter in each switch status, but the air conditioner starts and stops more frequently, the powers is also changed, increase rate is about 3.33%.

## 4. Conclusions

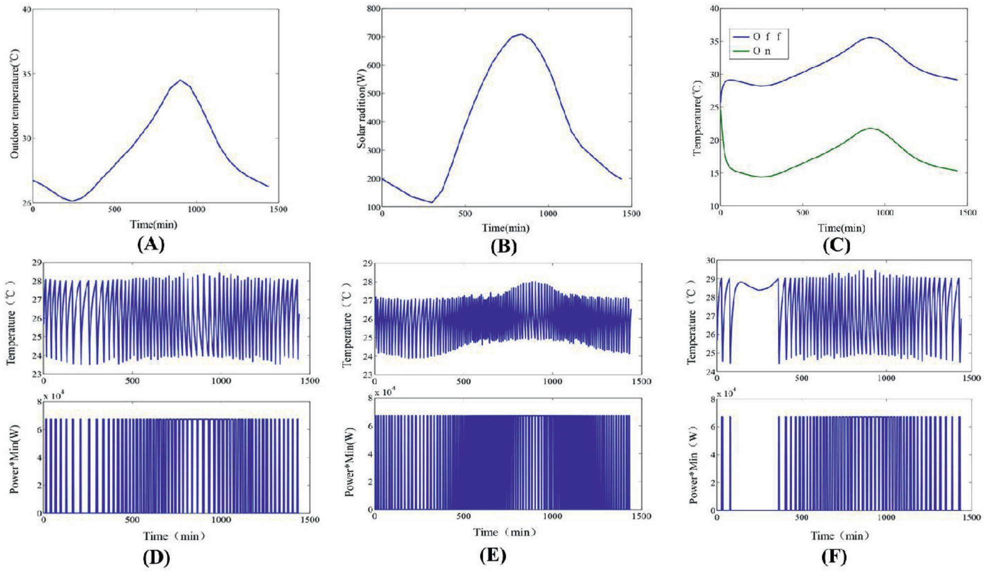


Fig. 2 Diural variation of temperature, solar radiation and power

In this paper, according to the first law of thermodynamics, an ETP model that about HVAC system is built to require the indoor air temperature and switch status which will then give grid. Simultaneously a demonstration project is used as a simulation experiment object to verify its effectiveness. The results show that the indoor temperature could be well controlled by the signals on-off and give the accurate feedback to the grid, thus the control strategies of the operation, for example pre-cooling or closing some equipment compulsory can be used through the ETP model on demand response and comfort residence to decrease the peak-average rate of the power grid and improve the load rate of grid.

In fact, humidity is also one of key factors about comfort, our future work will focus on study the enthalpy equation or other equations including the relative humidity thus well reacts the comfort level.

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