Proceedings of the 3rd International Conference on Green Energy, Environment and Sustainable Development (GEESD2022), X. Zhang et al. (Eds.)
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doi:10.3233/ATDE220378

Study on Energy Consumption Characteristics of Air Conditioning in an Existing Residential Building

Bin SUN[a,b,1], Jianing PAN[a,b], Pingshan WANG[a], Yan YAN[b], Wen LIU[b] and Jinjun LI[a]
[a] *East China Architectural Design & Research Institute (Co., Ltd.), Shanghai, China*
[b] *Institute of Shanghai Architectural Design & Research (Co., Ltd.), Shanghai, China*

Abstract. The enclosure, lighting and equipment of existing residential buildings have been determined. Therefore, the occupancy behavior has a great influence on the energy consumption of air conditioning in the existing residential buildings. In this paper, a residential building was selected as the research object, and the long-term energy consumption of the building was sorted out. Then through energy calculation and correction with the actual building energy consumption data, the air conditioning energy consumption characteristics which are related to personnel timetable, air conditioning control mode, room setting temperature and room temperature range are obtained. The characteristics have a good matching degree with the actual energy consumption, which can basically reflect the habit of using air conditioning for the occupants. The characteristics can help occupants to know the energy-saving potential and promote behavioral energy-saving.

Keywords. Existing residential building, occupancy behavior, energy consumption characteristics of air conditioning

1. Introduction

At present, the research on residential building energy efficiency focuses on the impact of thermal insulation [1, 2], energy consumption [3-5], indoor comfort [6], energy consumption prediction [7, 8] and ultra-low energy consumption technology [9, 10], which are mostly based on energy simulation or statistics of multi-unit energy consumption. Due to the uncertainty of human behavior, there is often a large deviation between the simulation results and the actual energy consumption. Many researchers have noticed this and studied the human behavior patterns and their impact on energy consumption [11-13]. These studies are mostly analysis of crowd behavior, and mainly used for planning and design.

This paper focus on the energy consumption characteristics of air conditioning in an existing residential building. The energy consumption characteristics of air conditioning represent the occupant's habit of using the air conditioning, such as the room temperature setting and the allowable room temperature range. Through the energy simulation of air conditioning load combined with human behavior, the characteristics of air conditioning

[1] Corresponding Author, Bin SUN, East China Architectural Design & Research Institute (Co., Ltd.); Institute of Shanghai Architectural Design & Research (Co., Ltd.), Shanghai, China; Email: sunbin@isaarchitecture.com.

energy consumption could be found, and then the characteristics are corrected by the actual data to reflect differences between actual and simulated result.

2. Methods

The research consists of three steps, which are described in detail below.

The first step, a high-rise residential building was selected as the research object, and its building plane, equipment, lighting, energy consumption data are sorted out.

The second step, for existing building, the energy consumption characteristics of air conditioning mainly depend on occupancy behavior. Occupancy behaviors are affected by multiple factors, such as the time of people in room, the control mode of air conditioning, the number of air conditioning, the room setting temperature and room temperature rang. This chapter analyses the influence of control mode and timetable to air conditioning energy consumption.

Finally, different room setting temperatures and room temperatures ranges are analyzed. The temperature in the room does not remain at the setting temperature, but fluctuates within a temperature range, which will affect energy consumption. Through analysis on the relationship between air conditioning load and temperature setting and ranges, the energy consumption characteristics of air conditioning can be obtained. After comparing with the actual energy consumption, the air conditioning characteristics can be corrected to make it consistent with the actual situation.

2.1. Building Selected

The high-rise residential building is located in Hongkou District, Shanghai, which was completed around 1990. There is no energy-saving requirement in the design. The building has two bedrooms and one living room, and the building area is about 40.2 m^2. The area of each functional room is shown in Figure 1.

Figure 1. Architecture & architectural plan.

Table 1 shows the main energy-consuming equipment of the building. The equipment data are obtained from the equipment nameplate, and the lighting power is confirmed by lamps, which is easy to obtain.

Table 1. List of main energy-consuming equipment in the building.

Room	Air conditioning equipment	Lighting equipment	Major energy-consuming equipment
Master bedroom	Fixed frequency split unit, cooling capacity 3.6 kW, heating capacity 4.3 kW, power consumption 1.1 kW	T8 fluorescent lamp 32 w	TV, 60 w Laptop, 80w
Second bedroom	Fixed frequency split unit, cooling capacity 3.6 kW, heating capacity 4.3 kW, power consumption 1.1 kW	T8 fluorescent lamp 32 w	integrated machine , 50 w
Living room	Fixed frequency split unit, cooling capacity 3.6 kW, heating capacity 4.3 kW, power consumption 1.1 kW	T8 fluorescent lamp 32 w	energy efficiency refrigerator 0.49 kWh/day
Bathroom	Exhaust fan, 23 w	Energy-saving lamp14 w	--
Kitchen	Hood, 350 w	LED, 22 w	Electric kettle, 1800 w

Figure 2 shows the schedule of the bedroom and living room. Through the typical work and rest time of the residents, the schedule of the bedroom and living room was obtained. The schedule is slightly different from the schedule given in the standard, which will better reflect the energy consumption characteristics of the occupants.

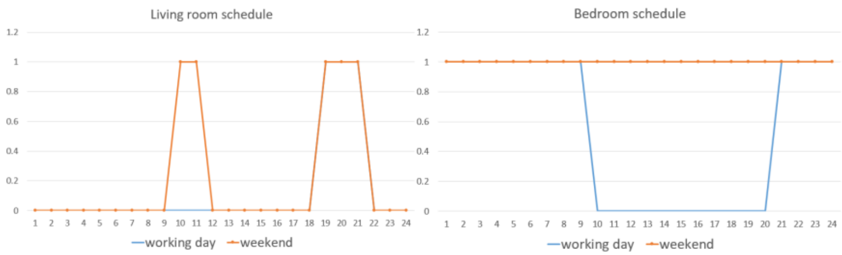

Figure 2. Schedule of personnel in bedroom and living room.

The energy consumption data of the residential buildings are obtained from the SGCC website and electricity bills. According to household's feedback, the building was in a relatively stable state of use before 2020. Due to the impact of COVID-19 epidemic, households work at home for a long time in 2020, and in 2021, households work at home from June to September. So, the energy consumption in 2020 and 2021 is different from before. The energy data from 2015 to 2017 and from 2020 to 2021 are selected for subsequent analysis. The typical energy consumption data of the buildings are shown in Table 2.

Table 2. Typical data of building energy consumption.

Year	Minimum monthly power consumption (kWh)	Maximum monthly power consumption (kWh)	Total annual electricity consumption(kWh)
2015	103	358	2089
2016	108	286	2081
2017	104	503	2297
2020	124	473	2995
2021	144	659	3881

The maximum monthly power consumption represents the highest value of building energy consumption in a single month, including heating, cooling, lighting and equipment energy consumption. Air conditioning is generally not needed in the transition season in hot summer and cold winter areas, so the minimum monthly power consumption can be considered as the sum of lighting and equipment energy consumption. Therefore, the monthly air conditioning energy consumption can be obtained as shown in Figure 3.

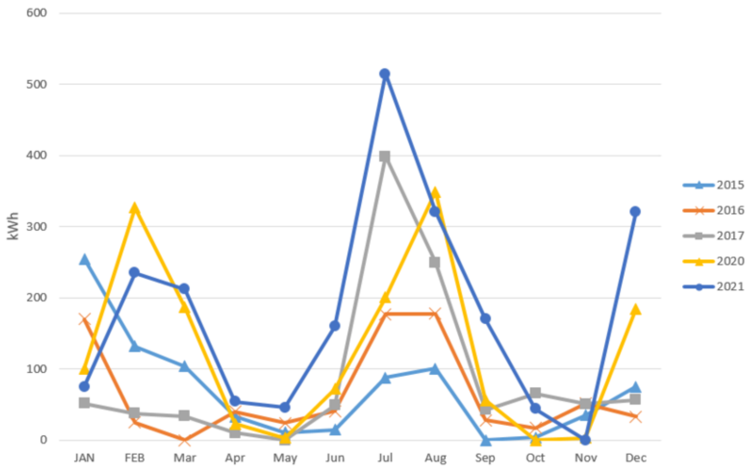

Figure 3. Monthly air conditioning power consumption.

Through the monthly data, the annual air conditioning energy consumption of the building is shown in Table 3.

Table 3. Annual air conditioning energy consumption of building.

Year	2015	2016	2017	2020	2021
Annual heating consumption (kWh)	601	280	232	803	843
Annual cooling consumption (kWh)	252	505	817	704	1310

2.2. Analysis of Control Mode

This chapter analyses the influence of control mode to air conditioning energy consumption, and some assumptions are made first. Although the load of each room is different, households will not supply cooling and heating simultaneously in residential buildings, so the load of the whole building was used. Generally, each room has an air conditioner. in this analysis, the average indoor temperature of the building was used to characterize the number that air conditioning opens.

There are mainly two ways to control the air conditioning in residential buildings: Mode 1, according to the outdoor air temperature to open air conditioning; Mode 2, according to the indoor comfort to start air conditioning. Mode 1 can ensure the maximum indoor comfort with high energy consumption. Mode 2 has relatively low energy consumption while also ensures the indoor comfort, but it is difficult to determine comfort.

The comfort involves the body temperature, wearing and other factors. This paper takes the natural room temperature as the judgment of comfort, and the graphic method was used [14]. Through the meteorological data of typical meteorological year (TMY),

Figure 4 shows the natural room temperature distribution of each room with the outdoor temperature.

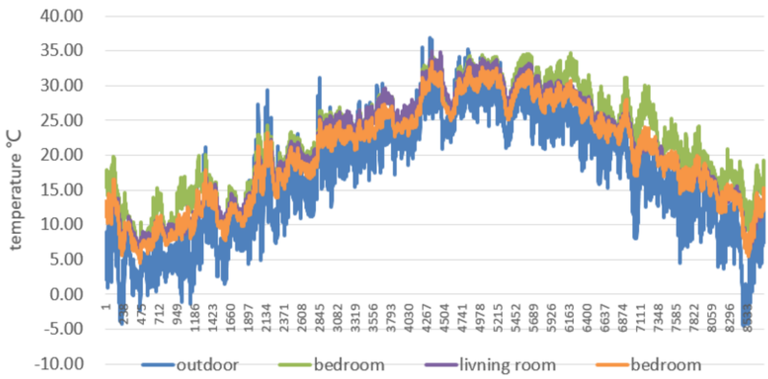

Figure 4. Outdoor temperature and natural room temperature.

When the natural room temperature exceeds the temperature range of comfort, the air conditioning will be open. Based on this, the paper analyses different control mode and timetable, which are shown in Table 4.

Table 4. Air conditioning control mode.

Mode 1	**Mode 2**	**Mode 3**	**Mode 4**
All year round & according to outdoor temperature	All year round & according to natural room temperature	Personnel schedule & according to the outdoor temperature	Personnel schedule & according to natural room temperature

DeST-h [15] was used as the simulation software in this analysis, and the energy-saving model plane was completely consistent with the actual building plane, which was shown in Figure 5.

The parameters in the energy consumption model are shown in Table 5.

Table 5. Simulation setting conditions.

Envelope parameters	Exterior wall: 200 mm reinforced concrete, without insulation, U-value: 3.0 w/m^2.k External window: aluminum frame with Low-E glass window, U-value: 3.20 w/m^2.k ; SC: 0.60 Air tightness: sliding windows, and so ACH: 23 m^3/m^2.h was used.
Lighting power density	Table 2
Equipment power density	Table 2
Schedule	The same as the actual use of the building

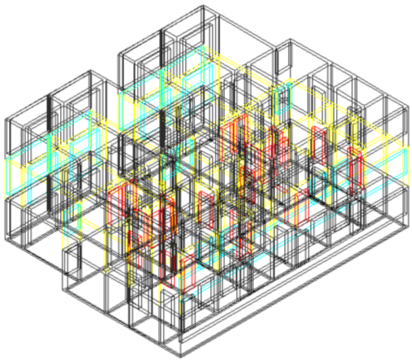

Figure 5. DeST-h Energy-saving model.

2.3. Analysis of Energy Consumption Characteristics

This chapter simulates and analyses the air conditioning hours and air conditioning load based on different room temperature ranges and room setting temperature to find the characteristics of air conditioning. Table 6 shows different conditions being calculated, and through fitting the results, the characteristics were obtained.

Table 6. Room temperature range and room setting temperature.

Settings	Temperature setting					
Minimum temperature in winter (°C)	18	17	16	15	14	13	12
Room setting temperature (°C)	18	17/18	16/17/18	15/16/17/18	14/15/16/17/18	13/14/15/16/17/18	12/13/14/15/16/17/18
Maximum temperature in summer (°C)	28	29	30	--	--	--	--
Room setting temperature (°C)	26/27/28	26/27/28/29	26/27/28/29/30	--	--	--	--

The relationship based on simulation result will be different from actual data, so when corrected by actual data, the characteristics of the occupant can be obtained, which reflect the inherent characteristics of buildings and the usage habits of residents.

3. Results and Analysis

3.1. Analysis of Air Conditioning Mode

Based on the analysis of indoor thermal comfort environment, the temperature range and natural room temperature distribution of the building meeting the requirements of class II thermal and humidity environment can be obtained.

Figure 6 shows that the natural room temperature is higher than the outdoor temperature in most time, and the natural room temperature is lower than the outdoor temperature in part of the transition season due to the thermal inertia of the room; Because of the building envelope, the natural room temperature fluctuates less and is more stable than the outdoor temperature, so different air conditioning operation modes will cause different air conditioning load and air conditioning hours.

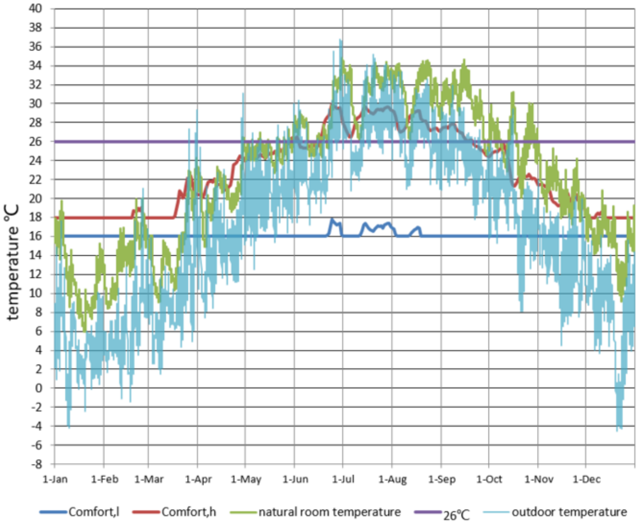

Figure 6. Temperature range and natural room temperature.

According to Figure 7, the reduction of cooling load based on timetable is more than based on the annual natural room temperature, the cooling hours are reduced by 55% and the heating hours are reduced by 35%. When the air conditioning open based on the schedule, the cooling time continues to decrease, but the cooling load will not decrease in the same proportion, indicating that the timetable is the main factor affecting the cooling load. Based on the timetable, the heating load will still be significantly reduced, indicating that the control according to the natural room temperature has a significant effect on reducing the heating load.

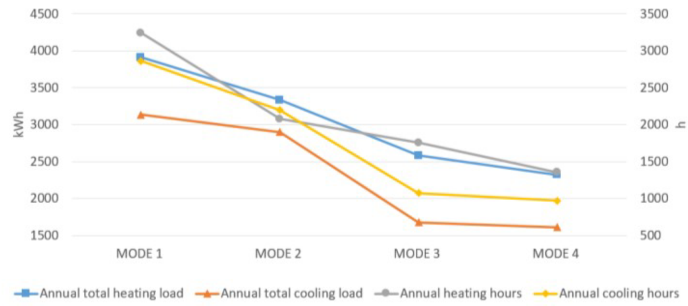

Figure 7. Comparison of air conditioning load and hours in different modes.

Since the energy consumption of air conditioning in hot summer and cold winter areas is mainly in summer, the air conditioning open according to outdoor temperature based on timetable was used as the basic characteristics of personnel behavior mode. The result of other mode can be adopted as the correction coefficient of cooling and heating load. The correlation coefficients are obtained from the calculated loads, as detailed in Table 7.

Table 7. Load Correction coefficients of different mode.

Air conditioning start conditions	Mode 1	Mode 2	Mode 3	Mode 4
Annual cooling load correction coefficient η_{cold}	1.87	1.73	1.00	0.96
Annual heat load correction coefficient η_{hot}	1.52	1.29	1.00	0.90

3.2. Analysis of Energy Consumption Characteristics of Air Conditioning

Figure 8 shows the relationship between air conditioning cooling load and hours in summer with the highest room temperature, which means when the room temperature exceeds the temperature, air conditioner will be open.

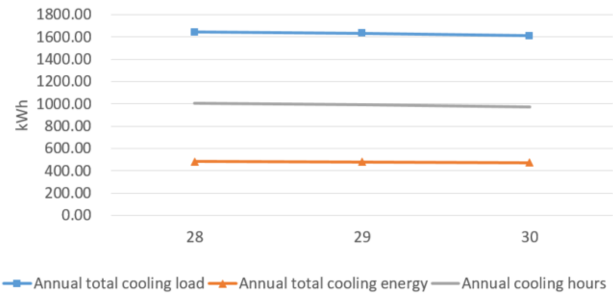

Figure 8. Relationship between cooling load and startup temperature.

According to Figure 8, when the indoor temperature is set as 26°C, the cooling load and cooling time are independent with the highest room temperature. Therefore, for cooling condition, the cooling load is only related to the room setting temperature.

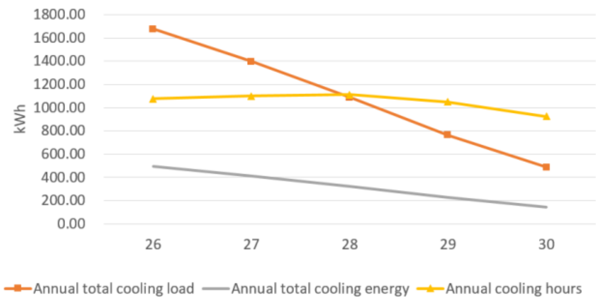

Figure 9. Relationship between indoor set temperature and cooling load.

When calculating the annual cooling load, it can be assumed that there is a linear relationship between the envelope load (including heat transfer and solar heat gain), the load of fresh air and the temperature difference between indoor and outdoor. Therefore, the relationship is fitted according to the data in Figure 9, and the annual cooling load calculation formula of the building was as equation (1).

$$Q = K\Delta T = KT_e - KT_i = 9620.3 - 304.8T_i = 304.8\times(31.6 - T_i)[kWh/year] \tag{1}$$

where, $K = 304.8$ is a constant related to the building and Occupancy behavior, $T_e = 31.6$ is the mean outdoor temperature used for calculation. Considering the influence of cooling load correction coefficient η_{cold} in Table 7, equation (1) can be revised as equation (2).

$$Q = \eta_{cold}\times 304.8\times(31.6 - T_i)[kWh/year] \tag{2}$$

where the coefficient η_{cold}=0.96~1.87 .

Table 3 shows the actual cooling power consumption of the residence, and the actual power consumption varies greatly year by year. In 2021, residents work at home in the whole summer, therefore, the load correction coefficient can be considered as 1.87, and the cooling energy consumption calculated according to the formula is $Q = 1.87\times 304.8\times(31.6 - 26) = 3192kWh$, considering the COP of the air condition is 3.2, the cooling energy is about 997 kWh, and the actual power consumption is 1310, there is a large deviation between the calculation result and the actual one. It shows that the K value obtained by software calculation need to be corrected. Based on the actual data in 2021, T_i will not change, so K value was revised to 400.5, then the cooling load calculation formula is modified as equation (3).

$$Q = \eta_{cold}\times 400.5\times(31.6 - T_i)[kWh/year] \tag{3}$$

When the building operates according to the timetable and the indoor temperature is set at 26°C, the reasonable air conditioning energy consumption is 700 kWh, which is the same as that in 2020, indicating that the formula is reasonable under normal using. From 2015 to 2016, the energy consumption of air conditioning was greatly reduced compared with the calculated value, and it was considered that the room temperature was set at 27°C to 28°C in 2015 to 2016. It also means that in actual use, the three air conditioners are not turned on at the same time, but only one or two of them are turned on, so that the temperature of the whole room does not drop to 26°C.

Table 8 shows heating load under different conditions in winter.

Table 8. Annual total heat load kWh under different working conditions.

Setting temperature / Minimum temperature	18	17	16	15	14
18	2582.00	--	--	--	--
17	2471.00	2135.00	--	--	--
16	2319	2018.00	1720.00	--	--
15	2193.00	1916.00	1643	1376.00	--
14	2037	1788.00	1544	1303.00	1069
13	1825.00	1609.00	1397	1189.00	982.00
12	1621	1433.00	1250	1069.00	890
11	1414.00	1252.00	1095	940.00	788.00
10	1166	1033.00	904	778.00	655

The heating load is related to the indoor setting temperature and indoor minimum temperature, and there is an obvious linear relationship between them.

According to the air conditioning load calculation principle, the heating load is proportional to the temperature difference between indoor and outdoor, so the annual heating load can be obtained by equation (4).

$$\begin{aligned} Q &= \sum_{1}^{n} K\Delta T_n = K\sum_{1}^{n}(T_i - T_e) - K_1\sum_{1}^{m}(T_{em} - T_{Min}) \\ &= KnT_i - KnT_e - K_1 mT_{em} + K_1 mT_{Min} = K_n T_i + K_m T_{Min} - C \end{aligned} \tag{4}$$

where: Q is the annual heating load; K is a constant related to the building and Occupancy behavior, K_1 is a constant equal to T_{Min} proportional correlation with outdoor temperature; n is the heating time; m is the heating time when $(T_{em} - T_{Min}) \geq 0$; T_e is the outdoor temperature, T_{em} is the mean outdoor temperature that larger than T_{Min}, T_i is the indoor setting temperature.

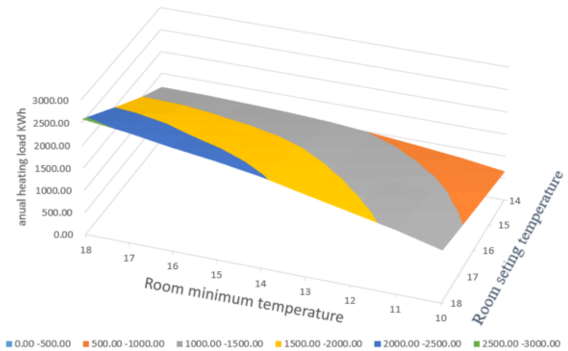

Figure 10. Relationship between heating load and startup temperature and indoor set temperature.

According to Figure 10, the relationship between the annual heating load and the indoor set temperature and the startup temperature can be obtained as equation (5).

$$Q = 239T_i + 119.5T_{Min} - 4032.5 \tag{5}$$

The heating load then corrected with the correction coefficient η_{hot} in Table 7, and the formula of the annual heating load after correction is equation (6).

$$Q = \eta_{hot} \times (239T_i + 119.5T_{Min} - 4032.5) \tag{6}$$

where, η_{hot}=0.9~1.52 .

Table 3 shows the actual heating power consumption, and due to the impact of the COVID-19 epidemic in 2019, the air conditioning operation in 2020 is closer to full load operation, so the load correction coefficient η_{hot} can be considered as 1.52, and the heating energy consumption calculated when $T_i = 18$℃, and $T_{Min} = 15$℃, is 3134 kWh.

considering the COP of the air condition is 3.9, the heating power consumption is 803 kWh, it's the same with the actual data of 2020. Therefore, it can be considered that the household usually sets indoor temperature to 18℃, and turns on the air conditioner at 15℃ for heating.

When T_{Min} is set to 16℃, the calculated heating power consumption is 559 kWh, which is 7% different from the actual operation data in 2015. In 2016 and 2017, the heating energy consumption is 40% of the calculated value. According to equation (6), the indoor setting temperature of the household is about 14℃.

4. Conclusions

For existing residential buildings, it can be considered that the residential buildings already have the basic energy consumption characteristics. By comparing the simulation results with the actual data, this paper obtains the energy consumption characteristics of air conditioning for the building. The formula has a good matching degree with the actual energy consumption of the residence, which can basically reflect the energy consumption characteristics of household and express its energy consumption habits. At the same time, it can also help occupants choose energy-saving measures and energy-saving potential in the use of air conditioning.

Acknowledgements

The study has been supported by the National Key R&D Program of China (Grant No. 2020YFD1100404-5).

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