Household Air Conditioning in Small Towns in Cold Regions under Winter Conditions
Experimental Research on Demand Response

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Abstract
The proportion of clean energy grid connection is gradually increasing, and the pressure of balancing the power supply side and the user demand side is also increasing. Building flexible electricity can effectively alleviate the contradiction between power supply and demand on both sides. However, the current research on flexible power consumption is mostly simulation research, and mainly based on air conditioning summer conditions. In many areas of China, air conditioning is also used for heating in winter. At present, there are few experimental studies on air conditioning electricity consumption in winter. Therefore, this paper studies the flexible regulation of air conditioning electricity consumption in small towns under winter conditions in cold regions, and obtains the application effect of different regulation strategies under this condition.

Highlights
- Review the current research and conclusions on demand response
- Point out the shortcomings of existing research
- Different flexible regulation strategies in demand response are tested experimentally

Introduction
In recent years, with the continuous development and progress of science and technology, people's living standards are gradually improved, and they have higher and higher requirements for living comfort. As the main part of electricity consumption in residential buildings, the electricity consumption of air conditioning system occupies a large amount of power load. Summer and winter is the peak period of air conditioning electricity, especially in the developed areas, the use of air conditioning system is higher. Air conditioning load in some large and medium-sized cities has accounted for 30%~40% of the peak load. In this context, the imbalance between supply and demand of the power grid is increasingly serious, and there are often large power fluctuations and valley peak difference, causing serious waste of resources and resulting in the rapid growth of residential power load at peak times. And for a long time to come, residential electricity consumption will only increase.

Demand response technology is one of the solutions to the above problems. In the future, some response technologies, namely flexible control strategies, will be adopted to reduce or delay the electricity load in a certain period without affecting the use effect of air conditioning equipment as far as possible, so as to ensure the stability of the residential building electricity system and realize the peaking and valley filling and load transfer of power grid operation. For most buildings, there are three main ways of demand-side response: (1) renewable energy generation; (2) charging and discharging of energy storage device; (3) Electrical equipment control. Generally speaking, the main means that can be better implemented in residential buildings is electrical equipment control, so electrical equipment control has become the first choice of technology for buildings to participate in demand response. Air conditioning equipment is also the main equipment suitable for flexible regulation. As a demand response terminal, it regulates the target users through some regulation strategies such as start-stop control and changing the supply air temperature, so as to complete the demand response activities of the user side, effectively reduce the peak power load, and realize the purpose of smooth operation of the power grid.

By providing background information on buildings and the grid, Juha Haakana (2023) et al. analyzed the impact of flexible heating loads on the distribution network, and then concluded that the flexibility potential of the residential power end-user's electric heating system on the impact of the distribution network load. The proposed method is validated with test data from a region of Finland. Yongbao Chen (2019) et al. proposed a more systematic approach to quantifying building electrical flexibility. These quantitative factors include the thermal mass of the building: a lamp, heating, ventilation, and air conditioning (HVAC) systems, as well as occupant behavior. They improved the accuracy of analysis by establishing models and verifying each other with experiments. Manar Amayri (2022) et al. proposed a method based on machine learning technology to intuitively reflect the flexibility of residential buildings' electricity consumption. They identify the use of devices with higher flexibility by establishing the way of electricity load monitoring. Finally, the total electricity consumption collected by smart meters alone can characterize the use of flexible electrical equipment with higher accuracy. Rasmus Elbæk Hedegaard (2017) et al. simulated residential buildings in
Denmark during a heating season based on historical market data, demonstrating that the total cost savings of existing buildings increased from 2.9% to 5.6% by adding transactions to the traditional day-before market price control problem. Fabiano Pallonetto (2022) et al. reviewed the current development of demand response plans and referred to a large number of residential buildings. They evaluated methods and procedures for building energy flexibility and demand response planning, and provided optimization schemes for demand response planning, but focused on numerical models and available control algorithms, lacking actual experimental data support. Han Li (2021) et al. systematically introduced various types of flexible loads, indexes, methods and applications in residential buildings from different levels, and quantified related evaluation indexes. Zihang Dong (2023) et al. proposed a new control strategy, aiming at the winter heating condition, adopted an iterative algorithm to coordinate the space heating of multiple residential households with different thermal parameters. They then adjusted the indoor heating plan through demand transfer and thermal comfort compensation to achieve personal cost savings while effectively shaving the total peak demand at the power system level. Arman Kolahan (2021) et al. solved demand-side management problems of community residential buildings based on blockchain intelligent management system. They improved occupants’ thermal comfort by modelling heating, lighting and electrical systems, which were verified by measurements taken from a building in northern Italy.

The current the research mainly focuses on theoretical research and simulation, and the experimental research is insufficient and lacks relevant experimental support. Even if there are some experimental studies, there is a lack of comprehensiveness, only studying the working conditions in summer or not conducting experimental studies in cold regions. Therefore, the research in this paper is an experimental study on the demand response of household air conditioning under winter conditions in small towns in cold regions. The reason why this study takes small town housing in cold regions as the research object. On the one hand, the heat load and cold load in winter and summer in cold regions are relatively average and prominent, and the demand for heating in winter and cooling in summer is very large. This climate is more suitable for studying the cold and heat load in winter and summer. On the other hand, most of the residential buildings in small towns do not have central heating, and air conditioning is also needed for heating in winter. Compared with other types of buildings, it has better independence and flexibility, which makes it more convenient to study flexible electricity consumption. Therefore, this study selects a typical residential building in a cold area as the research object, and studies the winter electricity flexibility of its air conditioner. Through specific experiments, the actual effects of different flexible control strategies are tested to provide some experimental data support for this research.

**Test building**

**Research object**

Geographically, the research object is located around Zhengzhou, Henan Province. In terms of climate, it belongs to a typical cold region with four distinct seasons. The building load in this climate zone is relatively large in cold load/heat load. On the whole, the annual accumulated cooling and heat load of the building and the seasonal accumulated cooling and heat load imbalance rate are low. In the stage of semi-urbanization, the energy-saving measures are relatively simple and the popularity is low. The heating and cooling are mainly air conditioning, and the adjustment space is large.

![Figure 1: The annual average temperature of Zhengzhou City](https://doi.org/10.26868/25222708.2023.1532)
Experimental arrangement

(1) Experimental plan

Taking winter operating condition as an example, based on the control effect of the indoor temperature set point under the operating condition, three operating strategies are proposed and implemented in this paper, as shown in the table below.

<table>
<thead>
<tr>
<th>Number</th>
<th>Flexible control strategy</th>
<th>Regulation strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reference condition</td>
<td>20 °C /Moderate</td>
</tr>
<tr>
<td>1</td>
<td>Reduce the set temperature</td>
<td>17 °C /Moderate</td>
</tr>
<tr>
<td>2</td>
<td>Reduce the air supply speed</td>
<td>20°C /Low</td>
</tr>
<tr>
<td>3</td>
<td>Start-stop control</td>
<td>Early shutdown</td>
</tr>
</tbody>
</table>

Table 1: Experiment content.

(2) Experimental measuring points and instruments

<table>
<thead>
<tr>
<th>Number</th>
<th>Instrument Name</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Anemometer</td>
<td>WWFWZYZ</td>
</tr>
<tr>
<td>2</td>
<td>Black-ball thermometer</td>
<td>HQZY-1</td>
</tr>
<tr>
<td>3</td>
<td>Solar irradiator</td>
<td>TES-1333R</td>
</tr>
<tr>
<td>4</td>
<td>House-service meter</td>
<td>DDSY1886</td>
</tr>
<tr>
<td>5</td>
<td>Hygrothermograph</td>
<td>RC-4HC</td>
</tr>
</tbody>
</table>

Table 3: Experimental instruments

Evaluation criteria

A The flexible electricity consumption of air conditioning is carried out on the premise that it does not affect the thermal comfort level of indoor human body. Therefore, there are two most direct evaluation methods for the flexible control strategy: (1) 24h electricity consumption; (2) PMV.

(1) 24h electricity consumption: Charging meters are placed at the target users to measure real-time electricity per hour, so that users can intuitively get real-time electricity consumption.

(2) PMV: The evaluation index representing human thermal response is mainly affected by temperature, wind speed and humidity. By arranging relevant instruments in target users and giving real-time feedback to relevant
experimental parameters, the change degree of human thermal comfort brought by the strategy can be measured.

**Table 4: PMV**

<table>
<thead>
<tr>
<th>Thermal comfort</th>
<th>PMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>-3</td>
</tr>
<tr>
<td>Cool</td>
<td>-2</td>
</tr>
<tr>
<td>Slightly cool</td>
<td>-1</td>
</tr>
<tr>
<td>Comfortable</td>
<td>0</td>
</tr>
<tr>
<td>Slightly warm</td>
<td>1</td>
</tr>
<tr>
<td>Warm</td>
<td>2</td>
</tr>
<tr>
<td>Hot</td>
<td>3</td>
</tr>
</tbody>
</table>

PMV

\[ M - \text{Metabolic rate, W/s} \]

\[ W - \text{Human body does power, W/s} \]

\[ P_w - \text{Water vapor partial pressure in ambient air, Pa} \]

\[ t_a - \text{Air temperature, } ^\circ\text{C} \]

\[ f_s - \text{The ratio of the surface area of the dressed body to the naked body} \]

\[ t_{oa} - \text{The average temperature of the outer surface of the human body, } ^\circ\text{C} \]

\[ h_e - \text{Heat exchange coefficient, W/s} \cdot \text{m}^2/\circ\text{C} \]

**Results and discussion**

In the legend of the following image, "normal" represents not operating the air conditioning according to the experimental plan in Table 1 and Table 2, but operating the air conditioning according to the actual living habits of indoor personnel; The "experimental" represents running the air conditioning according to the experimental plan in Tables 1 and 2.
Comparisons under different demand response strategies

This section comprehensively considers the actual indoor temperature, comfort, air conditioning energy consumption and operating costs, and evaluates the operating effects of the three strategies. In order to better observe the actual effect brought by different control strategies, that is, the transfer amount and transfer efficiency of electricity load in the experimental process,
the air conditioning power consumption is relatively independently separated by the air conditioning power splitting method and the blank control method, and an energy consumption curve close to the real air conditioning power consumption is fitted.

Table 5: The main power consumption equipment

<table>
<thead>
<tr>
<th>Power utilization equipment</th>
<th>Power consumption per hour (kW·h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Television</td>
<td>0.075~0.3</td>
</tr>
<tr>
<td>Computer</td>
<td>0.25~0.4</td>
</tr>
<tr>
<td>Kitchen cookers</td>
<td>0.5~1.3</td>
</tr>
<tr>
<td>Lighting fixture</td>
<td>0.1~0.4</td>
</tr>
<tr>
<td>Washing machine</td>
<td>0.2~0.5</td>
</tr>
</tbody>
</table>

In the above table, due to the complexity of power consumption equipment in real life, only equipment with high power and long single use time, such as kettle, which has high power but only about 5 minutes per use, is not considered. Combined with the following table, the specific power consumption of some power-consuming equipment is estimated by recording the power consumption without air conditioning and the human behavior in different time periods.

Figure 7: 24h power diagram without air conditioning operation

It can be seen that in the 11:00-13:00 time period and 19:00-23:00 time period, the electricity consumption increased, the main reason is related to the influence of cooking, watching TV, lighting and other people’s behavior. Therefore, the air conditioning power consumption of various control strategies is estimated in the above way. Due to the particularity of the start-stop control strategy, that is, the operation of the air conditioner is directly stopped after a period of time, the change of power can more intuitively show the load change brought by the implementation strategy. Therefore, the air conditioning electricity is split first.

Figure 8: Start-stop control- 24h power diagram

The power load curve under the two start-stop control strategy is almost the same during the experiment. Combined with the human behavior and the energy consumption of the electrical equipment on the day, it can be assumed that the power load of the air conditioning experimental state is about 2.5 kW·h. At the same time, the power load curve of the blank experiment also fluctuates up and down at 2.5 kW·h, so it can be roughly concluded that the power load of the experimental state is about 2.5 kW·h, so a close to the real state, start-stop control strategy of air conditioning energy consumption curve.

Figure 9: Start-stop control- 24h air conditioning power diagram

On average, each start-stop control transfers 2.35 kW·h electrical load. Under this premise, the thermal comfort of the experimental parameters measured indoors is calculated. The PMV value decreases by 0.45 on average, and the response time is about 25 min. That is, there is no obvious thermal comfort change in the first 25 min of the implementation of the control strategy, and the thermal comfort is gradually affected in the subsequent time.
Figure 10: Reduce the set temperature - 24h power diagram

The curve trajectories of the two experiments roughly coincide, but it is obvious that the red curve has a larger valley-to-peak difference, which is an inevitable normal phenomenon. There is a large valley-to-peak difference time period. Considering the high-intensity electricity consumption behavior such as home office at night and watching TV in the living room, the electricity consumption curve of the ground air conditioner under this strategy is roughly as shown in the figure.

Figure 11: Reduce the set temperature - 24h air conditioning power diagram

The average transfer load is 1.195 kW·h, the average fluctuation of thermal comfort is 0.23, and the response time is about 40 min. The indoor temperature and humidity fluctuate little within 1 h after the operation of the strategy, and it will have a significant impact after more than 1 h.

Figure 12: Reduce the air supply speed - 24h power diagram

Figure 13: Reduce the air supply speed - 24h air conditioning power diagram

The average transfer load is 1.02 kW·h, the average fluctuation of PMV value in the process of operation strategy is about 0.21, and the change of wind speed is instant. When the air supply speed is changed, it can be immediately reflected in the air supply speed of the air conditioning. The influence of wind speed on the thermal comfort of human body depends on the instant air dry bulb temperature and air supply speed. Therefore, when the air supply is carried out at 20 °C, the actual thermal comfort is less affected.

Conclusion

Through the experimental test of the air conditioning power consumption of a typical house, the actual influence of different control strategies on household air conditioning is studied. The specific conclusions are as follows:

(1) Combined with the experimental data, it can be seen that among the three control strategies, from the perspective of peak load shifting and power load transfer, the start-stop control has the best effect on peak load shifting and power load transfer, with an average transfer of about 2.3 kW·h electricity and the most obvious income. However, at the same time, the thermal comfort of the
human body is also most significantly affected, with an average reduction of PMV value of about 0.45. The timeliness of the strategy is outstanding because its response time is also short, so it is suitable for use in a short time, that is, considering that the start-stop control will not have much impact on thermal comfort in a short time.

(2) The strategy of reducing the set temperature has the best comprehensive effect. Under the premise of less impact on thermal comfort, the effect of load transfer is also better. The average transfer power load is about 1.2 kW \cdot h. Within the specified 1 h, the thermal comfort has no obvious change, and the PMV fluctuation is about 0.23.

(3) Under the control of this strategy, the average transfer power load is about 1.02 kW \cdot h, and the average fluctuation of PMV value is about 0.21. Compared with the first two control strategies, the operation effect of reducing air supply speed strategy is more special. The influence of wind speed on comfort depends largely on the supply air temperature, and the change of wind speed is instant. As long as the supply air temperature meets the human body heat demand reasonably, the influence of wind speed change on human body thermal comfort will be relatively small.

Acknowledgement

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