Thermal-Economic Performance Evaluation of Air Conditioning for Office Buildings

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Abstract. Building energy consumption accounts for about 40% of the total energy consumption in China. Among them, for hot summer and cold winter areas, the energy consumption of air conditioning and refrigeration in summer is the main part, based on the current situation of air conditioning application in this area, it is significant to improve the energy efficiency of refrigeration equipment in summer by analyzing the energy-saving potential of operation energy consumption and comprehensively evaluating its economy. Based on the theoretical thermodynamic perfection of equipment refrigeration, taking the split type air conditioning system in Guiyang office buildings as an example, this paper selects the typical refrigeration equipment and analyzes its energy-saving potential and economy based on its energy price status, in order to clarify the office building split air conditioning equipment energy-saving capacity and its operation economy. The preliminary analysis shows that when the service life of air-conditioning exceeds 5 years, its energy-saving performance and economy can reach the agreement, that is, the best energy-saving air-conditioning economy is also the best.

Keywords: Thermal Consumption · Energy Consumption Evaluation · Energy Saving Potential · Air Conditioning

1 Introduction

For the past few years, China's economy has developed by leaps and bounds, but this process has also brought us a huge amount of energy consumption. Among the major energy consumption of our society today, building energy consumption accounts for about 40% of the total China energy consumption. For HVAC energy consumption, which is the bulk of building energy consumption, the study of its energy saving potential and energy saving economy is an important direction for the development of building energy efficiency [1]. Most studies today are based on the technical and operational evaluation of air conditioning units in large public buildings in typical cities. These studies provide an in-depth analysis of the energy efficiency of HVAC equipment operation, but rarely analyze the economic aspects of such equipment, making it impossible to make an intuitive evaluation of the energy efficiency and economy of building air conditioning. In this study, a typical city in the hot-summer and cold-winter region of Guiyang is

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chosen as the target for the study. The study analyses the energy consumption of split air conditioning in office buildings, explores its energy saving potential and establishes a dynamic model of the economics of air conditioning operation on this basis, so that the energy saving and economics of building air conditioning can be weighed more intuitively.

2 Calculation of Thermodynamic Perfectness and Research Methods

2.1 Ideal Coefficient of Performance

As shown in Fig. 1, the reverse Carnot cycle is the ideal cycle of refrigeration, consisting of two isothermal processes and two adiabatic processes. Assuming that the thermodynamic temperature of the low-temperature heat source, the cooled object, is T_0, and the thermodynamic temperature of the high-temperature heat source, the ambient medium, is T_k, the temperature of the mass in the heat absorption process is T_0, and in the exothermic process is T_k, the process assumes that there is no temperature difference between the mass and the low-temperature heat source and the high-temperature heat source in the heat absorption and exothermic processes, and that the heat transfer process is carried out isothermally, and that the compression and expansion processes are carried out without any losses. The cycle process is as follows: the mass draws heat from the cold source under T_0 and carries out isothermal heat absorption process, then through the adiabatic compression process, its thermodynamic temperature rises from T_0 to the thermodynamic temperature of the ambient medium T_k, and then carries out isothermal exothermic process under the temperature of T_k and releases heat to the high temperature heat source q_k, and finally carries out adiabatic expansion process to make its temperature drop from T_k to T_0, and the mass returns to the initial state4, thus completing a cycle. The cooling coefficient of this cycle is:

$$COP = \frac{T_0}{T_k - T_0} \tag{1}$$

The COP based on the reverse Carnot cycle is an economic indicator used to characterize the corresponding refrigeration cycle, where the value of the cooling coefficient under this condition depends only on the thermodynamic temperature T_k of the heat source and the thermodynamic temperature T_0 of the cold source.

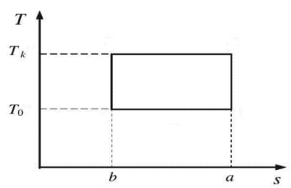

Fig. 1. The reverse Carnot cycle

2.2 Actual Coefficient of Performance

The irreversible process in the actual air conditioning operation makes the Coefficient of Performance under the actual working condition smaller than it under the reverse Carnot cycle, so the COP' under the actual working condition is defined as the ratio of the cooling capacity E_0 produced under the actual cycle working condition to the cycle power consumption E of the actual cycle.

$$COP' = \frac{E_0}{E} \tag{2}$$

2.3 Thermodynamic Perfectness

Since the actual refrigeration cycle generates irreversible losses, thermodynamic perfectness η is introduced to measure the degree of irreversibility of the actual cycle. Thermodynamic perfectness η is the ratio of the COP of the actual refrigeration cycle to the COP of the reverse Carnot cycle in the same operating temperature interval.

$$\eta = \frac{COP'}{COP} \tag{3}$$

Its amount reflects the closeness of this refrigeration cycle to the reverse Carnot cycle at the same temperature, depending on the level of the air conditioning manufacturing process, and can be regarded as a constant value within a certain range of thermal operating conditions [2].

2.4 Research Methodology

Guiyang is located in the southwest of China, in the hot summer and cold winter climate region of China, the summer temperature is always moderate and rarely hot, the average temperature is always at 16–24 °C, and it belongs to the area without central heating. Research shows that the thermal neutral temperature in hot summer and cold winter areas obtained by PMV calculation is around 18 °C, and in areas without centralized heating, people not only have lower expectations of indoor temperature, but also have some psychological comfort with lower indoor temperature [3]. Under the condition of meeting the indoor thermal comfort zone, the summer interior design temperature is taken to be 18 °C.

Under the laws of China, the workers who establish labor relations in various organizations and enterprises implement the working hour system of 8 h of work per day and 40 h of work per week, and according to the survey statistics, most of the workers in Guiyang enterprises work daily in the time period of 8–18 h [5], without considering the influence of overtime hours, so the summer day by day 9 to 17 h is selected as the office building air conditioning operation time for calculation.

The outdoor meteorological data used in the study were obtained from the meteorological data stored in the Energy Plus database, and the 24-h, day-by-day temperature of March 2005 in Guiyang was used to calculate and analyze the energy consumption of split air conditioners in office buildings based on different thermodynamic perfectness conditions.

3 Energy Consumption and Economic Analysis

3.1 Typical day Energy Consumption Analysis

The study uses four air conditioners of KFR-35GW type with different energy efficiency levels for simulations, and the performance parameters of each air conditioner are shown in Table 1. In order to analyze the performance of different air conditioners, the COP value for level 5 is higher.

Table 1. Performance parameters of air conditioners of various energy efficiency levels

Energy efficiency level	Refrigerating capacity [W]	Refrigeration power [W]	*COP*	*COP′*	η
1	3500	750	24.4	4.7	0.19
2	3500	900	24.4	3.9	0.16
3	3500	980	24.4	3.6	0.15
5	3500	1130	29.3	3.1	0.11

The highest average temperature day and the lowest average temperature day from 9 to 17 in summer as a typical day, air conditioning operation energy consumption analysis: as shown in Fig. 2, the highest average temperature day from 9 to 17 is July 31, with an average temperature of 29.4 °C; the lowest average temperature day from 9 to 17 is August 22, with an average temperature of 18.3 °C, while the typical daily power consumption of each different thermodynamic perfectness of air conditioning is shown in Fig. 3.

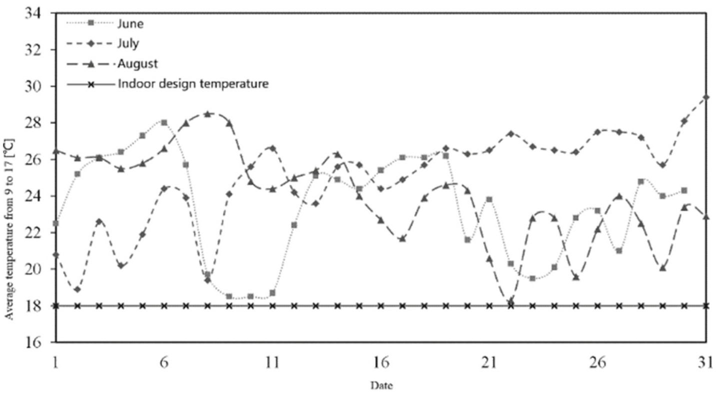

Fig. 2. Average temperature change curve for summer months from 09–17 pm

As shown in Fig. 3, the energy consumption of air conditioning decreases with the increase of thermodynamic perfectness, when the thermodynamic perfectness increases

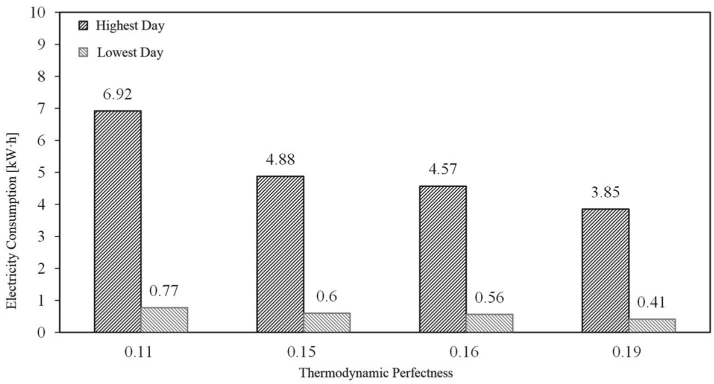

Fig. 3. Electricity consumption on a typical summer day for air conditioners with different degrees of thermodynamic perfectness

from 0.11 to 0.19, the energy consumption of air conditioning on the highest day decreases from 6.92 kW·h to 3.85 kW·h, a decrease of 44.36%. The difference in energy consumption between the same air conditioner on the highest day and the lowest day is huge, as the thermodynamic perfectness increases from 0.11 to 0.19, the difference in energy consumption between the highest day and the lowest day decreases from 6.15 kW·h to 3.44kW·h, a reduction of 44.07%. The energy saving of the same air conditioner on the lowest day compared to the highest day is nearly 90%. This shows that the higher the degree of thermodynamic perfectness under the same working conditions, the smaller the energy consumption of the air conditioner and the smaller the energy savings of the air conditioner; the outdoor temperature has a greater impact on the energy consumption of the air conditioner than the degree of thermodynamic perfectness.

3.2 Month-By-Month Energy Consumption Analysis

The analysis of the energy consumption of the air conditioner on a typical day mentioned above shows that the outdoor temperature and the difference between indoor and outdoor temperatures have a significant impact on the power consumption of the air conditioner in operation. The smaller the thermodynamic perfectness of the air conditioner, the greater the power consumption under the same operating conditions. Therefore, the energy analysis is performed with the air conditioner of energy efficiency class 5 as the operating air conditioner to find the maximum energy consumption in the selected air conditioner, and thus the maximum energy saving potential of the air conditioner can be obtained.

From the analysis of a typical day, it can be seen that the air conditioner with the smallest thermodynamic perfectness has the largest power consumption under the same temperature environment conditions, so the air conditioner with five energy efficiency levels is used as the operating air conditioner for energy consumption analysis in order to obtain the maximum energy consumption among the selected air conditioners, so as to obtain the largest air conditioner energy saving potential value, and its monthly power consumption for each month of operation in summer is shown in Fig. 5.

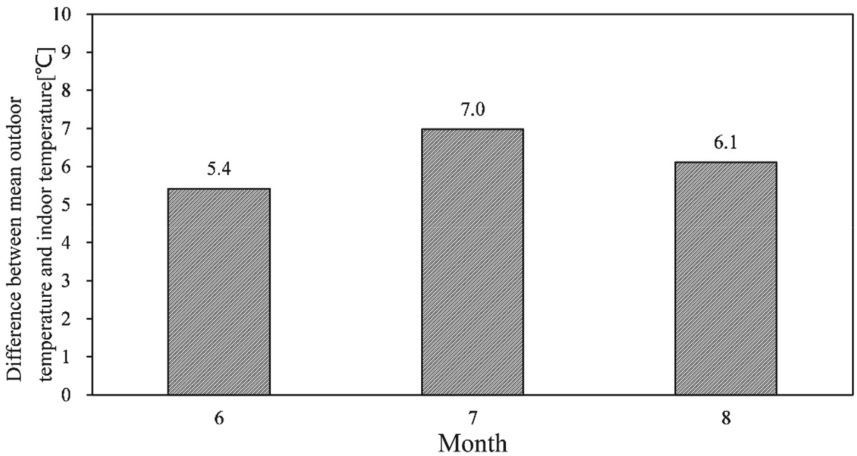

Fig. 4. Average difference between indoor and outdoor temperatures from 9 to 17 h in each summer month

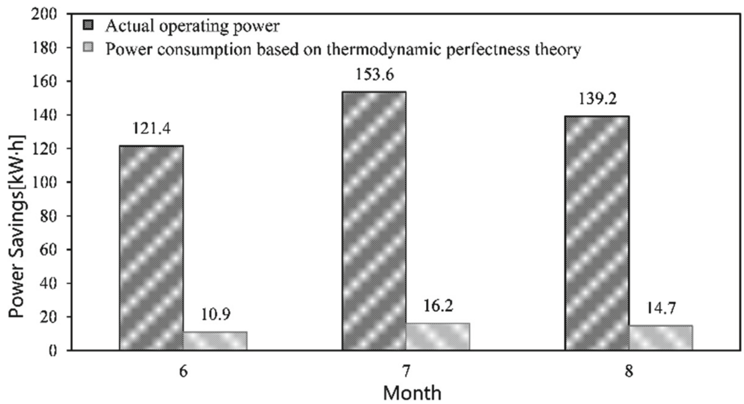

Fig. 5. Power consumption for each month of operation of class 5 energy-efficient air conditioners

Figures 4 and 5 show the difference between the average indoor and outdoor temperatures from 9 to 17 in each summer month and the power consumption of energy-efficient air conditioners in each month, respectively. The results show that the higher the average difference between indoor and outdoor temperatures from 9 to 17, the higher the power consumption of the air conditioner. 1.6°C higher than the average difference between indoor and outdoor temperatures in July than in June, the power consumption of the air conditioner is 32.2kW-h more, and the relative percentage of power consumption is 26.5%. That is, for the same model of split type air conditioner, a small change in the temperature difference between indoor and outdoor can lead to a large change in power consumption. The graph also shows that for the air conditioner with the smallest thermodynamic perfectness, the actual power consumption due to various irreversible factors is much higher than the power consumption calculated based on the theoretical thermodynamic perfection, and the actual power consumption in each month is almost 10 times of the theoretical power consumption, which means that the split air conditioner has great potential for energy saving in operation.

3.3 Energy-Saving Measures and Economic Analysis

From the analysis of the monthly operating energy consumption of the air conditioners in energy efficiency class 5, it is already known that there is a lot of room for energy saving in the actual operation of the air conditioners in summer. For the four selected split type air conditioners with different thermodynamic perfectness, their energy saving potential in summer operation is shown in Fig. 6.

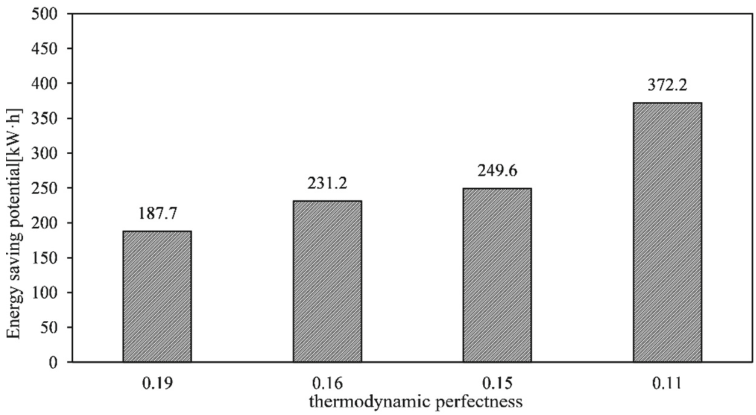

Fig. 6. Graph of air conditioning energy saving potential with thermodynamic perfectness

As shown in Fig. 6, the higher the thermodynamic perfectness degree, the smaller the energy saving potential of the air conditioner, because the increase of the thermodynamic perfectness degree means that the actual working condition of the air conditioner is closer to the theoretical working condition, and the space for energy saving will be smaller, but at the same time, it also means that the energy saving effect is better. From the graph, we can also see that when the thermodynamic perfectness degree is 0.11 and 0.19, the energy saving potential is almost double, that is, the energy saving effect is almost double, so we can start from improving the thermodynamic perfectness degree of split type air conditioners to do energy saving design, improve the efficiency of the compressor, increase the condenser and outdoor heat source side of the heat transfer capacity and effective use of condensate to take away condensation heat and other measures can be effective. The thermodynamic perfectness of split air conditioners can be improved [6], and it can be seen from Fig. 6 that a small increase in thermodynamic perfectness within a certain range can lead to a large increase in energy efficiency, which means that it is very cost-effective to improve energy efficiency by increasing thermodynamic perfectness within a certain range. However, as shown in Fig. 7, as the degree of thermodynamic perfectness increases, the rate of improvement of the energy-saving effect by increasing the degree of thermodynamic perfectness will become smaller and smaller, which will lead to a smaller and smaller cost performance by increasing the degree of thermodynamic perfectness, therefore, when increasing the rate of energy-saving by increasing the degree of thermodynamic perfectness in split type air conditioning equipment when the degree of thermodynamic perfectness is larger, it is necessary to make a certain trade-off between economy and energy-saving.

China regulations, the general use of split-type air conditioners do not exceed 10 years, so the maximum use of the air conditioner for ten years to calculate the length of air conditioning operation, Fig. 7 shows the four different thermodynamic perfectness of split-type air conditioners for ten years of operating investment costs curve.

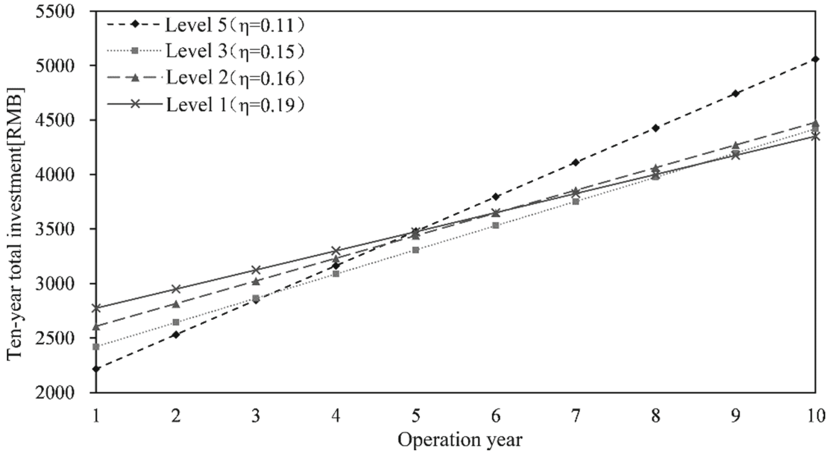

Fig. 7. Ten-year operating investment curve for each split type of air conditioner

As shown in Fig. 7, the initial investment of the split type air conditioner with five energy efficiency levels is the lowest, but the slope of its total investment curve is the largest, which means that its annual investment is the largest, and the initial investment of the split type air conditioner with one energy efficiency level is the highest, but correspondingly its total investment curve slope is the smallest and its annual investment is the smallest, and the total investment after ten years of operation under the same conditions is the smallest for the split type air conditioner with one energy efficiency level and the largest for the split type air conditioner with five energy efficiency levels, from the perspective of economy, if the long-term use of the same air conditioning equipment, the use of thermodynamic perfectness of the best economy of split-type air conditioning equipment; short-term use of the same equipment, you can choose a smaller degree of thermodynamic perfectness of split-type air conditioning equipment to seek a better economy. From the point of energy efficiency, whether long-term or short-term, the use of thermodynamic perfectness of split-type air conditioning equipment has the best energy efficiency.

4 Conclusion

Based on the theoretical thermodynamic perfection of refrigeration equipment for building air conditioning, taking the split type air conditioning system in Guiyang office buildings as an example, this paper selects the typical refrigeration equipment and analyzes its energy-saving potential and economy based on its energy price status, in order to clarify the office building split air conditioning equipment energy-saving capacity and its operation economy. From the preliminary case study, the following conclusions can be drawn.

(1) When the low temperature heat source temperature is certain, the smaller the temperature difference between the cold and hot sources, the larger the cooling coefficient of the split type of air conditioner and the higher the energy efficiency.
(2) Improving the thermodynamic perfectness of a split type of air conditioner within a certain range can significantly improve the energy efficiency of the air conditioner, but as the thermodynamic perfectness increases, the cost of improving the thermodynamic perfectness increases while the energy efficiency rate decreases, and the cost performance decreases.
(3) The greater the degree of thermodynamic perfectness, the better the economy of split air conditioners in long-term investment; and regardless of long-term investment or short-term investment, priority should be given to split air conditioners with a greater degree of thermodynamic perfectness in the case of energy-saving effects.

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