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ARTICLE

Heating, Ventilation and Air Conditioning Design for Commercial Complex Buildings: Theory and Method Based on Inverse Problem

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ABSTRACT

Scientific and technological progress and innovation help the design industry, which plays an important role in sustainable development. It will improve the operation efficiency of enterprises and explore a blue sea for enterprise. In essence, design should be the process of deriving the optimal scheme from different schemes or imaginary scenes. Based on this, this paper proposes an overall optimization method for Heating, Ventilation and Air Conditioning (HVAC) design. Compared with the traditional design method, under certain constraints, it can obtain the optimal design scheme that maximizes the value of the designed product. This study provides new inverse problem ideas and methods for HVAC designers, and provides solutions for enhancing the value of HVAC design products.

1. Introduction

Since the outbreak of the epidemic in 2020, the development of enterprises has also been affected. At the same time, with the continuous development of society, the internal and external competition between enterprises is also constantly sublimated. This is both an opportunity and a challenge for most enterprises. The progress of science and technology provides more opportunities for the development of modern enterprises, and also puts forward higher standards for the quality of enterprises' products. Therefore, strengthening the exploration and guidance of scientific and technological innovation and optimizing the product structure of enterprises have played a crucial role in the development of enterprises.

The energy consumption of building operation is about one third of the commercial energy of the whole society. China is in the high-speed stage of economic development, which has continued the rapid growth of GDP for more than ten years, and the annual growth rate of energy consumption is also high. As a pillar industry of GDP growth, the construction industry's annual total construction volume is close to half of the global annual total construction volume. Building energy consumption increases with the increase of the total number of buildings. Whether China can achieve sustainable development is not only closely related to the improvement of people's quality of life, but also related to the implementation of national en-

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ergy strategy and resource conservation strategy, as well as global climate change and sustainable development.

At present, China's building energy consumption (excluding rural non commodity biomass energy) has been maintained at 20% ~ 25% of the total social energy consumption and is increasing. From 2000 to 2010, the energy consumption for construction and operation increased from 289 million tons of standard coal to 677 million tons of standard coal. From 2030 to 2040, China's population will reach a peak of 1.47 billion, and the urbanization rate will reach 70%. Under this background, the urban residential and industrial building areas will further increase. Some scholars pointed out that in the future, China's total building volume will reach 91 billion square meters, which is twice the current total building volume, which will also increase the energy consumption brought by buildings. The International Energy Agency (IEA) predicts that by 2030, China's total energy consumption will reach 5.81 billion tons of standard coal, including 1.52 billion tons of standard coal for building energy consumption.

In 2018, China's carbon emissions reached 9.8 billion tons, accounting for about 28.8% of the world's total. The total carbon emissions from building operation and construction are about 2.35 billion tons, accounting for 24% of the national carbon emissions, and the building materials are about 1.65 billion tons, accounting for 16%, accounting for 5% of the global total carbon emissions.

Therefore, research on building energy conservation is not only an important way to achieve energy conservation and emission reduction in China, but also related to the sustainable development of global energy and environment.

HVAC energy consumption is a large part of building operation energy consumption, and due to the complexity and large size of HVAC equipment, the HVAC system will also affect the building scheme. On the one hand, the refined HVAC design method can effectively reduce the energy consumption of the HVAC system. With the help of optimization design, the energy consumption problem in the later period can be solved in the early stage to save energy consumption. On the other hand, the building layout can be reasonably used to improve the use value of the building.

The traditional HVAC design concept is generally to solve the direct problems: know the building envelope information, climate conditions and indoor personnel, the heating of lights and equipment and ventilation times, and the layout of machine room shafts, calculate the cooling and heating loads of buildings and the selection and layout of air conditioning and ventilation equipment. The limitations of the current design concepts include that the designers cannot know which enclosure structure can reduce the heating and air conditioning load as much as possible on the premise of meeting the indoor thermal comfort. It is impossible to know the ideal natural ventilation strategy and heating and air conditioning strategy. It is impossible to know the ideal HVAC room and shaft layout. The current design concepts are to solve the direct problems, not optimization. In order to solve the shortage of traditional design concepts, this paper proposes that HVAC design should solve the inverse problem. The objectives of this work are: (1) to put forward an approach for determining the ideal HVAC room and shaft layout. (2) to demonstrate the advantage of applying the approach in practice by using some illustrative examples.

2. Research Problem

In general, the traditional HVAC design is to solve direct problems (as shown in Figure 1). The reason and effect of this design idea are as follows: under the limited design conditions of building materials, designers cannot know what kind of thermal properties of building envelope materials can reduce heating and air-conditioning loads as much as possible. The optimal natural ventilation strategy cannot be determined. The minimum energy consumption of heating and air conditioning cannot be determined. The ideal positions of HVAC machine rooms and shafts cannot be known.

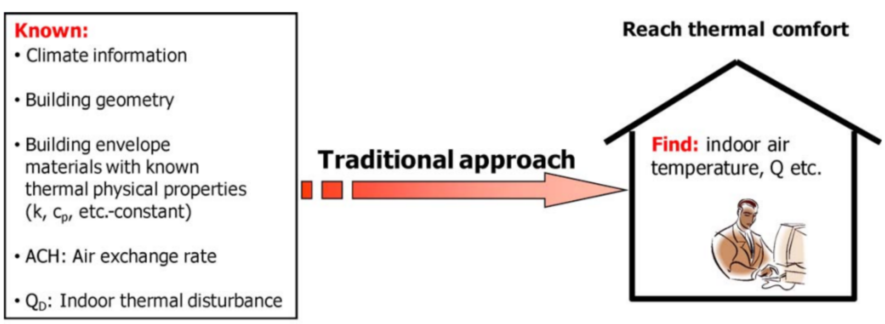


Figure 1. Traditional HVAC design ideas

This research attempts to apply the idea of inverse problem to HVAC design. Contrary to the traditional idea, this research idea takes thermal comfort requirements, load requirements, effective use area requirements, customer experience requirements, etc. as known quantities, and takes the thermal properties of the enclosure structure and the machine room shaft (including location, area, responsible area, and internal equipment air volume) as unknown quantities to solve (as shown in Figure 2) [1].

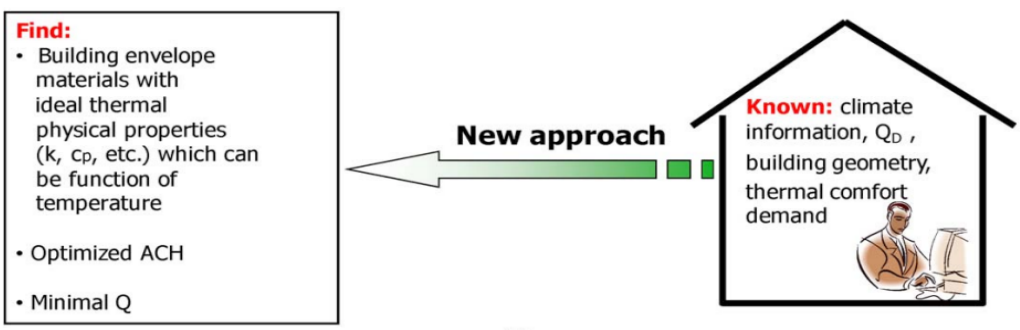
Because the parameters to be solved are functions, this kind of inverse HVAC problem is a nonlinear problem, which brings some difficulties to the solution. Because every inversion calculation in the inverse problem needs to solve the forward problem, the whole solving process is very tedious, so the large amount of calculation is another difficulty in solving the inverse problem.

2.1 Inverse Problem Introduction

Julia, a famous American mathematician described the inverse problem as follows: "Usually in mathematics, you will get an equation, and you need its solution. Now you have a solution, and you must find that equation. I am happy to do so." The inverse problem is relative to the positive problem. In the process of understanding the world, human beings always receive various signals according to their sense organs to explore the development laws of objective things. On the basis of understanding the development law of objective things, people can calculate the unknown parameters from the known parameters according to the law. The signal is called external cause, the relationship becomes internal cause (the difference between external cause and internal cause is that there is a changing temporal relationship between the former and the structure, while the latter does not). Finding the result from the cause (external cause and internal cause) is called a direct problem, and finding the cause from the result (external cause or internal cause) is called an inverse problem.

Generally, we will give the cause signal (such as initial condition, boundary condition, etc.) according to the theory and practical experience of predecessors, and then carry out gradual reasoning to get the results. But in practical engineering, the initial conditions and boundary conditions can not be completely determined sometimes. At this time, it is necessary to inverse solve the uncertain factors in the system through some information obtained in time and space.

The formulation of the inverse problem originated in the 1960s, and then rapidly developed into a new cross discipline, which is widely used in natural science and engineering practice [2-4]. For example, seismic exploration, whose mechanism is that the seismic wave generated by the ground explosion propagates downward and reflects to the ground, judges the distribution of the underground medium through the vibration data received by the sensor. In the process of spacecraft returning, due to aerodynamic heating, the surface heat flow density is extremely high, but its accurate value cannot be directly measured, so the inverse heat conduction problem can be solved to determine its surface heat flow. For vibration flaw detection, the ultrasonic signal generator is used to generate sound pressure, and the fault is judged according to the reflected echo captured by the ultrasonic detector due to encountering cracks. The problem of heart death is to diagnose heart disease through inversion of cardiac electric field. The principle of CT technology is to transmit some physical quantities (such as various rays, particles, waves, electromagnetic fields, etc.) that can pass through the object without damaging the structure of the object, and then analyze the received signals of these physical quantities to obtain the object structure. Through calculation and processing, a three-dimensional perspective image of the internal structure of the object is established. Although inverse problems are widely used in physics, chemistry, aerospace, biology and other engineering disciplines, they can still be classified from different perspectives [5,6].



(b)

Figure 2. New ideas for HVAC design

The inverse problem has the following three characteristics:

(1) Non linearity: Judge the linearity and nonlinearity of the parameter to be solved according to its position in the model, and the nonlinearity is universal. Most inverse problems are nonlinear, and many inverse problems corresponding to linear positive problems are nonlinear, which brings some difficulties to solve inverse problems.

(2) Inadequate: Due to the error of observation, the solution to the rhetorical question does not exist or is not unique, which is the characteristic of ill posed. This is the difficulty of inverse problem research and application.

(3) Large amount of calculation: Every iteration of variables in the inverse problem requires recalculation of the positive problem, which makes the whole inversion process very cumbersome and consumes a lot of calculation time.

2.2 Inverse Problem Solving Method

Because of the nonlinearity, ill-posedness and large amount of computation, it is difficult to solve the inverse problem. In order to overcome these difficulties, researchers have developed many methods to solve inverse problems, which can be divided into three categories:

(1) Analytic and semi analytical methods: starting from the analytical formula of the forward problem, find the integral equation that connects the known conditions with the inverse problem, and then use mathematical tools (such as integral transformation) to solve the integral equation. Analytic method can use various mathematical skills to solve specific inverse problems with specific mathematical methods. The advantages of this method are: low calculation cost. The disadvantage is that it is only applicable to some simple linear problems.

(2) Non heuristic inversion algorithm: search the whole model space according to certain constraints, calculate all these models forward in turn, compare the calculation results with the measured data, and select the appropriate model. Typical non heuristic inversion algorithms include simulated annealing, genetic algorithm, etc. This method has the advantages of strong global convergence and the disadvantages of many iterations.

(3) Heuristic inversion algorithm: the idea is to form an iterative format for nonlinear problems, and gradually approximate to solve inversion variables. The basic principle is to start from an initial model, search near the initial model according to a certain method, obtain the model correction amount, and modify the original model according to the correction amount to obtain a new model. Repeat until convergence is satisfied. Including: steepest descent method, conjugate gradient method, sequential quadratic programming method, etc. The advantages of this method are: fast convergence speed, small amount of calculation, and the disadvantages are: the global convergence is not perfect.

Based on the characteristics of HVAC design, sequential quadratic programming (SQP) is used to solve this kind of inverse problem. Sequential quadratic programming is a feasible direction method. This algorithm can be regarded as a generalization of unconstrained descent algorithm. The strategy is to start from the feasible point and search along the descending feasible direction to find a new feasible point that makes the objective function value descend. The main step of the algorithm is to select the search direction and the step size to move along this direction. The idea of sequential quadratic programming method is to transform the constrained optimization problem into an unconstrained optimization problem by modifying the original problem, and then use Newton's method. In each iteration, the Hessian matrix of the Lagrangian function is approximated by the quasi Newton method, which produces a quadratic programming problem and ensures the convergence of each problem. The solution of the problem is used to determine the search direction, and the step size of each iteration is determined by linear search. SQP method includes three steps: updating Hessian matrix of Lagrangian function, solving quadratic programming problem, linear search and benefit function calculation.

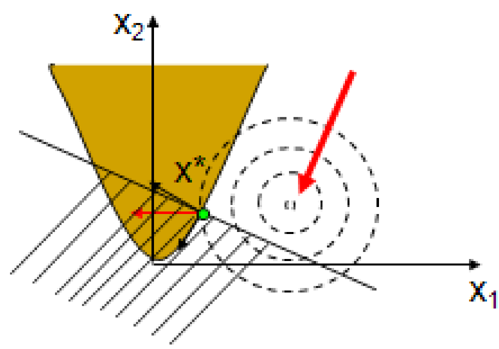


Figure 3. SQP categories

3. Results and Analysis

In order to reflect the advantages of applying the new HVAC design method to practical projects, this paper selects a commercial project in Beijing as an example for design. The project is a commercial complex building, with a total floor area of about 174688.45 m^2. There are three floors underground, and the total building area of the basement is about 60688.45 m^2. Business type: the first floor underground is equipment room, garage and non motor garage. The second underground floor is equipment room, garage, non motorized garage, property room, etc. The third underground floor is garage, non motorized garage, etc. Thirteen floors above the ground, with a total floor area of about 114000 m^2 (including 74145 m^2 for commercial buildings), and the first to fifth floors are for commerce, cinemas and children's entertainment. Office on the sixth to thirteenth floors. The building height is about 59.95 m.

Taking the second floor as an example, the lower right corner of this floor area is a commercial business, requiring air supply by air conditioning units. The design constraints are: there are three fire compartments in this area, and the system setting does not allow crossing the fire compartment. No more than one group of air conditioning rooms in a group of fire compartments. The area of the air conditioner room shall A_e not exceed 50 m^2. The radius of the responsible area of the air conditioning machine room L not exceed 30 m. The air volume of the unit in the air conditioning room V not exceed 50000 m^3/h. The design variables are the location X and size S of the machine room, the responsible area and the unit air volume V_{ef} in the machine room. The design goal is to make the commercial effective leasable area A_{ef} as sufficient as possible.

After quantifying the above optimization problems, the optimization model can be obtained as follows:

Optimization objective: max A_{ef} (X, S, V_{ef})

Restrictive condition: $A_e \leq 50$; $L \leq 30$; $V \leq 50000$

Then, the numerical model is used to solve this problem. According to the grid independence test, it is found that the appropriate grid size of the air conditioning room is 100 mm.

Absolute error of the commercial effective leasable area between the numerical model and the analytical model is 6% at three different conditions. Therefore, the numerical model in this paper is acceptable.

After SQP method is adopted for calculation, the location map of the second floor air-conditioning room can be obtained (as shown in the black boxes in different color filled areas in Figure 4).

In order to verify the rationality of optimization, this paper compares the commercial effective rentable area under several different machine room locations, and finds that the optimized location of air-conditioning machine room can make the commercial effective rentable area the most sufficient.

The commercial effective leasable area has increased by 13% after optimization when air conditioning room is evenly distributed in the commercial complex building. The commercial effective leasable area has increased by 20% compared to air conditioning room concentrating on a fire compartment. The commercial effective leasable area has increased by 26% after optimization compared to air conditioning room distributed by unprinciple. This shows that the HVAC design method in this paper has advantages and operability in improving design quality and value.

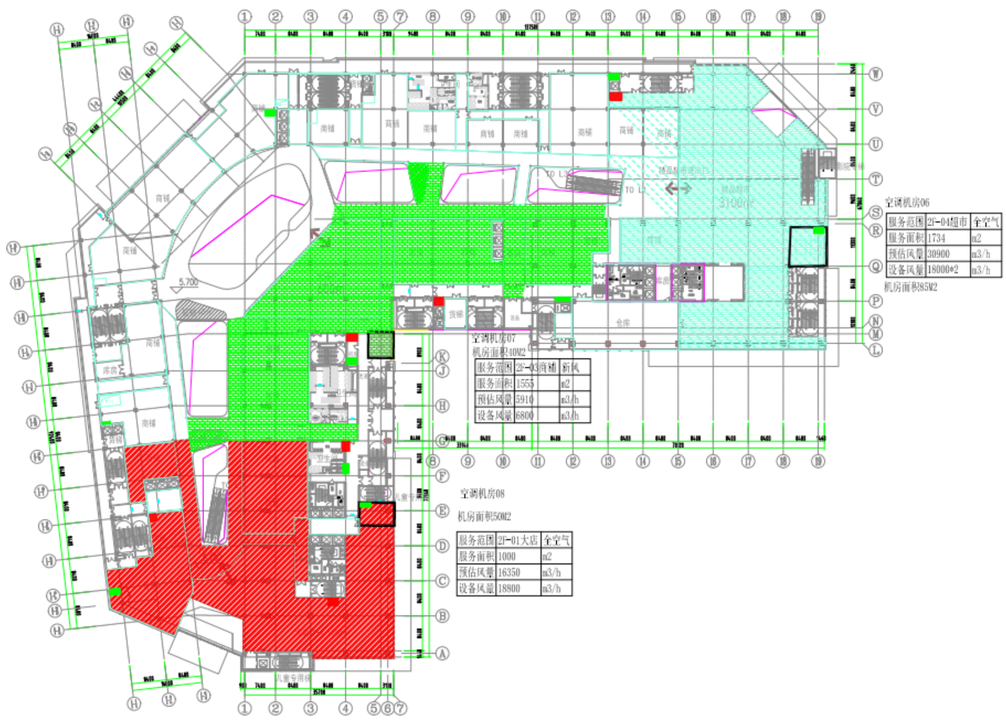


Figure 4. Layout plan of air-conditioning room on the second floor

4. Conclusions

(1) An approach of determining the ideal air-conditioning machine room distribution is put forward, which can realize the sufficient commercial effective leasable area.

(2) The result for a commercial project in Beijing as an example shows the optimal air-conditioning machine room distribution approaches a center distribution.

(3) The developed approach can also be used in the complex commercial for the purpose of designing.

This approach gives the guidelines for buildings' design in different regions to realize the energy conservation.

Conflict of Interest

There is no conflict of interest.

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