ANALYSIS OF THE EFFECT ON OPTIMIZED CONTROL OF INDOOR CLIMATE OF BUILDING WITH SOLAR AIR COLLECTOR FOR HEATING IN COLD AREAS IN CHINA

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Abstract

Stabilizing the indoor air temperature and optimizing the distribution of heat are the important parameters to improve the performance of solar air heating building. This study analyzed the influence of the concrete slab's behavior as thermal mass to smoothing the fluctuation of temperature by experimental research on the real building with south wall-mounted solar air collector under different conditions. Then, based on the experimental results, the impacts of different thermal mass levels and the position of thermal mass in the building on indoor thermal environment were analyzed by using the software EnergyPlus. Main conclusions are drawn as follows: the total thermal capacity of building bigger, the smaller the temperature's fluctuation, yet, when the capacity were big enough this effect can be neglected; the best capacity ratio of external thermal mass to internal thermal mass is 5：1; the heat transfer coefficient of internal thermal mass is the bigger, the better.

Keywords: solar air collector, concrete slab, sensible heat capacity, EnergyPlus

1. Introduction

Solar air heating buildings are widely used in China for its lower construction and operating cost, while the stability performance of the indoor thermal environment in it is poor, sometimes the daily range of indoor air temperature can reach above 10℃. According to the research, thermal mass in the building can effectively smooth the fluctuation of the indoor temperature [1-2], making it fluctuate between 16℃ to 20℃, which is acceptable. In China, most buildings are built with steel, concrete and bricks, these building materials with huge sensible heat capacity can play a great part in regulating the indoor thermal environment.

The studies on thermal mass with huge sensible heat capacity in building were explored by followings: 1) Balaras[3]reviewed the research on the thermal mass in building from the year of 1966, and then classified the methods of calculating building cooling load and indoor air temperature, among them most are formulized based on experimental results. 2)Yuguo Li, etc[4-5]simplified the heat transfer process between the thermal mass and the air based on the lumped parameter method, the mathematical models were established when the internal thermal mass or external thermal mass work respectively. They found both the phase shift and attenuation of the indoor air temperature fluctuation and building cooling load are determined by the time constant and the dimensionless convective heat transfer number. Based on these, Junli Zhou, etc[6]analyzed the indoor thermal response character for naturally ventilated buildings under the action of internal thermal mass and external thermal mass based on reaction coefficient method.3) Meanwhile, via changing the pattern using the thermal mass, the thermal effect of thermal mass can be improved. A numerical simulation of the temperature distribution of two different free cooling systems are analyzed and compared, of them the first is a traditional mixed ventilation system while the other is a thermal mass activation system that the outdoor ventilation air flows through the ducts of the hollow core concrete ceiling slab before entering the room in reference [7]. The optimization problem of coupling operation of the thermal mass and the air conditioning devices is discussed in reference [8].

This study places emphasis on the use of thermal mass in solar air heating buildings, and aim at the significant conclusions to guide practice. Based on the experimental results, the model in E+ software to analyze the effect of the total building sensible heat capacity、 the capacity ratio of external thermal mass to internal thermal mass and the pattern of heat transfer in solar air collector to the indoor thermal environment was set up.

2. Experiment setting

There are one testing room and one reference room in experiments, building area of each room is 3200mm×3200mm, and the south external wall of the testing room is composed of 200mm thick concrete slab plus 120mm thick XPS insulation. The other walls are composed of 200mm thick slag hollow brick plus 120mm thick XPS insulation, coated with 15mm thick lime mortar inside and 20mm thick cement mortar outside. The roof of the testing room is composed of 120mm thick concrete slab, 200mm thick air layer, 200mm thick XPS insulation; the roof of reference room is composed of 120mm thick concrete slab, 80mm XPS insulation. The thermal performance of the building envelope with external insulation and heavy materials facing the indoor zone directly has been proved to be the best in all climatic regions [9]. Solar air collector is fixed on the south wall of the testing room, not on reference room. The structure of the rooms and testing points are showing in Fig.1.

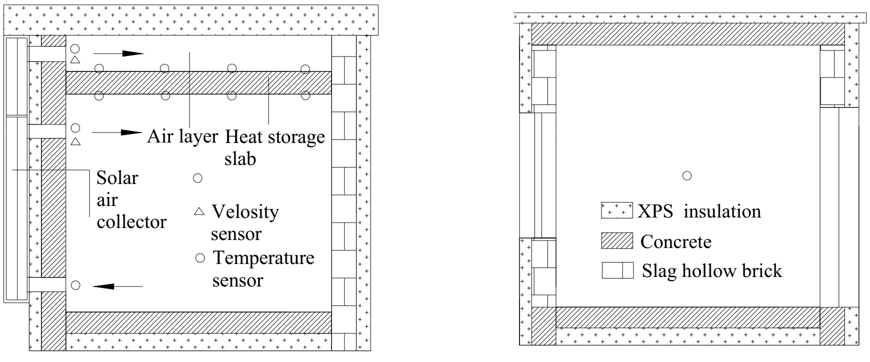

Fig. 1. The structure and testing points of the testing room and reference room

The testing system is composed of compute ring multipoint data logging system and outdoor weather stations, and it can automatically record the weather data, the air velocity at the outlet of solar air collector and the temperature of the air and the wall’ s surface for every 10min. The experiment date divided into the solar air collector working phase (January 11 to February 4, March 8-11) and not working phase (February 4 to March 7), and the operating time of solar air collector is from 9:30 AM to 4:30 PM in single day.

3. Experimental result analysis

3.1 Influence of thermal mass

The calculated total sensible heat capacity of testing room and referential room are 16150 kJ/℃ and 13500 kJ/℃, respectively. The thermal mass level of testing room is higher. Reference to the index of statistical analysis to evaluating the dispersion degree, we choose coefficient of variation as the index to analyze the fluctuation intensity of indoor air temperature.

$$V = {}^{S}\!/_{\overline{T}} \qquad (1)$$

V -coefficient of variation， S -standard deviation of temperature， $\overline{T}$ daily average temperature，

By using the coefficient of variation, we can compare the fluctuation intensity with different daily average temperature, and the thermal stability is poor when it has the bigger value of V . The coefficients of variation of daily air temperature are shown in Fig.2 on February 20-24, it is obvious that the thermal stability of testing room is better than referential room and the fluctuation of indoor air temperature is in direct ratio with the outdoor fluctuation.

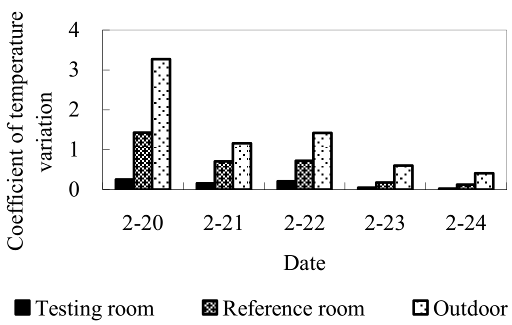

Fig. 2. Comparison of the thermal stability

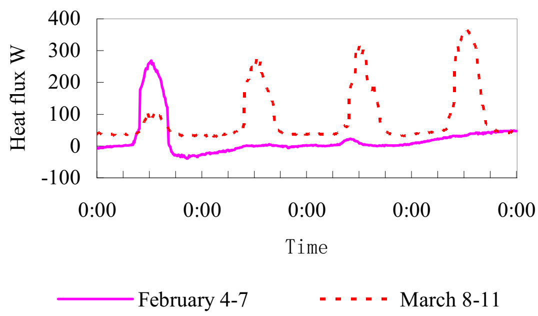

Fig. 3. Heat flux as a function of time in different date

3.2 Heat storage concrete slab

Heat storage concrete slab were studied by experiments for its important heat storage capacity. We consider the date of February 4-7 and March 8-11 as the phase for heat releasing and storage to concrete slab, because the solar air collector did not work from February 5 to March 7. By assuming there is only steady convective heat transfer between slab and indoor air within the period of 10 minutes, heat flux were calculated and the coefficient of convective heat transfer were adopted from reference[10]. The results are shown in Fig.3, the negative value represent the heat flow into indoor air from concrete slab.

As it can be seen from Fig.3, the heat flux values of March 8-11 are always positive, which means the heat keep going into concrete slab. But on February 5-6, the heat flux values keep negative, which means the heat releasing phase can go through 2 days after the solar air collector stop working.

4. Numerical analysis

In order to research the effects to the stability of indoor thermal environment caused by building's heat capacity, solar heating mode and thermal property of heat storage slab, we adopt the international general software EnergyPlus to do the numerical simulation in this paper. The studies [11-12] show that the mathematical model set up by EnergyPlus has much higher accuracy to simulate thermal response characteristics of the building.

4.1 Physical model and calculation conditions

In this paper, we set up the physical model based on the really existed testing room and chose the physical parameters of building materials according to the reference[13], the thermal conductivity of window glass is 0.9W/(m · K), ignore the heat loss caused by cold air infiltration through window and door's slits, and the effects of the humidity transfer process.

The process of solar air collector heating indoor air is simplified into internal heat source whose heat flux changes over time. Choose heat output of the collector in sunny day (January 25) as the simulation input value. According to the calculation, we found that heat supply basically changes in linear within half an hour. In order to simplify the calculation, we take the realistic average heat output per 30min as the heat output variation in simulation. This hypothesis is also one of the reasons of the simulation error.

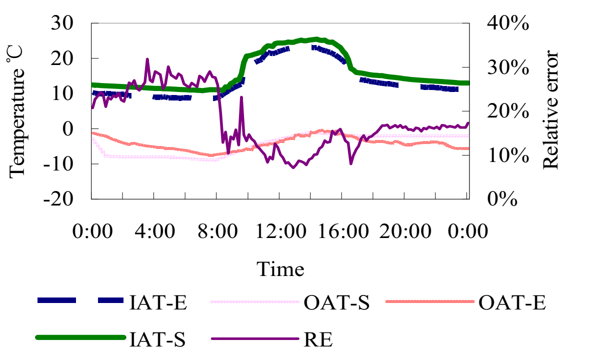

Fig. 4. Validation of the simulation and experiment (IAT-indoor air temperature OAT-outdoor air temperature E-experiment S-simulation RE-relative error)

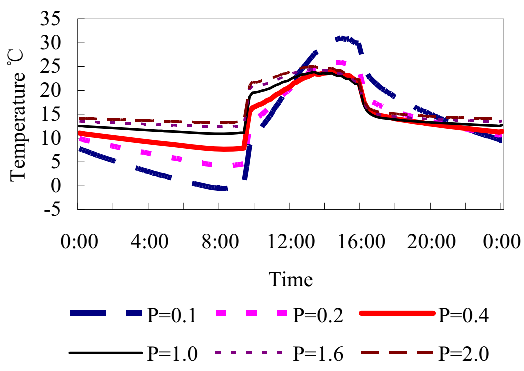

Fig. 5. Figure of temperature under different total heat capacity

4.2 Validation of the simulation

The weather data applied in simulation come from typical meteorological year, which has a little difference with the real tested data. So we picked data from January 25, of which weather data have the largest similarity, to validate the simulation. The temperature of experiment and simulation over time and relative error are shown in Fig.4. As it can be seen, the relative errors of indoor air temperature between simulation and experiment are within 20% since 9:00AM; especially in heating phase it have lower values due to the similar outdoor weather condition. In general, the model and assuming conditions used in the simulation can be considered right.

5. Numerical results and analysis

5.1 The impact of total sensible heat capacity

For solar air heating building, we adopt the total sensible heat capacity to analyze the impact of thermal mass level on indoor thermal environment. In simulation cases, the building heat loss coefficient L (W/℃) and outdoor weather conditions are the same, the fluctuation of indoor air temperature were shown in Fig.5 with the different total sensible heat capacity (J/℃).

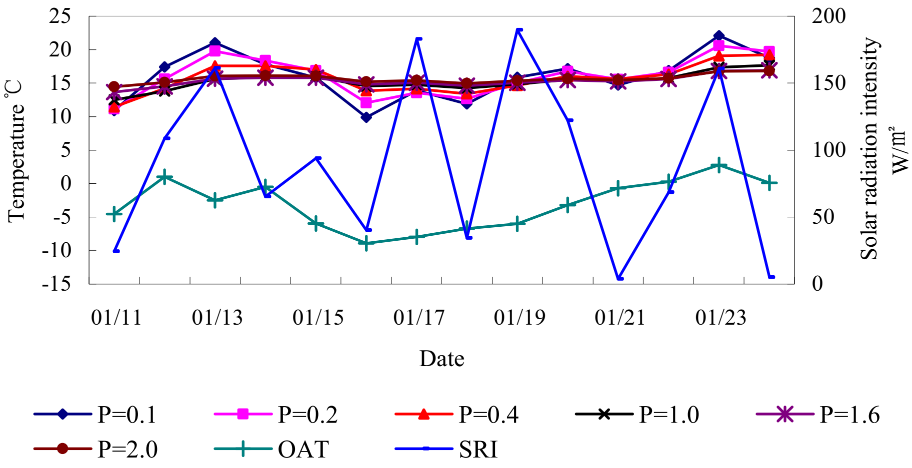

Fig. 6. Figure of daily average temperature (OAT-outdoor air temperature SRI-solar radiation intensity)

In Fig.5, P represents the ratio of simulating capacity and capacity of testing room. When P=0.1, the daily range of indoor air temperature can be high as 30.3℃, the temperature rise fast and down fast, and the thermal stability is poor. With the increase of total sensible heat capacity, the thermal stability is better. From P=1 to P=2, the configurations of temperature are similar to each other and the temperature changes are within 2℃; and also when value of P varied from 0.5 to 1, the indoor thermal stability is improved slightly. Therefore it is not worthy to improve the thermal stability by increase the thermal mass level of testing room; on the contrary, we can decrease the total sensible heat capacity by reducing the building material, even lower to its half.

Considering the long term effects of thermal mass, Fig.6 shows the variation figure of daily average operative temperature from January 11-24. it can be seen that daily average operative temperature maintained in 15℃ when P=1, however, it changed with respect to outdoor weather conditions dramatically when P=0.1, and its temperature difference can be higher than 10℃. Comparing the same conditions except the solar air collector do not work, similar conclusion were obtained, but the daily average operative temperature maintained in 4℃ when P=1.

5.2 Optimization of thermal mass' design in building

Thermal mass can be fallen into internal thermal mass and external thermal mass by position in the building. The former is exposed to the ambient environment, effected by ambient temperature and solar radiation, such as building envelope, and the latter is placed indoor, which interact with indoor environment. In the testing room, concrete slab belongs to internal thermal mass, and the building envelope belongs to external thermal mass. This study analyzed the effect of internal and external thermal mass on the indoor thermal environment by changing the heat capacity ratio of these. Meanwhile, optimization objects also contain heat exchange process between thermal mass and air, heat transport mode of solar air collector.

Therefore, it defines factor A as the ratio of building envelope to concrete slab, B as ratio of heat supplied into indoor to heat supplied into storage layer, and C as multiple of heat transfer coefficient to actual testing room. These three effect factors are interacted each other, so, it is unreasonable to analyze certain factor individually. In this study, it adopts orthogonal design method, and designs 16 groups of experiments by orthogonal table. Planning experiments by orthogonal table not only reduces the test frequency, and has the representation, but also possesses comprehensive comparability, which can analyze the effects of factor's level individually from the experimental results[14]. The level of factors of this experiment design is shown in table 1.

Table 1. Levels of factor

Level	Factor A	Factor B	Factor C
1	11：1	1：13	0.25
2	10：2	6：8	5
3	8：4	10：4	20
4	4：8	∞	50

The sensible heat capacities of building envelope and heat storage concrete slab in testing room are 13500KJ/℃ and 2650 KJ/℃, so the ratio of external and internal thermal mass' heat capacity is 5:1. In table1 the level ∞ of factor B represents all the heat from solar air collector were supplied into indoor directly. After simulating the 16 cases, the monthly average operative temperatures are shown in table2.

Table 2. The monthly average operative temperature in 16 different conditions

Number	1	2	3	4	5	6	7	8
Simulation case	$A_1B_1C_1$	$A_1B_2C_2$	$A_1B_3C_3$	$A_1B_4C_4$	$A_2B_1C_2$	$A_2B_2C_1$	$A_2B_3C_4$	$A_2B_4C_3$
Temperature℃	15.13	15.98	16.24	16.78	15.80	15.85	16.47	16.46
Number	9	10	11	12	13	14	15	16
Simulation case	$A_3B_1C_3$	$A_3B_2C_4$	$A_3B_3C_1$	$A_3B_4C_2$	$A_4B_1C_4$	$A_4B_2C_3$	$A_4B_3C_2$	$A_4B_4C_1$
Temperature℃	15.74	16.23	15.98	16.28	15.85	15.83	15.98	16.46

We can get the simulation cases with the highest and lowest monthly average operative temperature directly from the table2, which are case 4 and case 1. In order to analyze the effects caused by different levels of one factor, variable T_{jk} is defined and it is the summation of four values which represent the level k (k=1, 2, 3, 4) of factor j, and hence, $T_{j1}, T_{j2}, T_{j3}, T_{j4}$ indicate the impact of four levels of factor j on monthly average operative temperature. The analytical results are shown in Fig.7, and we can see the case $A_2B_4C_4$ is the best one.

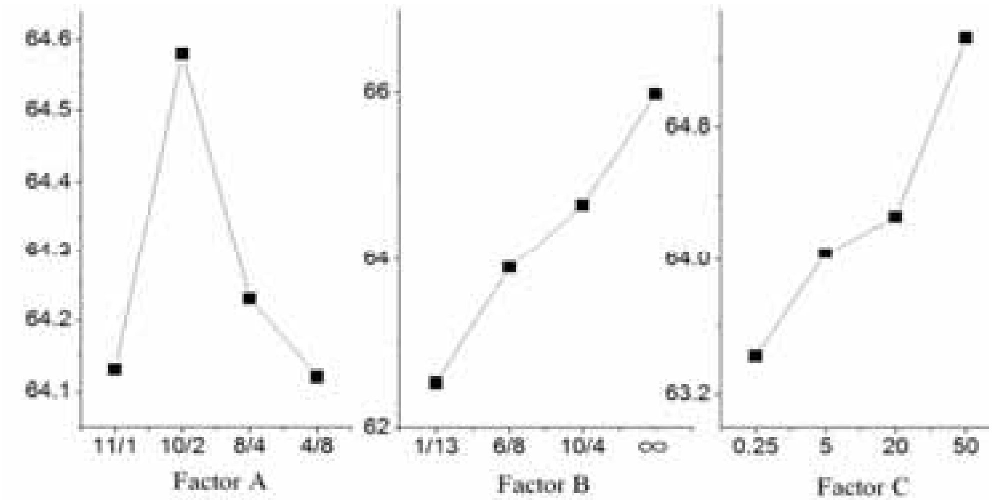

Fig. 7. Analysis of the different level of factor for the best case

The range $R_j = \max_{1 \le k \le 4}\{T_{jk}\} - \min_{1 \le k \le 4}\{T_{jk}\}$ is defined to compare the influence of different factor to the result, and the factor with larger range has the greater effect. By calculating, the ranges of factor A, B, C are 0.46, 3.46 and 1.91, respectively. So the factor B has the biggest influence. At last, the best conditions were obtained: all the heat from solar air collector should be supplied into indoor zone directly; the ratio of external and internal thermal mass' heat capacity should be 5:1; the heat transfer coefficient of heat storage concrete slab (internal thermal mass) is bigger, the better.

6. Conclusion

Solar air collector incorporated heat storage concrete slab is a new type of heat collect and storage, this study optimized solar air collector's operating mode and the design of this kind of building envelope by experiment and simulation methods.

Through the experiments, we found thermal mass in building can restrain undulation of the indoor air temperature, it means the design of heat capacity should be considered seriously. Based on the simulation research, when the multiple of building's heat capacity to the testing room varies from 0.5 to 2, the improvement of indoor thermal stability is not obvious. Consequently, while the new building's thermal loss coefficient L(W/℃) is equal to testing room, which total sensible heat capacity only need to reach 312 KJ/℃ per cubic meter in building volume. Due to the interacted effects of different factor, orthogonal design method on experiment is adopted. we found that: all the heat from solar air collector should be supplied into indoor zone directly, this factor has the biggest influence; the ratio of external and internal thermal mass' heat capacity should be 5:1; the heat transfer coefficient of heat storage concrete slab (internal thermal mass) is bigger, the better.

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