Study on load characteristics of different air conditioning systems in large space railway station

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ABSTRACT. The railway station is a representative kind of large space building, whose air-conditioning system design has always been paid a lot of attentions. At present, the air-conditioning system at a train station is mainly a stratified air conditioning mode with spout air supply outlets, which has a significant thermal stratification and energy waste in winter. In this paper, a large space waiting room of one railway station in Wuhan is taken as the analysis example, and the CFD method is used to simulate the airflow and temperature distribution under different air-conditioning terminal devices in winter and summer. The airflow organization models of the waiting hall under three typical air-conditioning systems have been established including stratified air conditioning system, air handling unit special for large space system and floor radiation system. The temperature and velocity distributions of the large space in the waiting hall are comparatively simulated under each system. The temperature stratification, the amount of cooling and heating requirements are obtained for three types of air conditioning systems. According to minimum amount of the annual cooling and heating loads, a terminal device form of air-conditioning system which is suitable for large space is provided. The results can provide a reference for the design of air-conditioning systems for similar large space buildings.

1. Introduction
The large space of the waiting hall of the railway station has the geometric features of high height and large span. At the same time, the gates of the ticket halls and the entrance gates of the passenger stations are basically kept open. The ticket exits also need to be opened during the passengers’ boarding times. Compared with ordinary public buildings, the air infiltration of the passenger station buildings is larger, and the energy consumption of air conditioning systems is much higher. At present,
stratified air conditioning system which is only responsible for cooling or heating of personnel areas is the most commonly used mode for large space area\textsuperscript{[1][2]}. However, stratified air conditioning has obvious disadvantage of thermal stratification in winter, and it wastes big amount of energy\textsuperscript{[3][4][5]}. In this paper, three air conditioning systems are analyzed for avoiding the phenomenon of thermal stratification. CFD program simulation is an effective mean to analyze the indoor thermal and humid environment in large space\textsuperscript{[6][7][8]}, which can be used to forecast the temperature and air speed distribution of the large space building, and to evaluate the indoor airflow organization in different air supply forms. This paper uses CFD software to simulate the airflow distribution in the train station waiting hall under the three air conditioning system, including stratified air conditioning system, air handling unit special for large space system and floor radiation system. Finally, annual energy consumption is compared, the best air conditioning system form suitable for large space is got, and the paper results provides reference for the air-conditioning design of large space.

2. Architectural overview

A railway station in Wuhan is taken to be simulated. The specific layout of the railway station is shown in figure 1. The railway station lies towards south. The ground floor is underground entrance hall (4184m$^2$); on the first floor, there are ticket halls, south entrance hall of the station (1913m$^2$), waiting room (1880m$^2$), VIP waiting room (3120m$^2$) and north entrance hall (4712m$^2$); on the second floor, there are a mother-and-baby room (808m$^2$) and an elevated waiting hall (18216m$^2$).

![Figure 1. The model of train station layout.](image1)

![Figure 2. CFD model of the waiting hall.](image2)

| Location of the building envelopes | Type of the building envelopes | Heat transfer coefficient (W/(m$^2$·K)) |
|----------------------------------|-------------------------------|----------------------------------|
| South wall                       | interior wall                 | 2                                |
| North wall                       | interior wall                 | 2                                |
| East wall                        | exterior wall                 | 1.456                            |
| West wall                        | exterior wall                 | 1.456                            |
| Roof                             | —                              | 0.485                            |
| Floor                            | Carry empty floor             | 0.7                              |

The elevated waiting hall is selected to investigate the suitable air-conditioning terminal form of the large space. The elevated waiting hall is 198m long and 92m wide. The roof, arched, the highest is 18m and the lowest is 13m from the ground. The elevated waiting hall is a typical large space.
upper part of the waiting hall has a width of 92m, and a shop with a depth of 13m on both sides below the height of 5m. Therefore, the bottom width of the waiting area is 66m.

The basic model is established by CFD simulation program (figure 2). To simplify the model, the arched roof is established as pentagon roofing with a height of 15m. Since the railway station was reformed in 2012, according to reference GB50189-2005[9], the heat transfer coefficients of the building envelopes of the waiting hall are set as shown in table 1.

3. Simulation results and analysis

The 0-2m average temperature (the height of the people) is maintained 18°C in winter and 27°C in summer by adjusting the air supply parameters. Then caloric calculation formula (1) was used to calculate the heating/cooling load. Finally, the formula (2) was used to obtain the heating/cooling load index, which will be compared comprehensively.

\[
Q = cm\Delta T
\]

Where, \(Q\) is the heating/cooling load (kW); \(c\) is the specific heat of air, which equals 1.01kJ/(kg·°C) in this paper; \(m\) is the flow rate of air (kg/s); \(\Delta T\) is the difference between return air temperature and supply air temperature (°C).

\[
q = \frac{Q}{S} \times 1000
\]

Where, \(q\) is the heating/cooling load index (W/m²); \(Q\) is the heating/cooling load (kW); \(S\) is the air-conditioning area of the high space (m²).

3.1 Winter

According to Chinese standard GB50736-2012[10], the winter outdoor air conditioning design temperature is -2.6°C in Wuhan; outdoor dominant wind direction is northeast; average wind speed is 3m/s. Now the indoor design temperature is set to 18°C. And the heat resistance of the clothing work is set as 2.05W/(m²·K), active state is very light labor.

By establishing a ContamW model, the amount of infiltration air in each opening of the waiting hall in winter can be calculated, as shown in table 2.

| Opening position       | Wind direction | Area (m²) | The amount of infiltration air (m³/h) |
|------------------------|----------------|-----------|--------------------------------------|
| South passage          | inflow         | 70        | 176265                               |
| North passage          | inflow         | 100       | 176326                               |
| East ticket exit       | inflow         | 3.6×8     | 20416                                |
| West ticket exit       | outflow        | 3.6×8     | 44052                                |
| East window            | outflow        | 19.2      | 147986                               |
| West window            | outflow        | 19.2      | 180964                               |

3.1.1 Stratified air-conditioning system. When adopting stratified air-conditioning system, the parameters of air-conditioning are set as table 3, the average temperature of 0-2m of the waiting hall is 18°C. The simulation results are shown in figure 3. According to DeST, the heating load index is 152.6W/m².
Table 3. The detailed settings of stratified air-conditioning system in winter.

|                     |               |
|---------------------|---------------|
| Height of outlet     | 4m            |
| Size of outlet       | 0.2m×0.2m     |
| Number of outlet     | 108 on both sides of the east and west |
| Distribution of outlet | distance between adjacent outlet is 1.8m |
| Supply air temperature | 40.4°C        |
| Supply air velocity  | 8.5m/s        |
| angles of airflow    | Downward 30°  |

When using stratified air-conditioning system, as shown in (a), there is a large vertical temperature difference, reaching 10°C. As shown in (b), there is a large number of low-temperature infiltration air enters into the waiting hall from south passage, north passage and east ticket of the waiting hall, so the local temperature is lower than the surrounding temperature, about 15°C; and the other areas of the waiting hall are mainly around 20°C. As shown in (c), the wind speed can reach 1m/s near the south and north passage; the wind speed in other areas is almost no more than 0.5m/s, and the average wind speed is 0.326m/s. As shown in (d), the PMV values of the waiting hall range from -0.5 to 1, the average PMV is 0.374, which reaches the thermal comfort level I.

![Figure 3. Air distribution characteristics of stratified air-conditioning system in winter.](image)

3.1.2 Air handling unit special for large space system. The air handling unit special for large space is an air conditioning device which cools or heats the air through the cold or heat exchanger in the
equipment, and then uses the air distribution device to evenly distribute the cold or hot air from top to bottom to balance the indoor temperature. The high-space air handling unit is hoisted on the roof, and the axial fan forces the top air to be sent down, with a stable air supply mode. It is mainly used in construction sites of 5-30m high, suitable for heating, cooling and ventilation in large space environments.

When air handling unit special for large space system was used, the parameters of this system are set as table 4, which make the average temperature of 0-2m of the waiting hall at 18°C. The simulation results are shown in figure 4. At this time, the heating load index is 107.5W/m².

**Table 4.** The detailed settings of air handling unit special for large space system in winter.

| Height of outlet | Size of outlet          | Number of outlet | Distribution of outlet | Supply air temperature | Supply air velocity | angles of airflow     |
|-----------------|------------------------|-----------------|-----------------------|-----------------------|--------------------|----------------------|
| 14m             | 0.2m×0.2m              | 5×18 at the top as an even distribution | distance between adjacent outlet is 11m | 36°C                  | 17.88m/s           | vertically downward  |

When using air handling unit special for large space system in the large space waiting hall, as shown in (a), the vertical temperature difference is 5°C, about 5°C lower than that of stratified air-conditioning system. As shown in (b), the temperature distribution at the height of 1m is similar to that of stratified air-conditioning system. As shown in (c), the wind speed at the height of 1m is slightly higher, about 1m/s, in the two kinds of place, where near the south/north passage and below the air handling unit; the wind speed in other areas is almost no more than 0.5m/s, when the average wind speed is 0.375m/s, slightly higher than stratified air-conditioning system. As shown in (d), the PMV value of the waiting hall is mainly range of -0.3~0.75, the average PMV is 0.089, reaching the thermal comfort level I, better than the stratified air-conditioning system.
3.1.3 **Floor radiation system.** When the floor radiation system is used in the waiting hall, average heat radiation intensity is 54.8W/m² if the average temperature of 0-2m of the waiting hall is 18°C. The simulation results are shown in Figure 5. Because the floor radiation has a downward heat transfer loss, the loss rate is assumed to be 22.4%[11], so the actual total intensity of the floor radiation at this time is 70.62W/m².

When floor radiation heating system is used, as shown in (a), there is almost no temperature difference in vertical direction. As shown in (b), the temperature distribution of 1m height is similar to the former two trends. As shown in (c), only the wind speed can reach 1m/s near the south and north passage; the wind speed in other areas is almost no more than 0.5m/s; the average wind speed is 0.297m/s, less than both of stratified air-conditioning system and air handling unit special for large space system. As shown in (d), the PMV value of the waiting hall is mainly range of -0.3~1, the average PMV is 0.539, only reaching the thermal comfort level II, which is hotter than the previous two system solutions.

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**Figure 4.** Air distribution characteristics of air handling unit special for large space system in winter.

**Figure 5.** Air distribution characteristics of stratified air-conditioning system.
3.2 Summer
According to Chinese standard GB50736-2012, the summer outdoor air conditioning design temperature is 35.2°C in Wuhan; outdoor dominant wind direction is east-northeast; average wind speed is 2.3m/s. Now the indoor design temperature set-point is 27°C, and relative humidity is 70%. And the heat resistance of the clothing work is set as 0.39 W/(m²·K), active state is very light labor.

By establishing a model using ContamW program, the amount of infiltration air in each opening of the waiting hall in summer can be calculated, as shown in table 5.

Table 5. The infiltration air in each opening of the waiting hall in summer.

| Opening position     | Wind direction | Area (m²) | The amount of infiltration air (m³/h) |
|----------------------|----------------|-----------|-------------------------------------|
| South passage        | out            | 70        | 128316                              |
| North passage        | out            | 100       | 55738                               |
| East ticket exit     | in             | 3.6×8     | 19966                               |
| West ticket exit     | out            | 3.6×8     | 20413                               |
| East window          | in             | 19.2      | 110595                              |
| West window          | in             | 19.2      | 73905                               |

3.2.1 Stratified air-conditioning system. When adopting the stratified air-conditioning system in the waiting hall, the detailed settings of air-conditioning system are set as table 6, meanwhile the average temperature of 0-2m of the waiting hall is maintained 27°C. The simulation results are shown in figure 6, when the cooling load index is 218.2W/m².

Table 6. The detailed settings of stratified air-conditioning system in summer.

| Height of outlet     | 4m              |
|----------------------|-----------------|
| Size of outlet       | 0.2m×0.2m       |
| Number of outlet     | 108 on each side of the east and west, 20 on each side of the north and south |
| Distribution of outlet | distance between adjacent outlet is 1.8m |
| Supply air temperature | 16°C            |
| Supply air velocity  | 11m/s           |
| angles of airflow    | upward 10°      |
| Supply air humidity  | 85%             |
Figure 6. Air distribution characteristics of stratified air-conditioning system in summer.

Figure 6 (a) shows that the vertical temperature difference is 5°C for stratified air-conditioning system in summer, which is lower than that in winter. As shown in (b), the main areas of the waiting hall are mainly around 26°C (because the floor is in contact with the outside world, making the bottom temperature is higher, the temperature at 1m height is about 26°C when the average temperature is 27°C). As shown in (c), except that the wind speed at the corner of the waiting hall is 0.7m/s, it is almost no more than 0.5m/s in other areas, meanwhile the average wind speed is 0.283m/s. As shown in (d), the PMV range of the waiting hall is from -0.5 to 1, the average value is 0.576, only reaching the thermal comfort level II.

3.2.2 Air handling unit special for large space system. When air handling unit special for large space system is used, the detailed settings of air handling unit special for large space system is set as table 7, while the average temperature of 0-2m of the waiting hall is 27°C. The simulation results are shown in figure 7, simultaneously, 234.3W/m² is the cooling load index.

When air handling unit special for large space system, as shown in (a), the vertical temperature difference is same as that in stratified air-conditioning system. As shown in (b), the main areas of the waiting hall are mainly around 26°C, but the distribution no better than stratified air-conditioning system; this system has a larger fluctuation. As shown in (c), except for the wind speed below the air handling unit about 1m/s, the wind speed in other areas is almost no more than 0.5m/s; the average wind speed is 0.234m/s, which is less than stratified air-conditioning system. As shown in (d), the PMV value of the waiting hall is mainly range of -0.5~0.75, the average PMV is 0.411, reaching the thermal comfort level I; this system has better thermal comfort than the former system.

| Table 7. The detailed settings of air handling unit special for large space system in summer. |
|---------------------------------|-----------------|
| Height of outlet                | 14m             |
| Size of outlet                  | 0.2m×0.2m       |
| Number of outlet                | 9×35 at the top as an even distribution |
| Distribution of outlet          | distance between adjacent outlet is 5.5m |
| Supply air temperature          | 16°C            |
| Supply air velocity             | 9.6m/s          |
angles of airflow
vertically downward
Supply air humidity
85%

Figure 7. Air distribution characteristics of air handling unit special for large space system in summer.

3.2.3 Floor radiation cooling system. For normal public buildings, if the floor radiant cooling system is used, the floor temperature should not be lower than 18°C to avoid condensation. At this time, the maximum cooling capacity of floor radiation is 45W/m², and other systems also need to be used for dehumidification and refrigeration[12]. For the railway station, the station entrance and the ticket gate are often opened, and the infiltration air is very large. Under the design condition of Wuhan that the outdoor air temperature is 35.2°C and relative humidity is 67%, the dew point temperature is 28.1°C. Considering the problem of condensation on the floor, the cooling capacity is much smaller even the system cannot be used. So for the building with large infiltration air, a floor radiant cooling system is not a sensible choice.

3.3 Annual energy consumption comparison

Because the floor radiation system is not suitable for the summer cooling in the large space station, one combined air conditioning system which stratified air conditioning system is used in summer and floor radiation system is used in winter is adopted. So the annual energy consumption of three air conditioning systems, namely stratified air conditioning system, large space air handling unit system and the combination system, is analyzed. Table 8 gives the comparison of the three systems’ cooling and heating loads and PMV. It can be seen that in the winter, for the large space of the waiting hall, the floor radiant heating method performs the best, and the air handling unit special for large space system is the second. The traditional stratified air conditioning venting method has the worst effect. Compared with the traditional stratification air conditioning, the heating loads of floor radiation system and air
handling unit special for large space system are decreased by 53.7% and 29.6% respectively. In summer, the stratified air conditioning air supply system has the lowest cooling load, and the air handling unit special for large space system has a 7.4% increase in cooling load, but the comfort is a little better. Floor radiation (winter) + stratified air conditioning (summer) system shows good energy consumption characteristics throughout the year.

In the southern region where summer cooling period is longer, the stratified air conditioning system is recommended respect to the annul energy consumption; in the northern region where winter heating period is longer, a floor radiant heating system is suggested; in areas with similar cooling periods and heating periods, it is recommended to use air handling unit special for large space system or floor radiation (winter) + stratified air conditioning (summer) system.

Taking Wuhan as an example, the annual energy consumption of the three systems is shown in table 8. The floor radiation (winter) + stratified air conditioning (summer) system has the lowest annual energy consumption. Compared to the tiered air conditioning system, floor radiant (winter) + stratified air conditioning (summer) system can save 18.5% of the energy consumption, showing good energy efficiency. This study only analyzes the superiority of the air conditioning system form the perspective of annual energy consumption, but lacks of economic analysis. The initial cost of large space air handling unit system investment is small. Floor radiation (winter) + stratified air conditioning (summer) system is formed of two systems, whose initial investment and maintenance costs are higher than single system. A more objective evaluation of the life cycle cost calculation for the cooling period and heating period of each region will be studied for the further research, which can provide more reference for the air conditioning design of large space buildings.

| System                              | Heating load /PMV | Change rate of heating load | Cooling load /PMV | Change rate of cooling load | Annul energy consumption (kW·h/(m²y)) |
|-------------------------------------|-------------------|-----------------------------|-------------------|-----------------------------|--------------------------------------|
| Stratified air-conditioning system  | 152.6             | /0.374                      | 218.2             | /0.576                      | 958                                  |
| Air handling unit special for large space system | 107.5           | /0.089                      | 234.3             | /0.411                      | 7.40%                                |
| Floor radiation (winter) + stratified air-conditioning (summer) system | 70.62           | /0.539                      | 218.2             | /0.576                      | 781                                  |

4. Conclusion

The CFD method is used to study airflow and temperature distribution for different air conditioning systems in the railway station. The three systems including stratified air conditioning, air handling unit special for large space system, and floor radiation system are analyzed. Detailed conclusions are draw:

(1) In winter, for the high space of the waiting hall, the floor radiant heating effect is the best, the air handling unit special for large space system the second, and the traditional stratified air conditioning system is the worst. Compared with the traditional stratified air conditioning system, the heating load of floor radiation system and air handling unit special for large space system are reduced by 53.7% and 29.6%, respectively.

(2) In summer, the cooling load of the stratified air conditioning air supply system is the smallest, and that of air handling unit special for large space system is increased by 7.4%.

(3) The annual energy consumption of the three systems in Wuhan is calculated, the floor radiation (winter) + stratified air conditioning (summer) system has the lowest energy consumption throughout
the year. Compared with the stratified air conditioning system, the energy consumption of floor radiation (winter) + stratified air conditioning (summer) system can save energy by 18.5%.

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