A Case Study of the Thermal Environment in the Airport Terminal Building under Natural Ventilation

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Abstract

This paper studies the summer natural wind environments inside an airport terminal building under two cases by the method of computational fluid dynamics (CFD). The two cases have different opening areas for glass curtain wall. Case 1 has the opening ratio of 10% while Case 2 has 30%. The paper also uses DeST to simulate the annual natural temperature distribution under two kinds of opening ratio in a whole year. At last, the energy consumptions under two conditions—without opening for glass curtain wall all through the year and with the opening ratio of 30% when air conditioning is not run are calculated respectively. The numerical simulation results show that: when the opening ratio of the glass curtain wall is 10%, the summer indoor natural wind environment is bad. The air change rate is less than 6times/h. But when the opening ratio is increased to 30%, the summer indoor natural wind environment becomes better. The air change rate goes above 10times/h. In addition, if 10% opening area of the glass curtain wall is opened completely all through the year, there are at least 2707 hours in which air conditioning is not needed for the airport terminal building. But when 30% opening area is opened completely in a whole year, there are at least 5398 hours in which air conditioning is not needed. In a whole year, if air conditioning is run to make heat or cool when the indoor natural temperature is less than 16°C or higher than 29°C, opening 30% of the glass curtain wall at the time that air conditioning is not run can save 21% of the energy that the case without opening in a whole year consumes. Increasing natural ventilation in summer can decrease the cooling load effectively. But in winter, increasing natural ventilation may increase the heating load.

Keywords: airport; natural ventilation; CFD; DeST

1. Introduction

Glass is one of the most favorite building materials by the people from all over the world and has been popularly applied as wall material in many high-grade buildings. One of these buildings is the airport terminal building. The airport terminal buildings around the globe are often enclosed by the glass curtain wall because it provides the occupants with artistic beauty and enough daylight. In order to maintain the aesthetic feeling that glass curtain walls take us, they are often closed in a whole year, which always causes the greenhouse effect inside the building. Without natural ventilation, those airport terminal buildings have to adopt the air conditioning to adjust indoor thermal comfort everyday and a large amount of energy is consumed. However, in the recent years, with the intensification of energy crisis, especially after the attack of SARS, human beings have waked up to the advantage of natural ventilation. More and more researchers advocated for the use of natural ventilation in the buildings. But the unsolved questions are that how much natural ventilation can be used and how to adopt natural ventilation well for a special building. This work takes an actual airport terminal building as the example and investigates its natural wind environment, natural temperature distribution and air conditioning load under natural ventilation, and to estimate its natural ventilation potential for the thermal comfort of the occupants.

Today, with the availability of numerical technology, computational fluid dynamics (CFD) has been thought to be a affordable, accurate, and informative method among all the prediction methods and popularly used in the prediction to the building environment¹⁻², especially for the large space buildings. CFD technology has ever been used in the design processes of many famous stadiums, theaters and airports, to predict their indoor
or outdoor air distribution and thermal comfort\(^5\)-\(^6\). In this paper, CFD method is used to simulate the natural wind environment in the airport terminal building. In addition, energy simulation software is used to analyze the hourly natural temperature of every room inside of the terminal building and the heating/cooling load of the whole building in a whole year.

2. Problem Description

The studied airport terminal building is located in China and has the size of 1167m(x)×890m(y)×39m(z). The whole airport is shown in Fig.1. It is surrounded by some low mountains and just faces the annual prevailing wind direction SW. The local outdoor mean wind speed is 1.8m/s for summer and 2m/s for winter. As shown in Fig.2., the airport terminal building includes one Main Building, one Connective Corridor and four Branch Corridors. The Main Building has four storeys. The Connective Corridor and four branch corridors have three storeys respectively. The envelope of the whole terminal building adopts glass curtain wall. And its current opening ratio is only 10%.

3. Analysis to Wind Environment under Natural Ventilation

3.1 Numerical Method

CFD is based on the resolution of the governing equations\(^7\) which describe the flow field in the computational domain. In this work, CFD software PHOENICS is used to simulate the wind environment. In the calculation, the method of finite volume is used on a rectangular Cartesian grid. The airflows in and around the terminal building are considered as threedimensional steady-state incompressible turbulence flow. The turbulence model adopts standard \(k-\varepsilon\) model. For steady-state incompressible flow, the transport equations of airflow around and inside of the airport terminal building can be described as follow;

\[
div (\rho V \Phi - \Gamma_{\phi,eff} \cdot grad \Phi) = S_{\phi}
\]

where \(\rho\) is the air density, \(\Phi=1\) for mass continuity, \(\Phi=V_j\) for three components of momentum, \(\Phi=k\) for turbulent energy, \(\Phi=\varepsilon\) for the dissipation rate of \(k\), \(\Phi=T\) for energy transport, \(V\) is the velocity vector, \(\Gamma_{\phi,eff}\) is the effective diffusion coefficient, and \(S_{\phi}\) is the source term.

Moreover, the QUICK scheme for space discretization is used to avoid the large numerical diffusion of the widely used upwind difference scheme. The coupling between pressure and velocity is obtained using SIMPLE procedure.

The authors simulate the outdoor wind environment of the airport terminal building at first. The size of computational domain is 1800m(x)×1800m(y)×200m(z). The numerical grid includes 1,600,000 cells. The mesh dependency is examined by solving the flow field for three mesh configurations made of 300,000, 819,200, and 1,600,000 cells, respectively, and we compare the velocity profiles in several sections for the three mesh configurations. Results show that up to 3.5% difference in the maximum velocity exists between the coarser and finer mesh and less than 0.25% difference exists between the two finer meshes, which indicate that the finer mesh results in mesh-independent solutions. As the inflow boundary, the logarithmic wind profile shown in Fig.3. is applied in conjunction with a convective outflow condition. From the simulation results of above outdoor wind environment of the whole airport terminal building, the velocity and pressure distributions near to the studied building are obtained. These velocity and pressure distributions are taken as boundary conditions to simulate the indoor wind environment in the next step. The analysis to wind environment under natural ventilation is only for summer because it is the most critical season in the local city. As to the simulation of the indoor environment, because the whole building is too big and complex, the Main Building, Connective Corridor and Branch Corridor are separated to analyze. Among the four branch corridors, only the Branch Corridor

Fig.1. A View of the Airport

Fig.2. Calculation Model of the Airport Terminal Building
A in the downstream is studied as an example here, which has the geometry size of 362m(x)×342m(y)×17.5m(z). And the computational domain with the size of 412m(x)×442m(y)×60m(z) are chosen for the analysis to its indoor wind environment. Three grids were used to examine the mesh independence. At last, the numerical grid for the indoor wind environment simulation of Branch Corridor A was determined to consist of 1,229,202 cells.

3.2 Evaluation Index to Indoor Wind Environment

People can’t feel air flow if the air speed is less than 0.5m/s. But the air speed greater than 5m/s is too strong for people to endure. Therefore, in this study, the regions in which air speeds are above or equal 0.5m/s but less than or equal 5m/s are thought to be the zones with comfortable wind speed. Other regions are uncomfortable zones. The region with the air speed less than 0.5m/s is looked as stagnation zone. The ratio of the uncomfortable area to the whole occupied region area(R) is taken as an important index for evaluation to numerical results. The smaller the R is, the more area in the occupied region is comfortable for most of occupants.

In addition, air change rate (ACR) is also considered for evaluation to the numerical results. Air change rate (ACR) is calculated by the flowing equation:

\[ ACR = \frac{F}{V} \]  

Where F is the wind flux flowing into the room, V is the volume of the room. Under natural ventilation, when the air change rate (ACR) of the room is less than 10times/h, the ventilation condition inside the room is bad. When the air change rate (ACR) is between 10times/h and 20times/h, the ventilation condition inside the room is good. When the air change rate (ACR) is over 20times/h, the ventilation condition inside the room is very good.

3.3 Results of Indoor Wind Environment

When the 10% opening area of the glass curtain wall is opened completely, the natural ventilation environment of the airport terminal building under summer prevailing wind is simulated. The calculation results of the evaluation index are listed in Table 1.

From Table 1., it can be seen that the natural ventilation condition in the whole terminal building is not good when the 10% opening area of the glass curtain wall is opened completely. Except the Storey 3 of the Connective Corridor, other storeys of the Connective Corridor, all the storeys of Main Building and Branch Corridor A have the uncomfortable area ratio higher than 45%. In addition, the air change rates in all investigated regions are less than 6times/h.

### Table 1. Calculation Results of Evaluation Index

| Evaluation index | R(%) | ACR(times/h) |
|------------------|------|-------------|
| Main Building    |      |             |
| Storey 1         | 54.8 | 4.4         |
| Storey 2         | 63.3 | 4.6         |
| Storey 3         | 57.6 | 3.8         |
| Storey 4         | 46.2 | 4.7         |
| Connective Corridor |      |             |
| Storey 1         | 97.1 | 1.8         |
| Storey 2         | 71.2 | 2.4         |
| Storey 3         | 8.7  | 5.1         |
| Branch Corridor A |      |             |
| Storey 1         | 81.7 | 0.9         |
| Storey 2         | 93.1 | 0.7         |
| Storey 3         | 79.2 | 1.2         |

### Table 2. Comparison of Evaluation Index under Two Cases for Branch Corridor A

| Evaluation index | R(%) | ACR(times/h) |
|------------------|------|-------------|
| Case 1: 10% opening area for glass curtain wall | |
| Storey 1 of Branch Corridor A | 81.7 | 0.9 |
| Storey 2 of Branch Corridor A | 93.1 | 0.7 |
| Storey 3 of Branch Corridor A | 79.2 | 1.2 |
| Case 2: 30% opening area for glass curtain wall | |
| Storey 1 of Branch Corridor A | 20.1 | 10.1 |
| Storey 2 of Branch Corridor A | 13.7 | 10.7 |
| Storey 3 of Branch Corridor A | 8.8  | 11.5 |

Along the summer prevailing wind, the Main Building is in the upstream, the Connective Corridor is in the middle stream, and the Branch Corridor A is in the downstream. From the calculation results of the evaluation index in Table 1., among the three investigated regions, the natural ventilation condition in the Main Building is best. The next is Connective Corridor. The worst one is Branch Corridor A. In every storey of the Branch Corridor A, over 75% occupied region area has the uncomfortable velocity for human body. And its air change rate in each storey is only around 1times/h.

3.4 Discussion

The following work is to investigate the potentiality of natural ventilation for this airport terminal building. The current opening ratio of glass curtain wall is only 10%. In this part, the opening ratio is increased to 30%. The indoor natural ventilation environment when the opening ratio of the glass curtain wall is 30% is also simulated. Limited by space, only Branch Corridor A is discussed here. The velocity distributions at the height of 1.5m above the ground of Branch Corridor A
under two cases are demonstrated in Fig.4~Fig.5. In Figs.4. and 5., only wind speed above or equal 0.5m/s is captured. They show that the velocities at the height of 1.5m above the ground are less than 5m/s and the maximum velocity is about 3.733m/s. Hence, the blank zone in these two figures stands for the velocity discomfort area for human body (air speed<0.5m/s). The calculation results of the evaluation index under 10% opening area (Case 1) and 30% opening area (Case 2) for the glass curtain wall are shown in Table 2.

Table 2 shows that when the opening ratio of the glass curtain wall is 30%, the percentage of velocity discomfort area in the occupied region for every storey of the Branch Corridor A is less than 20%. And the air change rate is above 10times/h.

The first storey of Branch Corridor A is composed of equipment room, subway station and office rooms. The second storey mainly has the first-class waiting room.
hall, stores, and office rooms. The third storey mainly includes the common waiting hall and stores. Compared with Fig.4., Fig.5. obviously has smaller blank area. It means that after the opening ratio of glass curtain wall is increased to 30%, the velocity discomfort area in the occupied region of Branch Corridor A decreases largely. But there are still some places especially the equipment room and subway station in the first storey of Branch Corridor A in which the velocity discomfort area is still large even under 30% opening area of the glass curtain wall.

Other branch corridors, the Main Building and Connective Corridor are not discussed here. But Branch Corridor A is in the downstream of the prevailing wind. From previous analysis, when the opening ratio of the glass curtain wall is 10% the Main Building in the upstream and Connective Corridor in the middle stream have better wind environment than Branch Corridor A in the downstream. Branch Corridor B is symmetric to Branch Corridor A along the prevailing wind direction. Branch Corridors C and D are in the upstream. The indoor wind environment of Branch Corridor A is improved remarkably when the opening ratio of glass curtain wall is increased to 30%. Hence, if the opening ratio of glass curtain wall is increased to 30% from 10%, the natural wind environment inside the Main Building, Connective Corridor and other branch corridors also will be improved.

4. Analysis to Natural Temperature

4.1 Method

In this study, DeST (Designer's Simulation Toolkit), developed by Tsinghua University, is used to calculate the annual dynamic natural temperature and heating/cooling load. DeST is an energy simulation software based on state space method. Stage design and simulation are its basic features. And its stage simulation concept makes connection between building and system possible. Meanwhile, both analysis of building's thermal characteristic and simulation of system performance could be achieved by DeST, and coupling problems between building and system could be solved. Compared with other simulation software such as DOE-2, ESP-r, BLAST, TRANSYS, etc., indoor natural temperature is used to connect building and system in DeST. The natural temperature is the room temperature without HVAC. It is the natural temperature rather than load that can reflect exactly the thermal properties of the building. In the stage of building thermal property design, the natural temperature can provide the designer a quantified description of how good or bad the thermal performance of the building which he designed is. Corresponding to the first design stage, the first stage using DeST is to acquire building information and calculate the natural temperatures of all the considered rooms in the building. After that, the heating/cooling load can be easily obtained from the natural temperature in case that the temperature set points are given.

4.2 Simulation Model

Based on the geometry size of the studied airport terminal building, its simulation model is established in DeST. The whole building is divided into 14 calculation rooms according to the use function. The function of each room is introduced in Table 3. Every calculation room has one natural temperature. In the dynamic simulation of natural temperature, the main envelope parameters are taken as follows: heat-transfer coefficient of external wall: 1.0 W/(m²·K); heat-transfer coefficient of external window: 2.5 W/(m²·K); shading coefficient of external window: 0.4; heat-transfer coefficient of roof: 0.55 W/(m²·K).

From the analysis to wind environment, the air change rate of the whole airport terminal building is about 3times/h when the opening ratio of the glass curtain wall is 10% while over 10times/h when the opening ratio is 30%. In order to know the opening ratio's effect on the natural temperature, the dynamic simulation to natural temperature by DeST includes the following two cases: case 1 has 10% opening area of the glass curtain wall, but case 2 has 30% opening

| Case          | Case 1 |     | Case 2 |     |
|---------------|--------|-----|--------|-----|
| Natural Temperature(°C) |        |     |        |     |
| Outdoor       | <16    | 16-29 | >29    | 16-29 | >29 |
| Room 1—including the corridor and arriving hall in the second storey of main building | 4110  | 4646  | 4      | 4110 | 4646  | 4 |
| Room 2—including the checking hall in the first storey of main building | 0      | 6503  | 2257   | 176  | 8584  | 0 |
| Room 3—including the arriving hall and baggage hall in the first storey of main building | 13     | 8350  | 397    | 2003 | 6757  | 0 |
| Room 4—including the shopping hall in the third storey of main building | 0      | 2707  | 6053   | 92   | 8668  | 0 |
| Room 5—including the leaving hall in the fourth storey of main building | 0      | 4754  | 4066   | 197  | 8563  | 0 |
| Room 6—including the waiting hall in the fourth storey of main building | 0      | 7644  | 1116   | 1311 | 7449  | 0 |
| Room 7—including the leaving hall in the south of connective corridor | 280    | 6601  | 1879   | 2930 | 5806  | 24 |
| Room 8—including the leaving hall in the west of connective corridor | 247    | 6632  | 1881   | 2915 | 5823  | 22 |
| Room 9—including the subway station in the first storey of branch corridor | 0      | 6138  | 2622   | 2862 | 5896  | 2 |
| Room 10—including the waiting hall in the south of connective corridor | 151    | 6132  | 2477   | 2981 | 5756  | 23 |
| Room 11—including the waiting hall in the west of connective corridor | 120    | 6167  | 2473   | 2936 | 5815  | 9 |
| Room 12—including the waiting hall in the third storey of branch corridor | 74     | 5705  | 2981   | 2890 | 5844  | 26 |
| Room 13—including the waiting hall in the third storey of branch corridor | 64     | 5988  | 2708   | 2879 | 5689  | 13 |
| Room 14—including the first-class waiting hall of branch corridor | 174    | 6541  | 2045   | 3359 | 5398  | 3 |
| Average of 14 rooms | 80     | 6098  | 2582   | 1973 | 6776  | 12 |
Table 4. Comparison of Heating/Cooling Loads under Two Cases

| Item                                      | Unit    | Case A | Case B |
|-------------------------------------------|---------|--------|--------|
| Maximum heating load in a whole year      | W/m²    | 37.4   | 38.2   |
| Maximum cooling load in a whole year      | W/m²    | 96.37  | 95.96  |
| Sum of heating load in a whole year       | kW-h/m² | 10.24  | 13.67  |
| Sum of cooling load in a whole year       | kW-h/m² | 173.75 | 132.34 |
| Sum of heating/cooling load in a whole year | kW-h/m² | 183.99 | 146.01 |

area. The opening areas of the glass curtain wall in two cases are opened completely in a whole year and air conditioning is not run.

4.3 Results

For the commercial building in China, the upper temperature limit for running air conditioning to make heat is 29°C, the low temperature limit for running air conditioning to make cool is 16°C. Only when the indoor natural temperature is higher than 29°C or lower than 16°C, the air conditioning will be run. After calculating the annual dynamic natural temperature under two cases by using DeST, for the 8760 hours in one typical meteorological year, the hour of natural temperature falling in different temperature ranges is counted, which is shown in Table 3. The hours that indoor natural temperature falling between 16°C and 29°C are the hours in which air conditioning is not needed to be opened.

From Table 3, it can be found that after the opening ratio of the glass curtain is increased from 10%(Case 1) to 30%(Case 2), the hour of natural temperature less than 16°C increases largely, and the hour of natural temperature above 29°C decreases largely. Moreover, the hour of natural temperature in the range of 16°C~29°C in Room 1, Room 3, Room 4, Room 5 and Room 12 increases obviously, but the hour of natural temperature in the range of 16°C~29°C in other rooms decreases. It is mainly because that the hour of natural temperature less than 16°C increases largely for these rooms.

In all, the hour of natural temperature falling in the range of 16°C~29°C for the whole airport terminal building increases when the opening ratio of the glass curtain wall is increased from 10% to 30%. For Case 1, in one year there are at least 2707 hours in which air conditioning is not needed for every calculation room. But for Case 2, in a whole year there are at least 5398 hours in which air conditioning is not needed for the 14 calculation rooms. In this calculation, the opening areas of the glass curtain wall in two cases are opened completely in a whole year. Compared with Case 1, the hour of natural temperature less than 16°C increases largely in Case 2. It shows that 30% opening area of the glass curtain wall is too big in some days such as winter day. Hence, the opening ratio of glass curtain wall should be adjusted according to indoor natural temperature, outdoor temperature, and the thermal comfort requirements of the occupants inside the building. In the hot days, the opening area of the glass curtain wall should be opened completely. But in the moderate days, only part of openings should be opened.

5. Analysis to Heating/Cooling Load

5.1 Method and Simulation Model

This part is to analyze the heating/cooling load of the airport terminal building when the glass curtain wall adopts 30% opening ratio. DeST is used to simulate the annual dynamic load. The simulation model is the same as the model for natural temperature analysis. But the calculation case is different from the cases used in the analysis to natural temperature. The calculation cases in this part are introduced as follows: Case A never opens the glass curtain wall and does not use natural ventilation in the whole year. When the indoor natural temperature is less than 16°C, the air conditioning will be run to make heat, and the heating control temperature is 18°C. When the indoor natural temperature is higher than 29°C, the air conditioning will be run to make cool, the cooling control temperature is 26°C. Case B adopts 30% opening ratio for the glass curtain wall and uses the changeable natural ventilation. The same as Case A, when the indoor natural temperature is less than 16°C, the air conditioning will be run to make heat, the heating control temperature is 18°C. When the indoor natural temperature is higher than 29°C, the air conditioning will be run to make cool, the cooling control temperature is 26°C. Case B has the smaller maximum cooling load and sum of heating/cooling load in a whole year than Case A. However, Case B has the smaller maximum cooling load and total cooling load in a year than Case A. And the total heating/cooling load in a whole year of Case B is less than Case A. Compared with Case A, 21% energy is saved in Case B. These results show that adopting natural ventilation in summer is helpful to decrease cooling load of the building. But excessive natural ventilation may cause the increase of heating load in winter. Hence, the opening ratio of the glass curtain wall should be adjusted according to indoor natural temperature, outdoor temperature, and the thermal comfort requirements of the occupants inside the building.

5.2 Results

The maximum heating/cooling load and sum of heating/cooling load in a whole year for the whole airport terminal building are used as the evaluation index. Their results under above two cases are displayed in Table 4. The smaller these evaluation index are, the more energy-efficient the design scheme is.

Table 4. shows that Case B has the bigger maximum heating load and total heating load in a whole year than Case A. However, Case B has the smaller maximum cooling load and total cooling load in a year than Case A. And the total heating/cooling load in a whole year for Case B is less than Case A. Compared with Case A, 21% energy is saved in Case B. These results show that adopting natural ventilation in summer is helpful to decrease cooling load of the building. But excessive natural ventilation may cause the increase of heating load in winter. Hence, the opening ratio of the glass curtain wall should be adjusted according to indoor natural temperature, outdoor temperature, and the thermal comfort requirements of the occupants inside the building.

In the hot days, the opening area of the
glass curtain wall should be opened completely. But in the moderate days, only part of the openings should be opened. The following methods can be adopted:

1. When the indoor natural temperature is higher than the upper temperature limit for running air conditioning and higher than outdoor temperature, the opening area of the glass curtain wall should be opened completely. After that, if the indoor natural temperature is still higher than the upper temperature limit for running air conditioning, the air conditioning should be run to make heat.

2. When the indoor natural temperature is below the low temperature limit for running air conditioning and lower than outdoor temperature, the air conditioning should be run to make cool.

3. When the indoor natural temperature is higher than the upper temperature limit for running air conditioning and lower than outdoor temperature, the glass curtain wall should be closed. Air conditioning should be run to make cool.

4. When the indoor natural temperature is lower than the upper temperature limit for running air conditioning and higher than outdoor temperature, the glass curtain wall should be adjusted according to indoor natural temperature, outdoor temperature, and requirement for thermal comfort of the occupants inside the airport terminal building.

5. When the indoor natural temperature is lower than the upper temperature limit for running air conditioning and lower than outdoor temperature, the glass curtain wall should be closed. Air conditioning should be run to make heat.

6. Increasing natural ventilation in summer can decrease the cooling load effectively. But in winter, increasing natural ventilation may increase the heating load.

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