Research on the performance of sidewall perforated plate air supply system that suitable for prefabricated buildings

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Abstract. Taking the rural prefabricated residential building as research object, prefabricated sidewall partitioned perforated plate air supply model and traditional jet air supply model were established respectively. Then, CFD commercial software was used to simulate the temperature field, velocity field, formaldehyde concentration of indoor air-flow distribution of the two air supply model that mentioned above. Simulation results show that in the indoor breathing zone, the valuation index of prefabricated sidewall partitioned perforated plate air supply system, such as the velocity non-uniformity coefficient, air diffusion performance index, ventilation efficiency are entirely superior to the traditional jet air supply system. Moreover, the maximum vertical temperature gradient and maximum horizontal temperature gradient of the prefabricated sidewall partition perforated plate air supply system were also small which means the new air supply system could satisfy the indoor air quality and human thermal comfort requirements.

1. Introduction
Prefabricated building technology originated in Europe, at the beginning of 17th century, developed countries such as England and Germany began to explore the road to industrialization of buildings. In the long-term engineering construction, they accumulated considerable experience in design and construction of prefabricated buildings. Prefabricated building have numerous advantages such as short construction period, small impact on the surrounding environment, and high recovery rate of building materials [1], so they are widely used in rural residential buildings[2]. And research results show that the life cycle energy consumption of prefabricated buildings ranges from 7.33 GJ/m³ to 13.34 GJ/m³, and the building energy consumption can be reduced by 16% to 24% in the recycling process [3]. With the development of prefabricated building technology, researches focused on prefabricated building become popular. Yi.So-Mi et al [4] integrated solar cell modules with the prefabricated building roof which could fully utilize the role of prefabricated roofing components, and greatly reduce labor force and material costs. Zalewski et al [5] adopted a method combined experimental research with numerical simulation to quantitatively evaluate the heat loss of the thermal
bridge of the light-weight prefabricated building wall, and introduced an infrared thermal imaging method for visualizing the thermal bridge and a complementary experimental method which can effectively determine the heat loss through the exterior wall of prefabricated buildings. Isopescu et al [6] found that the structural housing structure has good load carrying capacity and heat insulation effect through thermal analysis of GF+1F high-structured light steel prefabricated residential buildings. It also considers the occupant’s thermal comfort and controls the indoor humidity to reduce the risk of condensation. Dubravka Matic et al [8] evaluated the integrated design approach used in low-rise prefabricated residential building renovations. After intensive environmental analysis, a series of energy efficiency improvements were implemented to integrate building envelopes, natural and mixed ventilation, and energy delivery optimize to reduce building energy load, reduce CO₂ emissions, and improve indoor environment.

However, current researches on prefabricated residential buildings most focus on analysing its building energy consumption over the life cycle, and there few studies involving air-conditioning systems and the indoor air-flow distribution for prefabricated buildings. In addition, the traditional household wall-mounted air conditioner and central air conditioner can’t meet the indoor personnel's requirements for indoor air quality and thermal comfort [8]. Therefore, new research which integrates air supply system into prefabricated buildings should be carried out to improve the quality of the indoor environment while taking advantage of the prefabrication function of prefabricated buildings.

2. Prefabricated sidewall partitioned perforated plate air supply

2.1 System composition

Based on the current researches of prefabricated building, this article put forward a sidewall partition perforated plate air supply system which integrates HVAC equipment into prefabricated building. The air supply system mainly consists of three parts: air supply devices, return air devices and air treatment devices. Air supply devices mainly include fan, blower box, air supply duct, air valve, static pressure chamber and sidewall perforated plate. Return air grille, return air duct located under the floor and return air filter device make up of return air devices. While air treatment devices mainly consist of chiller, evaporator, chilled water pump and so on. All air supply system devices are in the interior of ventilated sidewall, as well as air treatment devices except chiller. Return air grille is located on the sidewall opposite the ventilated sidewall, and return air duct is primarily under the floor to connect the air return griller and filter. And the return air filter is also in the interior of ventilated sidewall.

2.2 Principle of the air supply system

The prefabricated sidewall perforated plate air supply system vertically partitions the ventilated sidewall, and each partition is separately equipped with a static pressure chamber. The blower box would send the treated cold air to the different static pressure chamber through the air supply ducts. Then, the cold air will send into the room through the sidewall perforated plate. Finally, the cold air which has heat and moisture exchanged with indoor air will be sent out the room through the return air grill located on the sidewall that opposite the ventilated sidewall. The return air duct is pre-buried in the floor layer and directly connected to the return air griller. The return air is returned to the ventilated sidewall through the return air duct and mixed with the outdoor fresh air. The mixed air will be sent into the evaporator for cooling, and then sent into the blower box by the fan once again to
accomplish a complete air supply circulation. Through the air supply circulation cycle, the purpose of improving indoor air quality and human thermal comfort could be achieved.

![Diagram of prefabricated sidewall partitioned perforated air supply system](image)

a, c, d-air supply perforated plate, b-air supply duct, f-interior wall, g-return air duct, h-floor, i-return air griller, j- blower box, k-fan, l-exterior wall, m-evaporator, n- filter , o- chiller, p-chilled water pump

**Figure 1.** Schematic diagram of prefabricated sidewall partitioned perforated air supply system

2.3 Indoor air-flow distribution

In air-conditioned room, effective ventilation and reasonable air-flow distribution are important for improving indoor air quality, controlling air pollutant levels, and improving personnel thermal comfort [9]. This is because air-flow distribution, as an important part of air conditioning, determines whether the air temperature, velocity and pollutant distribution satisfy the living and production requirements of indoor occupants. The methods studying indoor air-flow distribution usually include jet formula, regional model, model test and CFD method. Among of them, CFD method is most widely used owing to the low cost, short cycle and obvious visualization [10]. Therefore, in the present study, the air-flow distribution of a sidewall partition perforated plate air supply system of a prefabricated residential building is simulated by CFD. Then, the results are compared with the traditional jet air supply system, so as to analyse the advantages and disadvantages about the indoor air distribution of the proposed system, providing theoretical guidance for the practical engineering application.

3. Physical and mathematical model

3.1 Physical model and basic assumption

This paper takes living room of a rural prefabricated residential building in Hunan Province for example, and establishing simplified model of the prefabricated sidewall partition perforated plate air supply system and the traditional jet air supply system respectively. The prefabricated sidewall
partitioned perforated plate air supply system divides the ventilation sidewall into six identical parts, and the cold air is sent into the static pressure chamber from the internal inlet of the sidewall, and then sent into the room through the perforated plate. While the traditional jet air supply system directly sends the cold air to the living room. The parameters of above two models are consistent except the form and location of the air supply inlet. The heat source consists of indoor occupants, television and fluorescent lamps. Dining table and desk are indoor pollution sources, and the pollutant is formaldehyde. For grid partition and simulation calculations, both the heat and the pollution sources should be simplified and replaced by cuboid. Figure 2 and figure 3 show the arrangement of air outlet, heat sources, pollution sources, etc. in room, and their number and dimensions are shown in Table 1.

Figure 2. Sidewall perforated plate air supply system Figure 3. Traditional jet air supply system

Meanwhile, in order to simplify the problem and the numerical simulation process, the following assumptions are made on the actual indoor airflow on the premise of ensuring the reliability of the simulation results:

1. The flow of indoor airflow is a viscous incompressible flow under normal temperature and pressure, and its motion law follows the Navier-Stokes equation. Only considering the influence of density change on buoyancy, and the model satisfies the Boussinesq hypothesis; 
2. Indoor air is steady-state turbulent flow, and does not consider the heat dissipation caused by viscous work; 
3. Does not consider solar radiation and radiation between indoor heat sources 
4. The building envelope structure is airtight and doesn’t consider the effects of air leakage and seepage; 
5. The wall and the ground are both adiabatic walls, regardless of the influence of heat transfer in the surrounding room; at the indoor air inlet, the air jet parameters are uniform; 
6. The release intensity of formaldehyde is constant and doesn’t change with time.

3.2 Mathematical model

The core of simulating indoor airflow distribution using computational fluid dynamics is to solve the indoor turbulent flow control equation. The governing equations involved in indoor air heat and moisture transfer and mass transfer mainly include mass conservation equation, momentum conservation equation, energy conservation equation and component mass conservation equation. The general form of the above governing equation is:

\[ \nabla \cdot \rho \mathbf{u} = 0 \]  \[ \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla P + \nabla \cdot \left( \mu \nabla \mathbf{u} \right) + \mathbf{f} \]  \[ \rho c_p \nabla T = \nabla \cdot \left( \kappa \nabla T \right) + S_e \]  \[ \rho \sum \frac{\partial C_i}{\partial t} = \nabla \cdot \left( D_i \nabla C_i \right) + S_i \]
Under steady state flow, this general form can be simplified to:

$$f'$$

(2)

Where, $\delta$ is the air density; $u$ is the velocity vector, $\phi$ is a general variable, which can represent the solution variable such as velocity, viscosity coefficient, temperature and so on; $f'_\phi$ is the diffusion coefficient corresponding to $\phi$; $S_\phi$ is the source term.

### 3.3 Boundary conditions

The initial indoor temperature is set to 32°C, the supply air temperature is 20°C, and the initial formaldehyde concentration in the room is zero [11]. Air supply inlets of the two models are both velocity inlet boundary conditions, and the return air grills are both outflow boundary conditions. Walls and roof set as thermal insulation boundary condition, and window set as temperature boundary condition. Occupants, television and energy-saving fluorescent lamps which are indoor heat source set as heat flux boundary conditions. Dining table and desk which are the indoor pollution source set as mass flow inlet boundary condition. The boundary condition of the sidewall perforated plate is the porous-jump boundary type, which is a one-dimensional simplification of the multi-well plate, can effectively reduce the calculation workload under the premise of ensuring the accuracy of prediction [12]. The specific values of the numerical simulation boundary conditions are shown in Table 1.

#### Table 1. Model size and numerical simulation boundary conditions.

| Name                      | Number | Size (m)       | Boundary conditions    | Reference value      |
|---------------------------|--------|----------------|------------------------|----------------------|
| room                      | 1      | $5 \times 4 \times 3$ | Thermal insulation     |                      |
| door                      | 1      | $2 \times 1.2 \times 0.25$ | Thermal insulation     |                      |
| Static pressure chamber   | 6      | $4 \times 0.5 \times 0.3$ | Thermal insulation     |                      |
| Return air grille         | 1      | $4 \times 0.3$       | Outflow                |                      |
| Window                    | 1      | $1.2 \times 1.2 \times 0.25$ | Temperature           | 32°C                 |
| Dining table              | 1      | $2 \times 1 \times 0.8$     | Mass flow inlet       | 7.2e-11 Kg/s         |
| Desk                      | 1      | $1.5 \times 0.8 \times 0.4$ | Mass flow inlet       | 7.2e-11 kg/s         |
| Occupant                  | 2      | $0.4 \times 0.3 \times 1.75$ | Heat flux             | 64 W/m²              |
| Television                | 1      | $0.9 \times 0.5 \times 0.1$ | Heat flux             | 200 W/m²             |
| Fluorescent lamp          | 2      | $0.1 \times 0.1 \times 0.1$ | Heat flux             | 40 W/m²              |
| Perforated plate          | 6      | $4 \times 3 \times 0.02$   | Porous-jump           | 2.06e-10/6.3e+5      |
| Air supply inlet[1]       | 6      | $4 \times 0.5$          | Velocity inlet        | 0.15 m/s             |
| Air supply inlet[2]       | 1      | $0.5 \times 0.6$        | Velocity inlet        | 3 m/s                |

Note: 1 is the air supply inlet of the prefabricated sidewall perforated plate air supply system, and 2 is the air supply inlet of the traditional jet air supply system.

### 4. Numerical simulation results analysis

In the room, occupants are usually sitting, and the plane of the breathing zone is about 1.2 m. Therefore, the Z=1.2 plane is intercepted, and the sidewall partition air supply system of the prefabricated building (for convenience, the following is referred to as system one) and the traditional jet air supply system (for convenience, the following is referred to as system two) temperature cloud map, velocity cloud map, and formaldehyde (CH₂O) mass fraction cloud map were analysed and compared.
4.1 Velocity cloud map of plane \( Z=1.2 \)

From the velocity cloud map, it can be seen that the velocity of the system 1 in the \( Z=1.2 \) plane is kept below 0.3 m/s, which satisfies the requirements of the indoor air supply velocity in summer. And the velocity distribution in the plane is uniform, except for the eddy current in a small area near the heat source such as the human body, the air velocity is relatively large, and the air velocity in other areas is basically not changed much, and the air velocity fluctuation is small. However, the velocity distribution of the system two is obviously uneven. A large eddy current appears at the sidewall facing the air supply inlet, and the air velocity even reaches 1 m/s, which obviously can’t meet the indoor air supply demand in summer. In addition, there is a large area in the room where the air velocity is close to zero, which means the cold air doesn’t reach this area, forming a dead angle of ventilation, which will inevitably have an adverse effect on indoor temperature distribution and the removal of CH\(_2\)O.

4.2 Temperature cloud map of plane \( Z=1.2 \)

Since the indoor design temperature is 25°C, according to this standard, comparing the temperature distribution of the two systems, it can be found that the system one could keep the indoor temperature below 25°C under the same air supply volume and temperature. And the temperature distribution in the room is uniform, no obvious temperature fluctuations occur. The indoor temperature is almost the
same as the supply air temperature within a certain distance from the air supply sidewall. This is because the heat sources are far away from the air supply sidewall, so that the temperature change in this area is not evident. While the temperature distribution of the system two is also obviously not uniform, the temperature away from the inlet is much higher than that below the inlet, and the maximum temperature even reaches 31°C. This is because the air supply system has a dead angle of air supply, and the cold air can’t reach some areas, so that there is a large difference in the indoor temperature distribution, which eventually leads to the phenomenon of uneven heat and cold emerge.

4.3 CH₂O mass fraction cloud map of plane Z=1.2

The distribution of indoor pollutants is an important index to measure indoor air quality. This paper selects indoor typical pollutant formaldehyde as the research object, and judges the indoor air quality of the two systems according to the distribution of CH₂O mass fraction. From the cloud map distribution, it can be found that the CH₂O mass fraction of system one is significantly lower than that of system two except for the area close to the pollution source, which means that the system one has a stronger ability to remove indoor pollutants and the air quality is much better. Moreover, the CH₂O mass fraction of system one near the ventilated sidewall is close to zero, indicating that it is more suitable for indoor personnel activities near this area.

4.4 Evaluation index

To evaluate the indoor air-flow distribution more intuitively, the evaluation indexes such as the velocity non-uniformity coefficient, the air diffusion performance index, the ventilation efficiency, the maximum vertical temperature gradient and the maximum horizontal temperature gradient are selected based on the uniformity of the air-flow field, the indoor thermal comfort and the indoor air quality, and then analysing the advantages and disadvantages of the two air supply systems based on the evaluation results.

According to the simulation results, each evaluation index is calculated as shown in Table 2.

| Evaluation index | Air supply system |
|------------------|------------------|
|                  | Sidewall perforated | jet |

Table 2. The value of the evaluation index of the two air supply systems.
According to the values in the table, the sidewall partitioned perforated air supply system and the traditional jet air supply system can be analyzed and compared more intuitively. From the comparison of the average velocity and velocity non-uniformity coefficient, it can be seen that the average surface velocity of the sidewall partitioned perforated air supply system is 0.132 m/s, and the air velocity is small, which can overall meet the indoor air supply demand, and the velocity non-uniformity coefficient is only 0.122, the speed change is small, and the air-flow distribution uniformity is good. While the conventional jet air supply system not only has a higher average surface temperature, but also has a speed non-uniformity coefficient which is up to 0.537, a large range of velocity fluctuations, and poor air-flow distribution. From the perspective of air distribution characteristics, the sidewall partition perforated plate air supply system can ensure that more than 70% of the indoor area is within the comfortable range of the human body, while the traditional jet air supply system is less than 30%, and the overall thermal comfort of the room is poor. In terms of ventilation efficiency, the sidewall partitioning perforated plate air supply system is also significantly superior to the conventional jet air supply system, which means that the former has a stronger ability to remove indoor pollutants, and the indoor air quality is better.

### 5. Conclusion

This paper proposes a fabricated sidewall partition perforated plate air supply system, which integrates HVAC equipment into the sidewall and floor of the prefabricated building, and takes advantage of the prefabricated function of prefabricated buildings. In addition to guarantee the performance of the air supply system, it also saves installation time and improves efficiency. Furthermore, through the numerical simulation calculation and comparative analysis of the air-flow distribution of the prefabricated sidewall partition perforated plate air supply system and the traditional jet air supply system, the following conclusions can be drawn:

1) The overall air velocity of the prefabricated sidewall partition perforated air supply system is below 0.3 m/s, which can meet the demand of indoor air supply in summer, and the velocity non-uniformity coefficient is only 0.122, which is obviously superior to the traditional jet air supply system. The indoor air-flow distribution is much better.

2) The air diffusion performance index of the prefabricated sidewall partition perforated plate air supply system is 71.2%, which means the air supply system can ensure the most indoor area is in the thermal comfort state of the human body, and in the area close to the ventilation sidewall, the air velocity, temperature and air cleanliness is better than other areas, more suitable for indoor activities.

3) The ventilation efficiency of the prefabricated sidewall partition perforated plate air supply system is above 1 and much higher than that of the traditional jet air supply system, which indicates that the
prefabricated sidewall partition perforated plate air supply system has strong ability to remove indoor pollutants and can guarantee good indoor air quality.

4) The maximum vertical temperature gradient and the maximum horizontal temperature gradient of the prefabricated sidewall partitioned perforated plate air supply system are small, and indoor occupants will not feel obvious temperature fluctuation.

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