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Effect on Thermal Comfort and Energy Consumption of Different Installation Height and Supply Air Angle of Room Air Conditioner by Simulation

Zixu Yang **Baolong Wang, PhD** **Wenxing Shi, PhD** **Xianting Li, PhD**

ABSTRACT

Improving actual operation performance of room air conditioners (RAC) shows great importance in the indoor environment and building energy conversation. The installation height and supply air angle of the indoor unit of RAC directly affect thermal comfort and energy performance in heating conditions. In this paper, a combined simulation of building, indoor air distribution, and performance of RAC is proposed to investigate the influence of installation height and supply air angle. The combined simulation model was validated by experiment results. Based on the simulation model, a living room in Shanghai was analyzed. The results indicated that the indoor temperature and the heat transfer coefficient of the external wall vary from different installation heights and supply air angles. When the RAC was installed at a relatively low height, the return air temperature was significantly lower than that in higher height, and the thermal environment was more comfortable. Moreover, the heating capacity of RAC was increased by about 12.2%, and the energy efficiency ratio was increased by approximately 3.5% at the lower height position. The results highlight the issues of installation height and supply air angle, in order to improve indoor thermal comfort and optimize the actual performance of RACs.

1 BACKGROUND

With the rapid development of modern society and the improvement of people's living standards, room air conditioners (RACs) have become necessary household electrical appliances. According to the data of the National Bureau of Statistics, there are 360 million RAC for households in China (National Bureau of Statistics of China, 2018). RACs are widely used as heating equipment for residential buildings without domestic heating systems, and the occupants concerned about thermal comfort and energy performance in actual operation.

To analyze and calculate thermal comfort and energy performance of RAC, the simulation software and related numerical calculation methods are developed. The building energy simulation (BES) obtain the heating/ cooling load by related numerical software, with the boundary conditions including the settings of inner heat source, occupant's behavior. The normal BES software includes DOE-2 (M. Carriere, 1999), Energyplus (USA Department of Energy EnergyPlus, 2012), DeST (Yan, 2004), and TRNSYS (TRNSYS, 2015). In the simulation, it is considered that the return air temperature is equal to the indoor temperature when it calculates the energy consumption of the air conditioning system based on the assumption that the indoor air is uniformly mixed and regarded as a single-node model. Moreover, the computational fluid dynamics (CFD) cannot calculate the accurate air distribution as the boundary conditions are not clear.

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The installation height and supply air angle of RAC affect thermal comfort and energy performance directly. At first, the air distribution is significantly influenced by different installation heights and supply air angles due to the buoyancy during the heating period, which directly affects thermal comfort. Besides, it also affects the wall convective heat transfer coefficient. Furthermore, the uneven temperature distribution affects the thermodynamic performance of the RACs by influencing the inlet air temperature of the indoor unit.

In recent research, the combined simulation of BES and CFD mainly applied to optimize the location of the supply air of central air conditioning system in large space buildings (Zhai, Z. and Chen, Q 2004; Chen Q. 2007; Haves P. 2014). The efficient approaches, sensitivity analysis, and solution characters were introduced and studied to improve the accuracy of the calculation.

Therefore, this study focuses on the thermal comfort and energy performance under different RAC installation heights and supply air angles by combined simulation, which integrated with the energy performance of RAC simultaneously. In this paper, a combined simulation of BES-CFD and energy performance of RAC is proposed firstly. Then, the methodology is analyzed, and experimental validation is presented. Based on the experiment validation results, the model present adaptability and feasibility. Furthermore, the effect on the thermal environment and energy performance under different installation heights and supply air angles are illustrated through a practical example in Shanghai.

2 METHODOLOGY

2.1 Principle

The quasi-dynamic coupling method is applied for the proposed combined method (Zhai 2012). As for the two parallel coupled computing modules, i.e. *module A* and *module B,* the outputs of *module A* are turned into the inputs of *module B* at the current time, and then the outputs of *module B* at the current time are taken as the input of *module A* in the next step. In this case, the BES model (as *module A*) calculates the wall temperature as the boundary condition to the CFD model (as *module B*). Meanwhile, CFD simulates the return air temperature and wall heat transfer coefficient, which used to obtain the performance of RAC (as *module C*) and calculation of BES in next step. Moreover, the computed heating capacity and supply air temperature are utilized for BES and CFD, respectively. The accuracy of the quasi-dynamic coupling method is inferior to the full dynamic coupling method. Thus, due to the minor calculation, fast convergence rate and stable computation, it is widely used in the field of engineering.

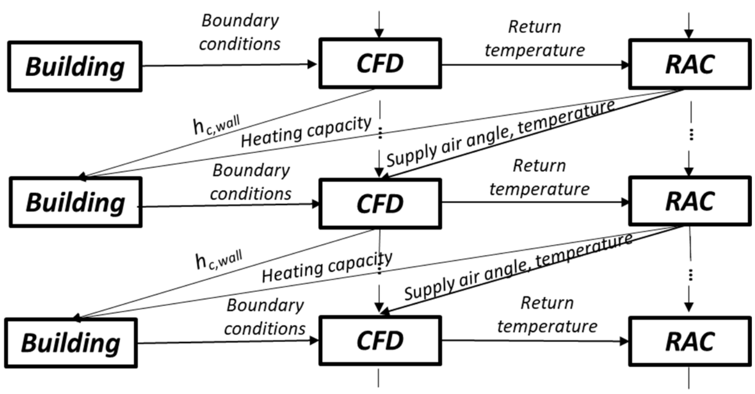


Figure 1. Combined simulation model of building, indoor air distribution and air conditioner

Figure 1 illustrated the calculation steps of the combined simulation model. As for the BES model, the one-dimensional heat transfer equations are applied to analyze the heat transfer progress. Furthermore, the indoor temperature and wall surface temperature are obtained in Matlab by the finite difference method. For the CFD model, the following assumptions are considered: 1) the indoor air is incompressible and conforms to the Boussinesq hypothesis; 2) the instantaneous flow is a steady flow. The parameters of jet flow at the air diffuser are uniform, and the properties are constant; 3) when the RAC operates, the doors and windows are closed, which indicates the influence of air leakage is not considered. For the energy performance model of RAC, it is the curve fitted by the maximum air volume and the highest supply air temperature based on the results in a psychometric calorimeter.

2.2 Settings of simulation

This paper calculated and analyzed the thermal comfort and energy performance of RAC on the typical day of a living room in Shanghai. Three kinds of air supply modes are used to analyze the influence of different air supply angles and installation locations. The air supply modes are shown in Figure 2. The angle of supply air maintains 35 ° downward in Case 1 and Case 3 in the higher installation height and lower installation height, and vertical downward in Case 2 in the higher installation height, respectively. The return air located relative to RAC has been marked. Meanwhile, the air supply flow maintains at 300m^3 / h in all cases. The operation time of RAC is 9:00 ~ 18:00. And the outdoor temperature variation is shown in Figure 3.

For the BES model, the size of the calculated room is 4.8m × 3.6m × 2.65m, of which three sides are external walls (North wall, east wall, roof), and three sides are internal walls (South wall, west wall, floor). For the CFD model, the k-ε turbulence model is used to simulate the thermal environment. As for the calculation of the RAC model, the experimental empirical model of KFR-35GW/Q2L was applied. The empirical model recognized that the heating capacity and energy efficiency are multi-variable correlation with the outdoor temperature and indoor return temperature, which were test under free frequency conditions in a standard psychometric calorimeter with the highest set temperature (Liu, 2006; Zhang, 2014). The assumptions in the simulation progress as follows: (1) the initial thermal parameters are consistent. (2) The RAC continuously operates with the settings of the highest temperature, and the unit adjusted its heating capacity according to the return air temperature.

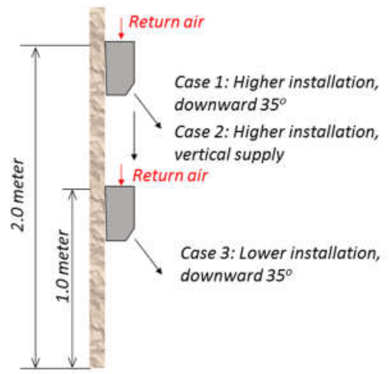


Figure 2. Different supply air mode

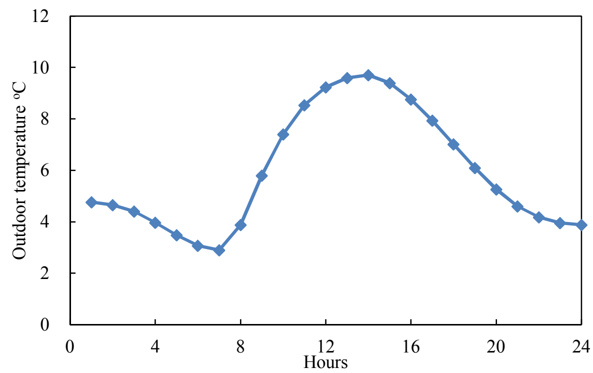
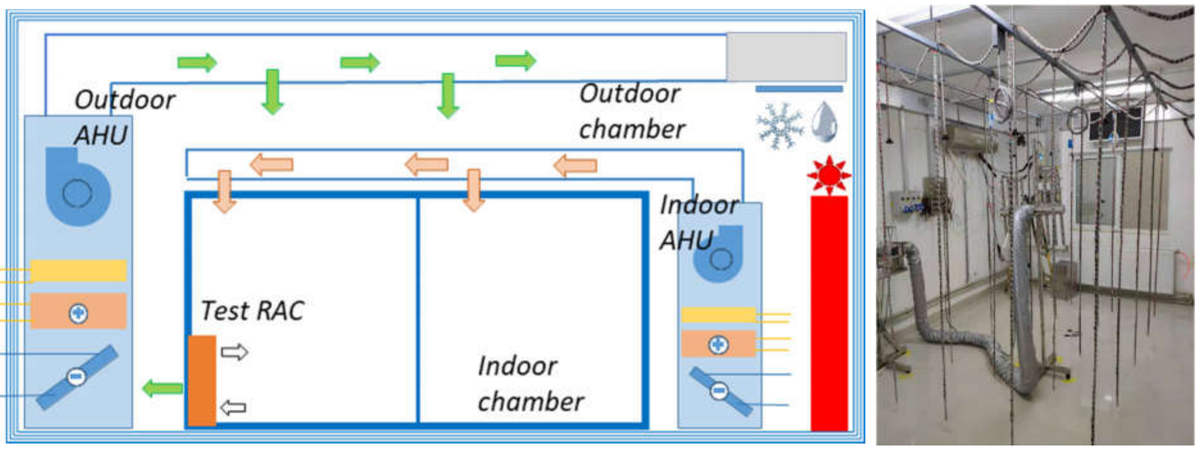


Figure 3. Typical outdoor temperature (Energy plus Weather Data, 2020)

2.3 Experimental validation

Before the combined simulation under different installation heights and supply air angles, the accuracy and feasibility of the proposed model should be verified. Therefore, to validate the feasibility of the purposed method, an experiment that measured thermal environment and energy consumption of RAC simultaneously is carried out in the RAC thermal comfort laboratory, which illustrated in Figure 4 (a). The dimensions of the indoor chamber are consistent with the simulation model in Section 2.2. 250 temperature measuring sensors (K type thermocouple thermometer) of 10 × 5× 5 were arranged to obtain accurate indoor temperature distribution, as shown in Figure

4 (b). The measured indoor temperature is the average value of all test points. The RAC thermal comfort laboratory consists of an indoor chamber and an outdoor chamber to simulate a real residential room, which maintains a steady thermal environment by chillers and air handle units. When the test RAC operated, the indoor air handle unit stop and the test RAC control the indoor environment of the chamber.



(a) Basic schematic of laboratory (b) Indoor chamber and temperature sensors installation

Figure 4. The basic construction of the laboratory

Figure 5 demonstrates the indoor temperature based on the laboratory test, single BES simulation and combined simulation. The input heating capacity is obtained by the field measurement equipment (Huang, 2017). It can be seen that the convective heat transfer coefficient has been significantly modified compared with the results of constant thermal properties in the single BES simulation, and the indoor temperature has been calculated more accurately. When utilized the combined method, the indoor temperature finally reached around 25 °C, which was close to that of the experiment. Compared with the results of the experiments, the combined model proves to be correct and effective.

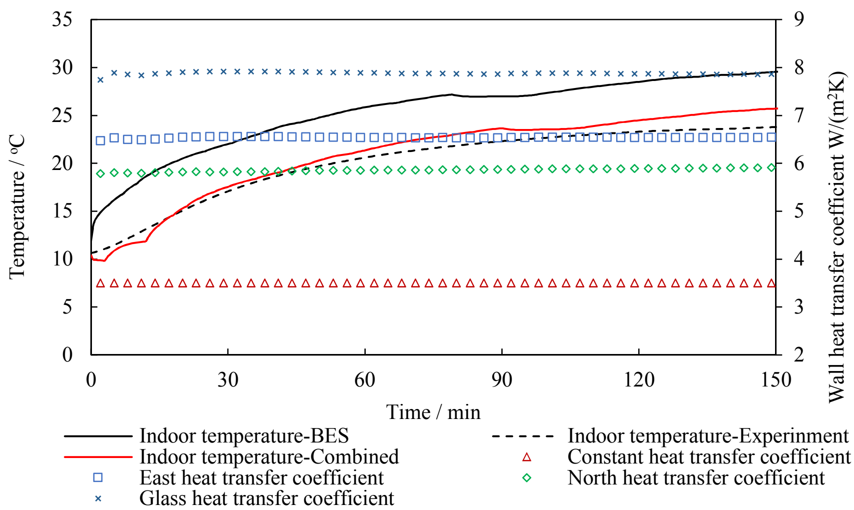


Figure 5. Indoor temperature based on the field test, BES simulation and combined simulation

3 RESULTS AND ANALYSIS

3.1 Thermal comfort and indoor environment

3.1.1 Overall thermal environment

Figure 6 and Figure 7 indicate the variation of wall convection heat transfer coefficient and supply/return air temperature of RAC under different supply air angles and installation heights, respectively, which are obtained from the CFD model and RAC performance model. It can be seen that the convective heat transfer coefficients are different. In a typical day, the wall convective heat transfer coefficient fluctuates over time and varies with varying locations of installation and air supply angles simultaneously. In this study, the overall wall convective heat transfer coefficient in Case 2 is slightly larger than that in Case 1, while Case 3 shown the highest coefficient in the simulation.

Different supply angles and installation positions also affect the return air, which leads to the different heating capacities of RACs concurrently. It can be seen that the return air temperature in Case 1 is slightly lower than that in Case 2, and the supply air temperature in both cases is basically identical. Nevertheless, the return air temperature in Case 3 is about 5 ℃ lower than that in Case 1. The main reason is that the heating capacity significantly large result from RAC considered that indoor temperature is far from the set value.

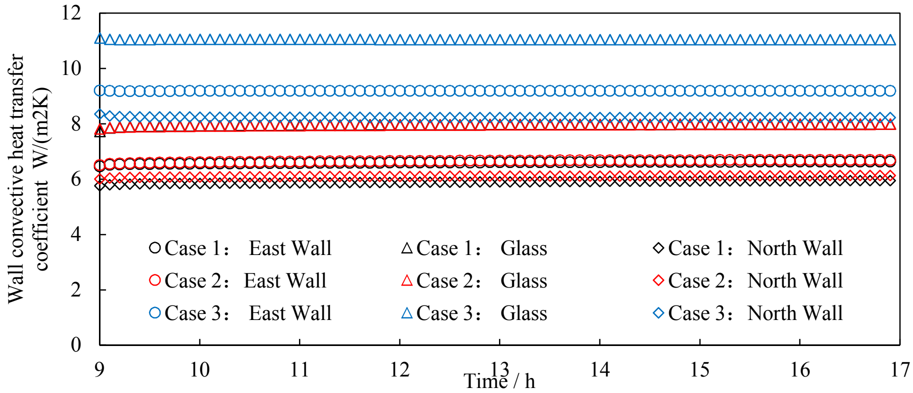


Figure 6. The convective heat transfer coefficient in the case study

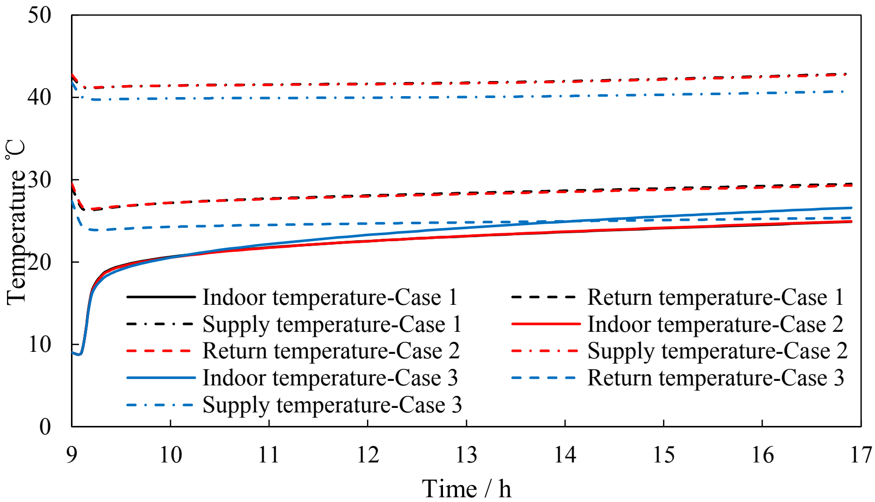


Figure 7. The indoor, supply and return air temperature in the case study

Different air supply modes create different indoor air distribution, which affects the wall convective heat transfer coefficient and return air temperature. In addition, it affects the room heat transfer and the actual heating capacity of the RAC, so that the average temperature of the room will be different. From the indoor temperature variation of a typical day in Figure 8, it is concluded that the indoor average temperature in Case 1 with inclined downward supply air angle is 0.1 °C lower than that in Case 2 of the vertical downward angle, and the indoor temperature in both cases can be stable around 24 ~ 25 °C. However, the indoor average temperature of lower installation in Case 3 is 27 °C, which is about 2 °C larger than that of higher installation.

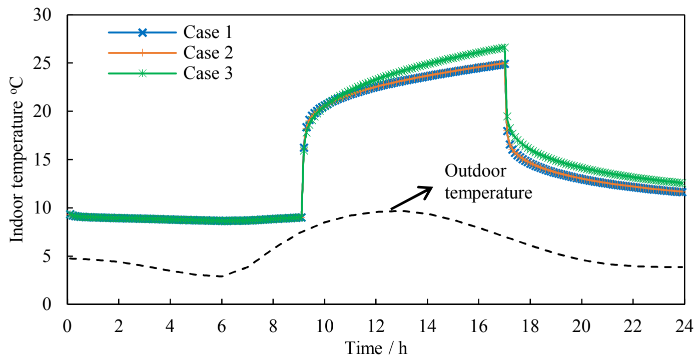


Figure 8. The average and outdoor temperature in case study

3.1.2 Thermal Nonuniform Conditions

The air temperature difference between the head and the ankle is important for thermal nonuniform conditions. Therefore, Figure 9 illustrates the vertical temperature distribution for different cases in steady-state. It is evident that the air temperature around the human ankle in Case 2 and Case 3 is much higher than in Case 1, and Case 1 is more likely to lead to the "hot head and cold feet" problem. Meanwhile, Case 2 with higher installation height and vertical downward supply air angel establish the most comfortable thermal environment considering vertical temperature distribution.

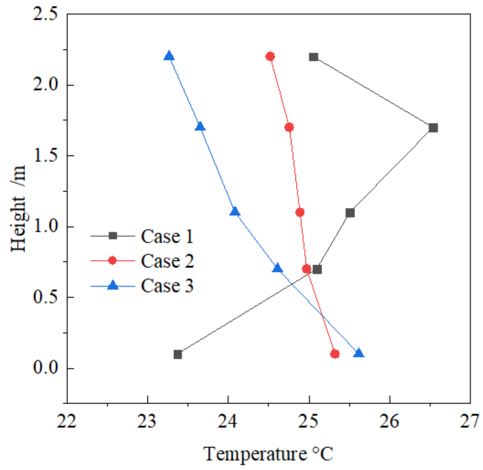


Figure 9. The vertical temperature distribution for different case in steady stage

In addition, the draft has been recognized as one of the most annoying factors in heating conditions, which is influenced by air velocity and air temperature. The percent of dissatisfaction with the draft is concluded in Figure 10 according to the calculation equation (Fanger, 1989). Case 1 illustrates that it brings about the most annoying thermal dissatisfied draft compared with other conditions, especially for the ankle.

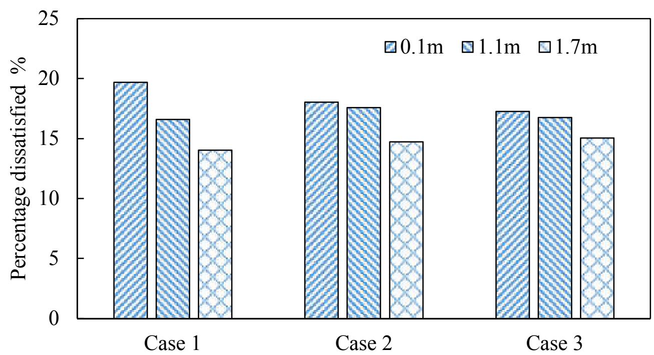


Figure 10. The percentage dissatisfied for different cases in steady condition

3.1 Energy Performance Factors

Figure 11 shows the heating capacity and energy efficiency of RACs in typical daily rooms in Shanghai. The total heating capacity of units in different cases is 18.1 kWh, 18.2 kWh and 20.3 kWh, respectively. The heating capacity of Case 1 is slightly lower than that of Case 2, while the heating capacity of Case 3 is the highest. The average energy efficiency ratios are 2.55, 2.56 and 2.64 respectively. In the higher installation cases, the heating capacity of Case 2 is 0.5% higher than that of Case 1, and the energy efficiency is 0.4% higher. Moreover, the heating capacity of the lower installation is 12.2% higher than that of the higher installation case in the same supply air direction, and the energy efficiency ratio is 3.5% higher. Due to the lower return air temperature of the lower installation, the condensing temperature of RAC is low, so the energy efficiency is improved.

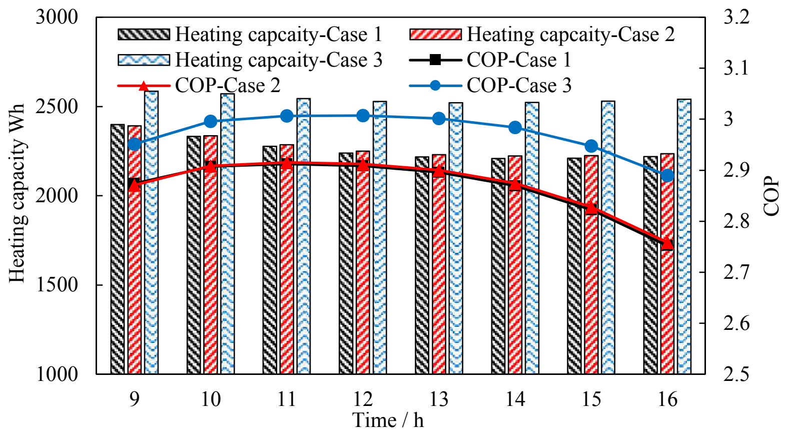


Figure 11. Typical heating capacity and energy performance in typical day

4 CONCLUSIONS

This paper mainly analyzes the difference in indoor thermal environment and energy performance of RAC with different installation height and air supply angles. Firstly, the principle of the combined simulation model (BES-CFD and performance of RAC), which enhance the accuracy of calculation is proposed, and the adaptability and feasibility are validated. The influence of different angles and installation height of heating condition of RAC on indoor thermal environment and energy consumption are illustrated through the simulation. The main conclusions are as follows:

(1) In this paper, the combined simulation of BES-CFD and performance of RAC is established. And the accuracy of the model is verified by experiments. The verification indicates that the error of the combined model is less than 2 °C, which significantly inferior to the single BES simulation.

(2) Based on the typical day simulation of Shanghai, this paper analyzes the difference in the performance of RACs with different air supply angles and installation positions. The results show that installation heights and air supply angles have significant effects on the wall convective heat transfer coefficient and the supply/return air temperature of RAC. As for the thermal environment, the lower installation height is more likely to result in a comfortable environment as it decreases local thermal discomfort.

(3) Different installation heights and air supply angles affect the energy performance of RAC. The heating capacity of RAC is increased by about 12.2%, and the energy efficiency ratio is increased by approximately 3.5% at the lower height position.

The combined simulation of BES-CFD and energy performance of RAC provide an effective method to calculate accurate indoor environment, building load, and RAC energy performance characteristics. Compared with the traditional separate calculation, the combined simulation is more precise in the dynamic simulation since it obtains real-time and accurate boundary conditions. On the other hand, compared with full dynamic coupling, the computing speed in the quasi-dynamic coupling method in the combined simulation is improved significantly, and there is no significant reduction of accuracy.

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