Integration of airflow zonal model and building energy simulation for large space buildings

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Abstract. Contemporarily, large spaces prevail in many diverse and complex buildings, but meanwhile, incur more demanding requirements about thermal comfort and energy saving. Conventional building energy simulation (BES) computes the whole building based on the assumption of quiescent and uniform air. By contrast, computational fluid dynamics (CFD) can obtain rich and detailed airflow results, but consumes tremendous computational time and resources. Then, the zonal model as an intermediate method between these two models has gradually approached to the visual field of the public, which plays an important role in rapidly predicting the overall thermal stratification of large spaces. Therefore, this paper discussed a practical and automatic method of integration of the zonal model and BES. In this way, annual dynamic energy consumption of large space buildings can be analysed, which will exhibit significant potential in the engineering field, especially at primary design stage.

1 Introduction

With the advent of information era, a recent trend has seen long-term dynamic simulations of building energy consumption. However, modern buildings gradually become more diverse and complex. For example, large spaces feature high ceilings, large volumes and transparent envelopes. There usually exists obvious thermal stratification and overheating due to many environmental factors. Such architecture generally connects surrounding rooms, which further strengthens exchange of airflow and energy. Nevertheless, people expect a more hospitable and energy-saving indoor environment of large spaces. Moreover, control strategies of heating, ventilation and air-conditioning (HVAC) systems should adapt to climatic conditions and building schedules accordingly.

Conventional BES lumps the air in a single room into one computational node. Hence, the energy use of the whole building can be readily obtained. If it is necessary to consider details of air motion and non-uniformity of thermal environments, an airflow model can be integrated with it to deal with multiscale airflow and heat transfer between the large space and surrounding rooms. CFD methods offer rich results but at the expense of substantial computational resources. As a result, some intermediate airflow models that can balance accuracy and efficiency have gradually approached to the visual field of the public. For instance, zonal models divide 10-100 zones [1] in a single space and obtain global information by simplified flow equations. However, common zonal models such as the Block model lack sufficient universality for different realistic buildings. Moreover, few researches have expanded the application of zonal models to BES. It is imperative to discuss some details about the connection of time and space in their coupling process.

Therefore, based on the simulation requirements and model characteristics, this paper provides a practical and automatic coupling method of velocity propagating (VPZ) zonal model [1] and BES for annual dynamic analysis of realistic large space buildings, especially in the engineering field at primary design stage.

2 Methodology

2.1 Building energy simulation

Generally, BES involves four main aspects: heat transfer from external disturbance such as solar radiation and outdoor temperature, heat transfer from internal disturbance including occupants, lamps and equipment, ventilation between the inside and outside, and heat input/extract of HVAC systems.

The Designer's Simulation Toolkit (DeST) [2] developed by Tsinghua University in 1989 has passed the ASHRAE 140 standard, which can be used for subsequent coupling simulation with building energy consumption. The air-conditioning load refers to the energy provided or removed by air-conditioning equipment per unit time in order to control the indoor temperature within a setting range. In the module of building analysis simulator (BAS) of DeST, the

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temperatures of all rooms in the building are calculated simultaneously. The state-space method is then utilized to solve the above overall heat balance equation, which is continuous for time but discrete for space.

2.2 Airflow zonal model

As demonstrated in Fig. 1, the VPZ model constructs a three-dimensional airflow network in the large space with air volumes and flow paths. Air information contained in each air volume propagates into the whole space via the two adjacent flow paths in different dimensions.

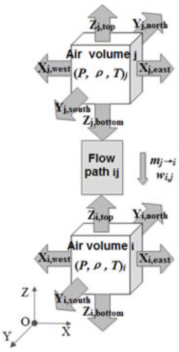


Fig. 1. Airflow network of the zonal model in the z-direction.

Inside each air volume, the air is assumed to be quiescent and homogeneous, satisfying the mass conservation (1), the energy conservation (2), and the ideal gas equation (3).

$$\sum \dot{m}_{j\to i} + \sum \dot{m}_{\mathrm{source}\to i} = 0 \tag{1}$$

$$\rho_i C_\mathrm{P} V_i \frac{\mathrm{d}T_i}{\mathrm{d}\tau} = \sum\nolimits_{j\neq i} C_\mathrm{P} \dot{m}_{j\to i}(T_j - T_i) + \frac{\lambda S_{ij}}{l_{ij}} + \sum h_{\mathrm{wall},i} S_{\mathrm{wall},i}(T_\mathrm{wall} - T_i) + \sum \dot{Q}_{\mathrm{source},i} \tag{2}$$

$$\rho_i = \frac{P_i}{RT_i} \tag{3}$$

$\dot{m}$ represents the mass flowrate of airflow, kg/s; T is temperature, K; P is air pressure, Pa; $\dot{Q}$ is heat flux, W; V is zonal volume, m^3; S is zonal interface area, m^2; l is the distance between neighboring air volumes; τ is time, s; C_P is air's specific heat at constant pressure, J/(kg·K); ρ is air density, kg/m^3; λ is air's thermal conductivity, W/(m·K); h is convective heat transfer coefficient, W/(K·m^2); R is gas constant for air, J/(kg·K). The subscripts i/j, source, and wall respectively refer to air volumes, heat or mass sources or sinks, and wall surfaces. The direction of the airflow entering a zone is supposed to be positive (+).

On each flow path, for example in the z-direction, the air is influenced by the gravitational force F_G, pressure force F_P, momentum force F_M, and viscous force F_V as derived in Eqs. (4)-(8). F_M can lead to acceleration or deceleration of air. Characteristic velocities w_i are defined according to the entering airflow across the boundaries in the same orientation as summarized in Table 1, which has a positive value when flowing toward the positive direction of the axis. This characteristic physical quantity can also ensure propagation of airflow into downstream zones. μ_a is the apparent viscosity as a tuning parameter, which is set to 0.001 Pa·s in this paper to compensate dissipation of turbulence and reflecting effect of boundary layers. l_{ij} means the length of the flow path, thereby reducing the impacts of zoning on simulation results. g is the gravitational acceleration, m/s^2.

$$S_{ij} l_{ij} \rho_{ij} \frac{\mathrm{d}w_{ij}}{\mathrm{d}\tau} = F_\mathrm{G} + F_\mathrm{P} + F_\mathrm{M} + F_\mathrm{V} \tag{4}$$

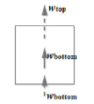
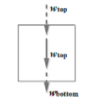
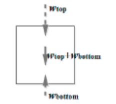
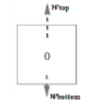
$$F_\mathrm{G} = -\rho_{ij} g S_{ij} l_{ij} \tag{5}$$

$$F_\mathrm{P} = S_{ij}(P_i - P_j) \tag{6}$$

$$F_\mathrm{M} = \rho_{ij} S_{ij}(w_i^2 - w_j^2) \tag{7}$$

$$\begin{cases} F_\mathrm{V} = \dfrac{(F_{\mathrm{zone},i} + F_{\mathrm{zone},j})}{2} \\ F_\mathrm{zone} = \mu_a \left\{ \left[\left(\dfrac{\Delta w}{\Delta x}\right)_{X+} - \left(\dfrac{\Delta w}{\Delta x}\right)_{X-} \right] S_{YZ} \right. \\ \qquad \left. + \left[\left(\dfrac{\Delta w}{\Delta y}\right)_{Y+} - \left(\dfrac{\Delta w}{\Delta y}\right)_{Y-} \right] S_{XZ} \right\} \end{cases} \tag{8}$$

Table 1. Assignment of the characteristic velocity of a zone in the z-direction.

Flow direction	Bottom to top	Top to bottom	Bottom and top to zone	Bottom and top from zone
Assignment of characteristic velocity				

Notes: The solid arrow represents the characteristic velocity in a zone, while the dotted arrow is the airflow entering or leaving the boundary in the same direction.

2.3 Model coupling and data interaction

2.3.1 Temperature-feedback coupling analytical model

The indoor environment in DeST are determined according to design requirements and uniformity assumption, which however, becomes the output result in turn in the zonal model. Moreover, the airflow and temperature distributions inside large spaces are complex and inhomogeneous indeed.

Outdoor meteorological conditions and indoor thermal disturbance fluctuate throughout the year. It is necessary to automatically decide whether the current air supply parameters can realize the expected thermal comfort. Otherwise, the air-conditioning system would be regulated, hence uncoupling its relationship with the indoor environment through feedback calculations. Based on the deviation between the actual temperature and the setting value in the air-conditioned zone of the large space, the air-conditioning cooling/heating capacity that needs to be input can be calculated. Additionally, indoor air design parameters are generally allowed to vary within a reasonable range, such as ±2 K.

Therefore, this temperature-feedback coupling analytical model can consider thermal comfort, building energy conservation, building schedule, air-conditioning system practice, and stability of algorithm.

2.3.2 Space connection

There is spatial discontinuity between the large space subdivided by multiple zones and surrounding conventional rooms as uniform nodes. The air separated along inner wall surfaces of the large space can be regarded as a relatively independent module with various boundaries. On the one hand, the zonal model focuses on the non-uniform thermal environment and air-conditioning load of the large space. Simultaneously, DeST provides detailed architectural description and boundary conditions for the large space by calling relevant calculation modules, including meteorological parameters, building schedule, air-conditioning setting, etc. On the other hand, DeST calculates its surrounding rooms, following the assumption of well-mixed air. In order to ensure the original consistency of the software framwok of DeST, the thermal condition of the large space is treated as the external disturbance when simulating surrounding rooms. In short, on the inner surfaces of the large space these two models are coupled and their data is exchanged.

Becasue vertical temperature stratification dominates in large spaces, which plays the foremost role in evaluating thermal comfort and building energy consumption. Moreover, the overall energy balance in DeST is established based on each room. Therefore, temperatures are supposed to vary along the vertical direction when transferring data between the zonal model and DeST. Choosing temperatures as the interacted data between indoor air and wall surfaces is a fast, convergent and effective explicit method.

2.3.3 Time connection — Chronological coupling and iterative mechanism

There is time discontinuity during the coupling process: not only the simulation time of the zonal model and DeST, but also the response time of indoor air and building envelops. The time step of the zonal model is usually set to 1 s, while DeST adopts 1 h [2]. In this study, a chronological coupling and iterative mechanism is implemented. The master-slave mode is adopted, so that DeST can decide when and how to exchange data.

Due to thermal inertia of walls, historical temperatures will affect the current values. At the first beginning, DeST assumes a uniform room temperature, and then eliminates the initial value error through pre-calculation for 30 days. This method can ensure the correctness at time ‘0’ in the formal calculation stage. In the following formal calculation, the ‘Ping Pong’ method [3] is applied. Specifically, when the zonal model performs simulations, the results of DeST at the previous time is regarded as its known boundary conditions. The zonal model then outputs its data to DeST at this moment. After that, DeST will activate a new round of calculation and information transmission at the next step. Zhai [3] suggested using 1 h as the coupling frequency, attaining a reasonable accuracy and a smooth result curve with limited computational resources.

The execution procedure is actually a quasi-steady coupling mode, which can avoid massive data interaction and improve efficiency in annual dynamic analysis of complex large space buildings.

2.3.4 FMI/FMU data interface

This paper applies the international functional mock-up interface (FMI) standard 2.0 [4] for the hourly coupling process. FMI is flexible, independent and suitable for co-simulation between multiple different software. DeST, the master management unit of co-simulation, communicates with the external functional mock-up unit (FMU) of the zonal model. The former contains the support libraries of Boost, Blitz, SQLite and XML. FMU includes the ‘.xml’ file describing model interface information, the C code or binary file realizing dynamic model function, and other files such as parameter libraries provided by users.

There are three sections in the co-simulation based on FMI/FMU.

- Preparation stage: The master manager loads the FMU model, allocates memories and obtain variables by using fmiInstantiateSlave function. Then the FMU instance is initialized through fmiInitializeSlave.
- Simulation stage: fmiSetReal sends the dynamic boundary conditions to FMU. fmiDoStep triggers the calculation of the non-uniform thermal environment and building load of the large space in FMU. fmiGetReal returns the FMU’s simulation results. Then the calculation move to the following moment and repeat the above procedure.
- Termination stage: The master manager calls fmiFreeSlaveInstance function to release the FMU instance.

3 Case study

3.1 Building description

Fig. 2 shows an atrium office building located in Beijing, China (N39°56′, E116°20′), which was founded in DeST. The atrium space is 15 m (X) × 15 m (Y) × 24 m (Z) with six floors in the north of the building. From the perspective of each floor, there are four rooms including the atrium. At the top of the atrium, a skylight is configured with a heat transfer coefficient of 5.7 W/(m^2·K) and a shading coefficient of 0.85. The activity zone on the first floor is air-conditioned from 7:00-20:00, with the design indoor temperature from 23°C to 25 °C. Personnel is distributed as 0-0.1 person/m^2, and each man has a heat dissipation of 66 W; lamps emit an energy of 0-18 W/m^2; equipment power is 0-13 W/m^2.

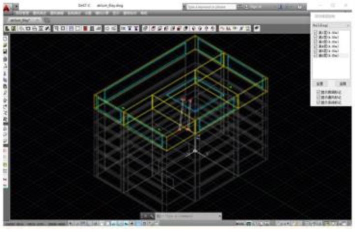
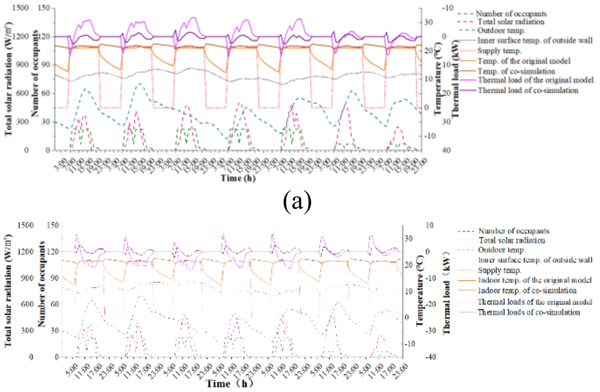


Fig. 2. Building model of the office atrium in DeST.

3.2 Results and discussion

In the VPZ model, the atrium space was decomposed into 3 (X) × 3 (Y) × 8 (Z) = 72 zones. Specifically, the air near the indoor thermal loads on the first floor and solar radiation through the skylight was further subdivided to two layers vertically.

The whole building was dynamically simulated throughout the year, consuming 2.7 CPU hours. Fig. 3 demonstrates the results during August 1st -7th in summer and January 1st -7th in winter (with 5 days as workdays) in the typical meteorological year as examples.



(a)

(b)

Fig. 3. Simulation results of the office atrium: (a) summer, and (b) winter.

In summer, when the ventilation rate was 2 h^{-1}, the maximum air temperature on the highest floor was less than 30 °C compared to that of 1 h^{-1}, hence satisfying indoor thermal comfort. Moreover, its building energy consumption was decreased by 0.75 kW, in contrast to that of the ventilation rate of 3 h^{-1}. The winter conditions were also considered, thereby setting 2 h^{-1} as the configuration parameter. In addition, the supply air temperature turned out to be 21-25 °C and the air supply volume was 10800 m^3/h, according to the temperature-feedback coupling analytical model.

In summer, the co-simulation showed that the cooling load reached the peak value of 11.9 kW at 13:00. By contrast, the result curve obtained by the original atrium model in DeST fluctuated more significantly with time. Its peak time in summer appeared at 14:00 and the maximum cooling load was 15.3 kW. For winter conditions, the maximum heating load of the co-simulation was 2.5 kW at 8:00, while the other model acquired 7.2 kW at 7:00. Both of them had cooling loads sometimes during winter, which means there was no need for heating. In this case, solar radiation was stronger, and simultaneously, the specified temperature range of the air-conditioned region was relatively narrow.

The deviations between the co-simulation method and the original simple atrium model can be explained as follows. Firstly, the predicted building load was more stable in this study, due to the effective adjustment of the temperature-feedback coupling analytical model. By contrast, in original DeST the temperature of the air-conditioned region was directly set to the upper limit of 25 °C in summer and the lower limit of 21 °C in winter. Secondly, the co-simulation results showed that the air-conditioned region on the first floor was less affected by the external environment. With a small incident angle of sunlight and a large area of internal building envelopes, the atrium can be seen as a buffer space. The reason was that this paper considered the airflow process and the relationship between the air-conditioned and non-air-conditioned zones in detail. Moreover, the coupling method in this study followed the chronological coupling and iterative mechanism. Consequently, the phase of the result curve was generally 1 hour ahead of the original DeST model. In addition, when the co-simulation was adopted, 40% energy consumption can be saved. This was because the air-conditioning system can be dynamically regulated, and the building load was intentionally stratified.

4 Conclusions

This paper provided the practical coupling method of the zonal model focusing on the thermal stratification of the large space and DeST considering the surrounding conventional rooms. In this way, the annual dynamic thermal conditions and building energy consumption of the whole large space building can be obtained, balancing simulation accuracy and computational costs. The method and data above can assist in indoor environment optimization and building energy saving, especially in the engineering field at primary design stage.

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