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Inverse identification of source location in a single-sided natural ventilation building

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Abstract. Natural ventilation is a common way of ventilation for urban residents, which is simple and energy-efficient. However, this ventilation not only introduces fresh air from outdoors into the indoor environment but also brings various pollutants from outdoors into the indoor environment, thus reducing indoor air quality and causing a series of human respiratory diseases in severe cases, such as asthma, pneumonia, bronchitis, etc. In a high-density urban environment, the proximity of rooms within a building can easily lead to cross-infection between occupants in the event of a public health emergency. Therefore, it is of great significance to quickly and accurately find the source of viruses or pollutants. The objective of this study is to accurately locate pollutant source which spread between units by wind effect. A model with three-storey building of wind-driven single-sided ventilation was built. Carbon dioxide (CO_2) was used as a tracer of indoor pollutants. Computational Fluid Dynamics (CFD) is used to accurately simulate and predict airflow and concentration fields in and around the building. The results indicated that the location of the predicted pollution source is close to the position where the pollutant is released. The results of this paper can provide vital information for preventing the spread of contaminants in buildings.

1 Introduction

With the development of urbanization, the population density in the urban centers is growing rapidly, and the building volume ratio is also gradually increasing. The crowded urban environment has created lots of environmental problems, such as energy waste, urban heat island, and urban air quality decline. To solve this series of problems, an old ventilation method, natural ventilation, is used by urban residents.

Natural ventilation, as a passive energy-saving technology, can improve both indoor air quality and indoor thermal comfort. However, the use of natural ventilation is bound to associate the indoor environment with the outdoor environment. The indoor pollutants or viruses enter the outdoor environment with the airflow and have a great potential to re-enter other indoor environments [1]. In order to prevent and stop cross-transmission of pollutants or viruses between rooms in a building, one effective way is to locate their source in time.

At present, there are two standard methods to find the location of contaminant sources in the indoor environment. One method is called the robot active olfaction method, which uses one or multi mobile robots to locate indoor contaminant sources according to a specific algorithm. Feng et al. [2] found the location of pollutant source in dynamic indoor environments with natural ventilation by using multi-robot olfaction method. Recently, Yang et al. [3] accurately found the time-varying indoor particle sources in indoor environment. However, due to the limitation of robot movement, the robot active olfaction method is currently only applied to study the localization of pollutant sources for a single room.

Another method is called the stationary sensor networks method, which uses the data recorded by the sensor combined with CFD model or multi-zone model to obtain the contaminant source location through forward and reverse calculation methods. Liu and Zhai [4] summarized the features of existing inverse modelling methods and categorized them into the forward method [5], the backward method [6], and the probability method. Compared with the first two methods, the probability method has the advantages of reducing calculation time and less demand for prior information. Wang et al. [7] proposed the probability method for locating the pollutant source in dynamic indoor environments with mechanical ventilation. Zeng et al. [8] established the probability density function (PDF) to characterize the instantaneous pollutant source released in a ventilation system. Recently, Xue et al. [9] applied adjoint probability method to accurately locate multiple pollutant sources in a three-dimensional urban environment with a mobile sensor. So far, the research and application of pollutant source localization is the pure indoor environment or pure outdoor environment. In contrast, few studies have been reported on source location of contaminants transmitted between units of the same building by natural ventilation.

Inter-unit dispersion by natural ventilation has been well studied previously. Ai et al. [10] used CFD

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simulation to study inter-unit dispersion characteristics of indoor pollutants in multi-story single-sided natural ventilated buildings and analyzed the effects of wind direction and balconies. Recently, Dai et al. [11] adopted outdoor scale experiment to explore the contaminant transmission route of natural ventilation buildings in the street canyon.

In this paper, the pollutant transmission route of a single-sided natural ventilation building will be revealed. The location of the room that has the greatest impact on other rooms will be identified and accurately located as the source room. A model with three-storey building of single-sided natural ventilation was built. This paper applied the inverse modelling of source identification in natural ventilation building. This study will contribute to finding and controlling the spreading of pollutants or viruses in buildings.

2 Methods

2.1 CFD methods

In this paper, we choose the (RNG) $\mathrm{K}-\varepsilon$ model in FLUENT software to solve the airflow and concentration fields in and around the building. The time-averaged governing equation for an incompressible fluid can be written in the general form as Eq.(1) below:

$$\frac{\partial}{\partial t}(\varphi) + \nabla(u\varphi) = \nabla\left(\Gamma_\varphi \nabla_\varphi\right) + S_\varphi \tag{1}$$

Where u is the velocity vector; φ stands for each of the velocity components, u(m/s), v(m/s), w(m/s), turbulent kinetic energy k (m^2/s^2), turbulent dissipation rate ε (m^2/s^3), and specious concentration c (kg/m^3); Γ_φ is the diffusion coefficient for each dependent variable φ; and S_φ is the source term.

The Renormalization Group (RNG) $\mathrm{K}-\varepsilon$ model is derived from a rigorous statistical technique, which was proposed by V. Yakhot et al. in 1986 [12]. It is formally similar to the standard $\mathrm{K}-\varepsilon$ model, but added the strain-dependent term R_ε to the ε equation which improves the accuracy for swirling flow. The added term R_ε is shown by the equation as:

$$R_\varepsilon = \frac{C_\mu \rho \eta^3 (1-\eta/\eta_0)}{1+\xi\eta^3} \cdot \frac{\varepsilon^2}{k} \tag{2}$$

2.2 Probability-based inverse modelling method based on CFD method

In order to find the location probability of pollutants, it is necessary to solve a set of adjoint equations derived from the forward pollutants transport equation [3]. The adjoint equation can be expressed as:

$$\frac{\partial \varphi^*}{\partial \tau} + \frac{\partial V_j \varphi^*}{\partial x_j} = \frac{\partial}{\partial x_j}\left[v_{c,j}\frac{\partial \varphi^*}{\partial x_j}\right] + (-q_0 \cdot \varphi^*) + \frac{\partial h}{\partial C}$$
$$\varphi^*(\vec{x}, 0) = 0 \tag{3}$$
$$\frac{\partial h}{\partial C} = \delta(\vec{x} - \overrightarrow{x_w}) \cdot \delta(\tau)$$

Where φ^* is adjoint probability, τ is the backward time, $\overrightarrow{\mathbf{x_w}}$ is place where the measurement is made. $-q_0$ is the outflow rate per unit volume, h is a function of the state system, C is the system state variable, $\frac{\partial h}{\partial C}$ is the load term specified by Neupauer and Wilson [13]. $\delta(\cdot)$ is the Dirac delta function.

Combining the obtained concentration information with the adjoint probability, Lin et al. proposed a conditional probability with N measurements can be expressed as:

$$f_x(X \ / C_1, \dots, C_N; \tau_0, X_1, \dots, X_N, \tau_1, \dots, \tau_N) = \frac{\int_{M_0} \prod_{i=1}^{N} P(C_i \ / M_0, X; \tau_0, X_i, \tau_i) f_x(X; \tau_0, X_i, \tau_i) dM_0}{\int_{M_0} \int_x \prod_{i=1}^{N} P(C_i \ / M_0, X; \tau_0, X_i, \tau_i) f_x(X; \tau_0, X_i, \tau_i) dx dM_0} \tag{4}$$

Where $f_x(X; \tau_0, X_i, \tau_i)$ is the SALP of the i-th measurement; C_i is the concentration of the i-th measurement; $P(C_i \ / M_0, X; \tau_0, X_i, \tau_i)$ is the probability for the measured concentration conditioned on the source mass M_0 and source location X.

$$P(C_i \ / M_0, X; \tau_0, X_i, \tau_i) \sim N(M_0 \cdot f_x(X; \tau_0, X_i, \tau_i), \sigma_\varepsilon^2) \tag{5}$$

Where C_i is the possible concentration value of the i^{th} measurement and σ_ε^2 is the variance for the N measurements. As concentrations are involved in the calculation, probabilities obtained with Eq.(4) are called conditioned adjoint location probabilities with concentrations, and are symbolized as CALP.

3 Results

3.1 Case design

A three-storey, three-room single-sided natural ventilation building was built, as shown in Fig.1 (a). The building model was at a reduced scale of 1:200. The dimension of each room was length × width × height=0.2m × 0.2m × 0.2m. An opening of 0.08m × 0.08m was fixed on the windward wall of each room. Each room has a point contaminant source (CO2) near the opening, and the pollutant concentration in each room can be monitored. The computational domain size was length × width × height =21H × 11H × 6H, as shown in Fig.1(b).

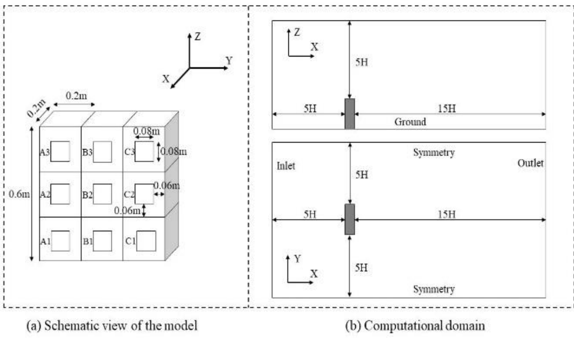

Fig. 1. (a) Schematic view of the model. (b) Computational domain.

Three mesh systems were adopted with minimum cell widths of 0.001, 0.0005, and 0.00025m, respectively. And the total numbers of hexahedra grids were around 3.8 million, 5.5 million, and 7.6million, respectively, were established to verify the dependence of numerical solutions of the different mesh systems. Fig.2 shows the mesh sensitivity test for non-dimensional wind velocity. The middle grid is selected because the velocity value results on the selected line are similar to the simulation results of the other two grids.

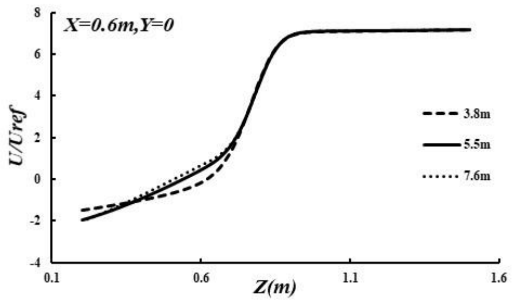

Fig. 2. Sensitivity test for the three mesh systems at line X=0.6m, Y=0m, Z=0.1-1.5m.

The inlet conditions were obtained by fitting equations wind velocity U, turbulent kinetic energy k, and turbulent dissipation rate ε. The profiles obtained for U, k, and ε at the inlet and the coefficients are summarized in table 1. The SIMPLE-consistent (SIMPLEC) is chosen to solve couple the pressure and velocity fields. The spatial discretization of all parameters chose second-order upwind scheme.

Table 1. Boundary conditions.

	Power law type
Domain inlet	$U=\frac{u^*}{k}\ln\left(\frac{Z+Z_0}{Z_0}\right)$ $k=\sqrt{C_1\cdot\ln(Z+Z_0)+C_2}$ $\varepsilon=\frac{u^*\sqrt{C_\mu}}{k(Z+Z_0)}\sqrt{C_1\cdot\ln(Z+Z_0)+C_2}$
Domain outlet	$\frac{\partial}{\partial x}(u,v,w,k,\varepsilon)=0$
Domain celling	$w=0,\frac{\partial}{\partial x}(u,v,k,\varepsilon)=0$
Domain lateral sides	$v=0,\frac{\partial}{\partial x}(u,w,k,\varepsilon)=0$
Domain ground	Enhanced wall functions
Building surfaces	Non-slip for wall shear stress
Von Karman constant	$k=0.4187$
friction velocity	$u^*=0.374$
Roughness height	$Z_0=0.00075$
Turbulence model coefficients	$C_1=0.025$ $C_2=0.41$ $C_\mu=0.069$

3.2 Concentration field

In this paper, each room is used individually as a source room to release tracer gas in its room and analyze the transmission route of pollutants in each case. Carbon dioxide (CO_2) was used as a tracer of indoor pollutants. The strength of the source is 100 kg/(m³·s).

To evaluate the tracer gas transportation between the source and other rooms, the quantifying method proposed by Niu and Tung [1] is used. The reentry ratio is defined as the fraction of the tracer gas from the source room that reenters another room. It can be calculated by the following equation:

$$R_k = M_{i-j}\frac{Vol_j(ACH)_j}{Vol_i(ACH)_i}$$

Where the M_{i-j} is the mass fraction, which is expressed as the ratio of tracer gas at infected unit ($C_j, kg/m^3$) to concentration at the source unit ($C_i, kg/m^3$).

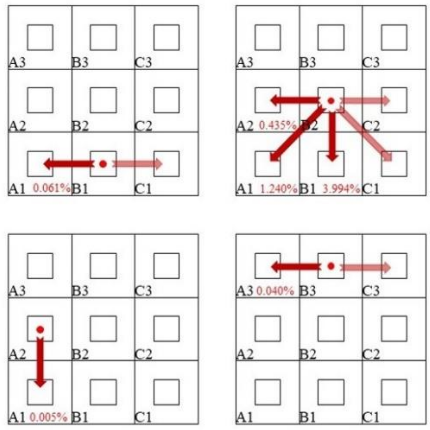

Fig. 3. Re-entry ratios of tracer gas from the source to other units.

Fig.3 shows the re-entry ratios of tracer gas from the source to other units, the red circle represents the location of the source. It can be seen that pollutants diffuse to both sides of the room when the middle room is the source room. It is difficult to affect other rooms vertically when the source room is located on the first and third room. It can be concluded that other rooms are susceptible to infection when room B2 is the source room.

3.3 Result of locating pollutant source

Through the analysis of pollutant transmission, room B2 is selected as the source room in this section, and the other rooms were selected as the monitoring rooms to detect the tracer gas concentration in the room. Fig.4 shows the main process of the adjoint probability method.

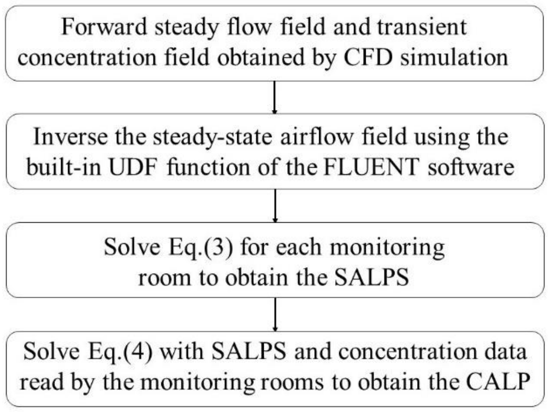

Fig. 4. Flow chart of the inverse modelling method with CFD method.

After 70s, tracer gas concentrations exceeding the limit values of 0.15 kg/(m³·s), 0.14 kg/(m³·s), and 0.09 kg/(m³·s) were detected in room A1, B1 and A2, respectively. The simulated concentration data are combined with three groups of SALP, and the distribution of CALP is obtained by solving Eq.(4). The CALP distribution indicating the location probability is shown in Fig.5.

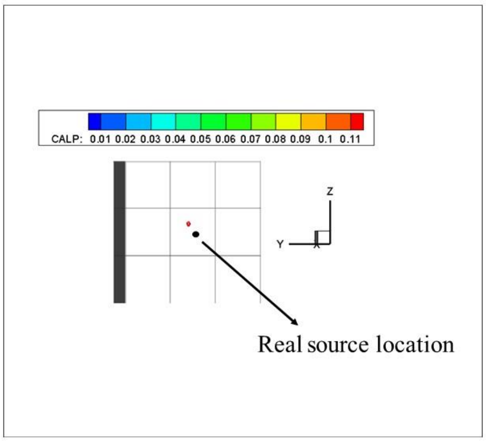

Fig. 5. Inverse calculation results of the source location probability of room B2.

4 Discussion

It can be seen that the maximum probability of pollutant location predicted by adjoint probability method is 0.11, which is located at room B2. This shows that this method can locate the specific location of the source room when pollutants diffuse. But there is still a deviation from the source position of the real release. This is due to the main purpose of this paper is to find the location of source room, rather than the specific location of the release source, based on this purpose our monitoring points are set up one in each of the other rooms. This leads to the limited information input in the reverse calculation process, so only the approximate location of the source can be determined which is the location of the source room. To find the location of the real source more precisely, additional monitoring points can be added in room B2 for a second round of inverse probability calculation, which will be done in our future work.

5 Conclusion

This paper analyzes the pollutant transmission route of single-sided natural ventilation building, and finds the location where the greatest impact on other rooms (room B2). Room B2 was set as the source room, and the location of the source room was successfully found by using the adjoint probability method. The conclusion indicated that the inverse modelling can be applied to locate the pollutant source in a single-sided natural ventilation building. The results intend to help in preventing the spread of pollutants or viruses in the building environment.

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