OPTIMIZATION OF THE POSITIONS OF INDOOR CONTAMINANT SOURCES AND SINKS BY USING A NEW CONCEPTION-SPATIAL FLOW INFLUENCE FACTOR

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ABSTRACT

A new concept, the spatial flow influence factor (SFIF), put forward by us in our previous paper, provides a new insight into the airflow structure. In this paper, several typical illustrative examples are presented to show: (1) how to optimally arrange the chemical pollutant sources and the occupied regions for a given indoor airflow; (2) how to optimize the position of adsorption materials. From the examples, it is seen that the concept is powerful in the control of indoor air gas pollutants.

KEYWORDS

Indoor air quality; Indoor air pollutant control; Ventilation assessment; Optimizing; *CFD*

INTRODUCTION

Chemical contaminant is a major part of indoor pollutants. Various control strategies are used to reduce the contaminant concentration in an indoor space to a level below the threshold defined by standards and codes. Ventilation is attached importance as an effective method to dilute indoor the contaminant and provide adequate fresh air. However, it is not necessary to regard the space as uniform, and it is enough to keep the concentration of the contaminant in the occupied (or target) region below the threshold, instead of the whole indoor space. Therefore, it is import to study how to optimize position of source regions and occupied regions to make air in occupied regions fresher. For an instance, some pollution sources such as computers and printers should be located on the downstream side of the breath region so that the pollution intake of a person is lower.

Many researchers have done interesting work on the influence of ventilation and airflow organization on the indoor chemical pollutant to assess and optimize ventilation design. Sandberg (1981, 1983a, 1983b) puts forward the concept of air age, which quantifies the air freshness level. Kato et al. (1994) presents the concept SVE4, which describes the concentration ratio of the air from a supply inlet. Widely used scales including ventilation efficiency for contaminant removal ability, SVE1 for indoor contaminant distribution, personal exposure effectiveness for the ratio of fresh air inhalation, accessibility of supplied air (ASA) and accessibility of contaminant source (ACS), etc. (Yang, 2004) are used to assess the indoor air quality and the indoor airflow. There are, however, some limitations to apply such scales. For example, it is difficult to apply the aforementioned scales to optimize the arrangement of pollutant sources/sinks and occupied regions because these scales do not provide the relationship of any two positions in the space from an airflow perspective. Considering that in practice the airflow velocity field strongly influences the pollutant concentration field, while the latter hardly influences the former, a new concept, the spatial flow influence factor (SFIF) was put forward by Zhang and Li (2006). With this idea, we provide a novel insight into the indoor airflow structure. For a steady airflow field, spatial flow influence factors can be easily calculated. The SFIF concept and the associated insight are very helpful for indoor air pollutant control: (1) for given indoor airflow and chemical pollutant sources, the optimal arrangement of the sources and breath zone can easily be obtained; (2) for the given positions of chemical pollutant sources and occupied regions (or target regions), the optimal indoor airflow pattern or organization can be determined.

SPATIAL FLOW INFLUENCE FACTOR: DEFINITION, PHYSICAL MEANING AND DETERMINATION (Zhang, Li and et al. 2006)

The contaminant concentration equation for a given space with steady airflow can be written as follows:

$$\nabla \cdot (\rho_a C\mathbf{v} - \Gamma_A \rho_a \nabla C) = S_i \tag{1}$$

where v is velocity vector, m/s; S_i is the intensity of the ith contaminant source, (i=1, 2, 3, …), kg m^{-3} s^{-1} ; ρ_a is the mass density of air and Γ_A is the mass transport coefficient of contaminant A in air. For the laminar airflow or stagnant air, Γ_A is the diffusion coefficient of contaminant A in air, D_A, m^2/s; for the turbulent airflow, Γ_A is the effective diffusion coefficient of contaminant A in air and can be written as (Tao, 2002)

$$\Gamma_A = D_A + \frac{\mu_t}{Pr}, \qquad (2)$$

where μ_t is the dynamic viscosity of turbulent airflow, Pr is the Prandtl number. For the turbulent flow, $\Gamma_A >> D_A$.

In practice, the influence of the chemical contaminant concentration field indoors on the air velocity field can be neglected. Therefore, for a given steady airflow indoors, if Γ_A and S_i are independent of contaminant concentration, we have the following contaminant concentration equation:

$$\nabla \cdot (\rho_a C\mathbf{v} - \Gamma_A \rho_a \nabla C) = \sum S_i. \qquad (3)$$

The boundary condition is: $S_j=C_j$ (C_j is constant, j=1, 2,…). It is noted that in eq. (3) and in the boundary condition, the contaminant emission rate density is assumed to be constant. This is reasonable when contaminant emission is slow such as volatile organic compounds (VOC) emission from dry building materials (Xu and Zhang, 2003, 2004).

If the position of a contaminant source is m (x, y, z) and the target position is n (x_0, y_0, z_0), the solution of Eq. (3) with internal and boundary contaminant sources can be written as follows:

$$C_A(x_0,y_0,z_0) = \int_V B_{m,n}(x_0,y_0,z_0,x,y,z,)S_i \mathrm{d}v. \qquad (4)$$

Obviously, $B_{m,n}(x_0,y_0,z_0,x,y,z)$ is the function of the airflow velocity field, the physical properties, the contaminant source and the target positions. For a given contaminant, $B_{m,n}(x_0,y_0,z_0,x,y,z)$ is only the function of the airflow velocity field. In other words, for a given contaminant, $B_{m,n}(x_0,y_0,z_0,x,y,z)$ describes the influence of position m on position n in the airflow velocity field. Therefore, we define $B_{m,n}(x_0,y_0,z_0,x,y,z)$ as the "spatial flow influence factor (*SFIF*)" of m to n. For convenience, $B_{m,n}(x_0,y_0,z_0,\ x,y,z)$ is designated as *SFIF* (*n*, *m*). In principle, *SFIF* (*n*, *m*) is the fraction of air molecules around point n from the molecules of air around point m. Considering that m, n are two arbitrary points, therefore, *SFIF* (*n*, *m*) describes a distinctive feature of the airflow structure, and presents a novel insight into the airflow field.

For a common 2-D or 3-D problem, equation (3) can be discretized as of the following form:

$$AC=b \qquad (5)$$

where C is a column vector representing discrete contaminant concentration of indoor space; A is the sparse matrix implying the information of flow field; and b is a column vector with the same size as C derived from source term and boundary condition.

From equation (5), equation (6) can be obtained as following:

$$C=A^{-1}b \qquad (6)$$

where A^{-1} is the inverse matrix of A.

Comparing definition of *SFIF* with equation (6), it can conclude that A^{-1} is just the discrete form of *SFIF*.

VALIDATION

For a given flow field and given pollutant source, we can calculate the contaminant not only by CFD method but also by definition of SFIF or equation (6). Definition of SFIF can be validated by comparing the results of the two methods.

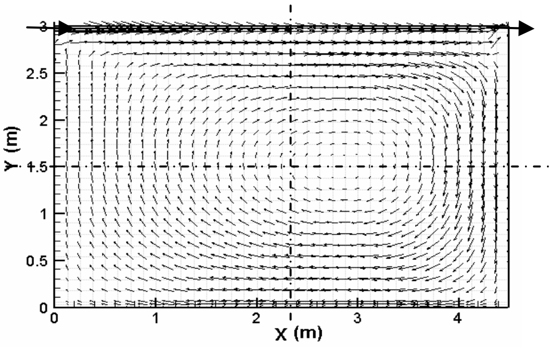


Fig.1 Schematic draw and flow field of Ito's experiment

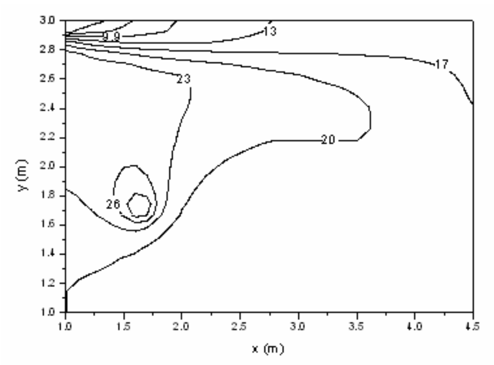
For simplification, a 2-D case is selected as Fig. 1. The corresponding flow experiment was conducted by Ito and et al. (2000) and the predicted flow field in Fig. 1 by *CFD* method fit the experimental data well. The geometric size and numerical conditions are listed in table 1.

Table 1 Geometric size and numerical conditions

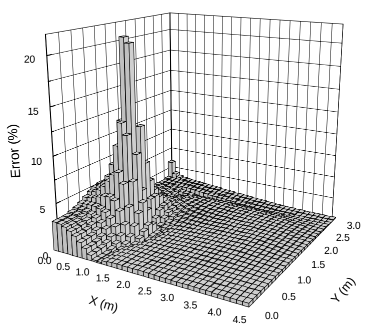
Number of grids and Room size (W×H)	36×28=4.5m×3.0m
Representative length L_0 (m)	0.06
Opening and exhaust slot width (m)	0.06
Supply air velocity U0(m/s)	1
Position of contaminant	Square enveloped by point (0.75, 0.90), (1.00, 0.90), (0.75, 1.12), (1.00, 1.12)
Intensity of source (kg/s)	0.1
Turbulence model	Standard k-ε model

Figs. 2(a) shows the concentration field by definition of *SFIF*. The relative difference of concentration on each grid by the two methods is illustrated in Fig.

2(b). It shows about 20% maximum relative deviation and less than 5% relative on most points, which can validate the definition of SFIF. The maximum relative deviation appears around source because of large grads.



(a) Predicted concentration by defineition of SFIF



(b) Error of predicted concentration of each position by SFIF definition compared with by CFD method

Fig.2 Comparison with CFD method

CASES OF OPTIMIZING POSITIONS OF CONTAMINANT SOURCES, OCCUPIED REGIONS AND ADSORPTION MATERIALS BY USING SFIF

Optimal Arrangement of Contaminant Sources and Target Regions for a Given Flow

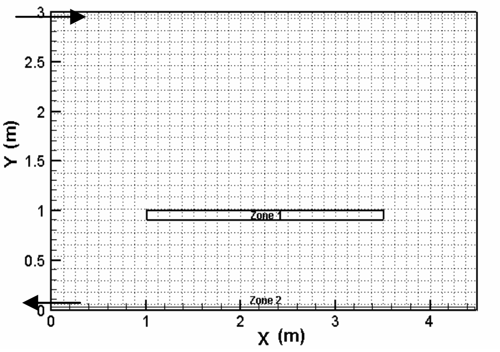
The following is an example for obtaining the optimal source and target region position by using *SFIF*. In a ventilated room whose geometric size and flow is shown as fig. 3(a). The breath zone of people is located at 1 m high with 1m width (8 grids). The available region (zone 1) to arrange breath zone is from 1m to 3.5m far from left wall in x direction as shown in Fig. 3(a). The source is located at floor with 2 m width (16 grids) which can represent a kind of chemical pollutant source such as carpet. The available region (zone 2) to arrange source is the whole floor as shown in fig. 3(a). *SFIF* is employed to optimize the positions of source and breath zone in available regions to make the average contaminant concentration at breath zone lowest. This can be expressed as the flowing mathematic problem:

$$\min f$$

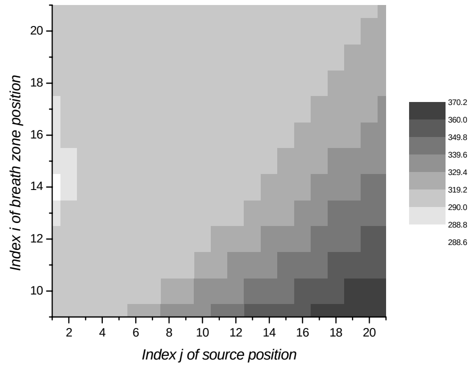
where $$f = \sum_{m=j}^{j+15} \sum_{n=36\times9+i}^{36\times9+i+7} A(n,m)/8 ,$$

$i \in [9,21], j \in [1,21]$, i and j are the index of available position of left sides of breath zone and source.

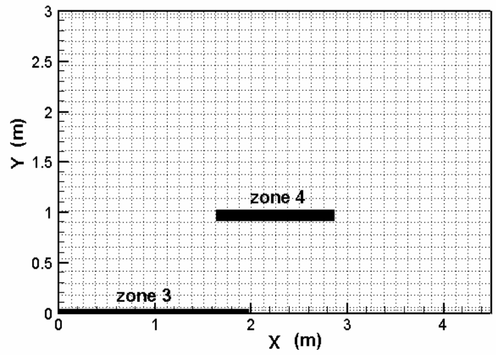
Fig. 3(b) shows the distribution of *f* when source and breath zone are located at different available position, which can obtained from SFIF matrix of the flow field easily. From that, it is seen that the target function f is minimum when source and breath zone are located at position j=1 (zone 3) and i=14 (zone 4) as show in fig. 3 (c). Therefore, when source and breath zone are located these two positions, the given flow can make its best influence.



(a) Available positions of source and breath zone



(b) Distribution of target function when source and breathe zone are located in different position



(c) Optimal positions of source and breath zone
Fig.3 Optimization of positions of source and breath zone

Optimization of Position of Adsorption Material for Given Contaminant Sources and Target Regions

As in fig. 1, the room's geometric size and air supply are the same as before. The contaminant source, carpet, is located in zone 1, and target region is zone 2 and the region occupied by adsorption material is signed as zone 3. The length of adsorption material is 1 m and the available positions of the center of the material are from P1 to P11. If the adsorption amount is assumed in proportion to local contaminant concentration with proportion factor k1, then the discreted equation (5) can be rewritten as equation (7):

$$AC = -k_1 DC + b \tag{7}$$

where, V is the position diagonal matrix in which the element is adsorption area in corresponding grid. From Eq. (7), the concentration on each grid can be calculated by Eq. (8).

$$C = -k_1 A^{-1} DC + A^{-1} b = -k_1 A^{-1} DC + C^* \tag{8}$$

Where, C* is the concentration without adsorption material, A-1 is the descreted SFIF. This equation can be rewritten as Eq. (9)

$$\begin{bmatrix} C_1 \\ \vdots \\ C_k \\ \vdots \\ C_n \end{bmatrix} = -k_1 \begin{bmatrix} a_{1,1} & \cdots & a_{1,k} & \cdots & a_{1,n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{k,1} & \cdots & a_{k,k} & \cdots & a_{k,n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{n,1} & \cdots & a_{n,k} & \cdots & a_{n,n} \end{bmatrix} \begin{bmatrix} 0 & & & & 0 \\ & d_k & \vdots & & \\ & \cdots & d_j & \cdots & \\ & & \vdots & d_{k+N} & \\ 0 & & & & 0 \end{bmatrix} \begin{bmatrix} C_1 \\ \vdots \\ C_k \\ \vdots \\ C_n \end{bmatrix} + \begin{bmatrix} C_1^* \\ \vdots \\ C_k^* \\ \vdots \\ C_n^* \end{bmatrix} \tag{9}$$

That means

$$C_i = -k_1 \sum_{j=k}^{k+N} a_{i,j} d_j C_j + C_i^* \qquad j \in zone\ 3 \tag{9-1}$$

$$\begin{bmatrix} C_k \\ \cdots \\ C_{k+N} \end{bmatrix} = -k_1 \begin{bmatrix} a_{k,k} d_k & \cdots & a_{k,k+N} d_{k+N} \\ \vdots & \vdots & \vdots \\ a_{k+N,k} d_k & \cdots & a_{k+N,k+N} d_{k+N} \end{bmatrix} \begin{bmatrix} C_k \\ \cdots \\ C_{k+N} \end{bmatrix} + \begin{bmatrix} C_k^* \\ \cdots \\ C_{k+N}^* \end{bmatrix} \tag{9-2}$$

The concentration in the region occupied by adsorption material can be calculated from Eq. (9-2) by the Eq. (9-3):

$$\begin{bmatrix} C_k \\ \cdots \\ C_{k+N} \end{bmatrix} = \begin{bmatrix} 1 + k_1 a_{k,k} d_k & \cdots & k_1 a_{k,k+N} d_{k+N} \\ \vdots & \vdots & \vdots \\ k_1 a_{k+N,k} d_k & \cdots & 1 + k_1 a_{k+N,k+N} d_{k+N} \end{bmatrix}^{-1} \begin{bmatrix} C_k^* \\ \cdots \\ C_{k+N}^* \end{bmatrix} \tag{9-3}$$

Then the concentration in the target region can be predicted by Eq. (9-3). It is obviouse that calculation is easier by Eq. (9-3) than by CFD method because only target region is treated. Fig. 5 shows the average concentration in zone 2 and the whole chamber calculated by mentioned above method when adsorption material is placed in from point 1 to point 11 respectively based on the parameters, together with the average concentration without adsorption material. It is seen that the adsorption material make the best effect when it is placed in P4 though P1 is closer to the source than P4. That is because that most of purified air by adsorption material goes out of the chamber directly and the influence of P1 on zone 2 is less than P4, which can also be seen in Fig. 5. From Fig. 5, it seen that when average SFIF of one zone to the target zone is larger, the clean effect of adsorption material in this zone on the target zone is better. Therefore, we can optimize the position of adsorption materials directly through comparing the average SFIF of available positions on the target zone, which is more convenient than by the preceding method.

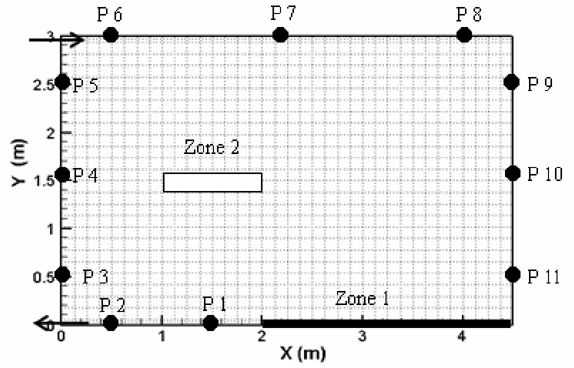


Fig. 4 Schematic showing positions of the contaminant source, target zone and adsorption material.

Table 2 Parameters of source and adsorption

Intensity of source per area (g $m^{-2}s^{-1}$)	0.04
Area of source (m^2)	2.5
Adsorption coefficient ($m^{-2}s^{-1}$)	0.1
Area of adsorption material (m^2)	1

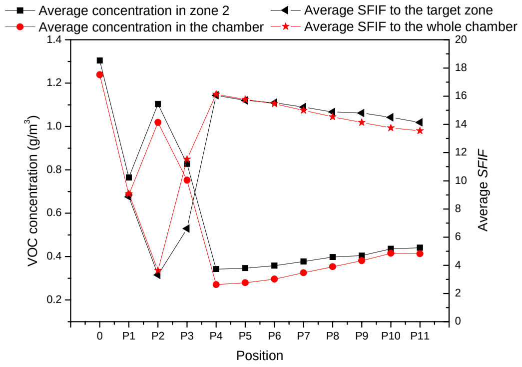


Fig.5 Average VOC concentration in target region and the whole chamber without adsorption material and with adsorption material placed in different position and average SFIF to different regions

CONCLUSIONS

Spatial flow influence factor is a new concept for characterizing indoor air flow and can be easily used to optimize indoor air flow to lower contaminant concentration in target region in three ways: (1) Optimizing arrangement of source and breath zone to make the given air flow more effective to improve indoor air quality; (2) Optimizing position of adsorption materials to make clean effect better. However, as a new concept, there are some limits for SFIF unable to be employed to optimize indoor air flow under some conditions such as: (1) Transient case; (2) Boundary conditions, source and adsorption effect are not linear; (3) Arrangements of source and breath zone strongly affect air flow. To overcome the disadvantages, more researches should be conducted.

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