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Field synergy analysis and optimization of decontamination ventilation designs

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Abstract

The field synergy principle has been validated to be an effective tool for enhancing convective heat transfer capability. Since convective mass transfer is analogous to convective heat transfer, the field synergy principle has been extended to convective mass transfer analyses to enhance the overall decontamination rate of indoor ventilation systems. According to the field synergy principle, the overall decontamination capability and the utilization efficiency of the air are both influenced by the synergy between the velocity vectors and the contaminant concentration gradients. Furthermore, in order to derive a method to improve the synergy based on the essence of convective mass transfer, the mass transfer potential capacity dissipation function is defined, and then the convective mass transfer field synergy equation is obtained by seeking the extremum of the mass transfer potential capacity dissipation function for a set of specified constraints. The convective mass transfer field synergy equation can be solved to find the optimized air velocity distribution to increase the field synergy and the overall decontamination capability. The optimized air velocity field provides guidance for optimizing ventilation system designs.

Keywords: Field synergy principle; Convective mass transfer; Capacity potential dissipation function; Field synergy equation; Ventilation

1. Introduction

Indoor air quality, which is mostly a function of the contaminant concentration, is very important to people's health and comfort [1,2]. Indoor air needs a certain amount of fresh air to dilute indoor contaminants for good indoor air quality. However, fresh air flow rates in air conditioning systems have been reduced to save energy since the energy crisis in the 1970s. Meanwhile, volatile ornamental materials, household appliances and office equipment (e.g., computers, televisions and printers) that emit contaminants have become much more widely used. These two factors have caused increased indoor contaminant concentrations, which resulted in serious air quality problems. The Environmental Protection Administration (EPA) of the United States reported that the contaminant concentrations in many civil and commercial buildings were several dozen times higher than in outdoor air, sometimes even in excess of 100 times more [3]. The direct economic loss caused by indoor air pollution is more than 40 billion dollars every year [4]. Indoor air pollution had been classified into one of the most serious threats to people's health [5].

The most effective and simple method to remove airborne contaminants is to bring more outdoor fresh air into indoor spaces to dilute the polluted air around the occupants. However, cooling or heating outdoor fresh air usually consumes much energy. Therefore, fresh air must be utilized more effectively, which demands excellent ventilation arrangements. Many numerical and experimental studies have analyzed the ventilation efficiency for various intake sizes, building structures and pollution sources [6–10]. However, they could only compare a very limited number of ventilation schemes, so they probably did not find an optimum solution. In addition, most studies lacked a solid theoretical

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Nomenclature

A, B, C_0	Lagrange multiplicator
c_p	specific heat capacity, J kg^{-1} K^{-1}
D	mass diffusion coefficient, m^2 s^{-1}
F	additional volume force per unit volume, N m^{-3}
$\vec{n}$	outward normal unit vector
P	pressure, Pa
S	surface area, m^2
T	temperature, K
u, v, w	velocity component in x-, y- and z-directions, m s^{-1}
$\vec{U}$	velocity vector
V	volume, m^3
x, y, z	Cartesian coordinates, m
Y	mass fraction
Z_m	mass transfer potential capacity dissipation function, kg s^{-1} m^{-3}
Z_q	heat transfer potential capacity dissipation function, W K^{-1} m^{-3}
ρ	air density, kg m^{-3}
μ	dynamic viscosity, kg m^{-1} s^{-1}
η	generalized diffusion coefficient
φ	dissipation function
ϕ	universal variable
λ	thermal conductivity, W m^{-1} K^{-1}
$\delta_{t,x}$	thermal boundary layer thickness, m
Φ	viscous dissipation function, W m^{-3}
∇	divergence operator
Ω	flow domain
Γ	flow domain boundary
Π	Lagrange function

Subscripts

cs	contaminant surface
in	inlet
nms	surface without mass exchange
out	outlet
w	wall

basis that would enable optimization of the ventilating system designs to improve the ventilation efficiency.

The ventilation decontamination process is a mass transfer process, which is analogous to the heat transfer process in some cases. For example, the governing equation for heat conduction is Fourier's law and for molecular diffusion is Fick's law. Both can be expressed as

$$\text{Flux} = \text{Diffusivity} \times \text{gradient}.$$

The governing equation for convective heat transfer is the energy conservation equation while for convective mass transfer is the species conservation equation. Both can be expressed as

$$\rho\vec{U} \cdot \nabla\phi = \eta\nabla \cdot \nabla\phi.$$

Because of the analogy between heat and mass transfer, existing heat transfer theories can be extended to mass transfer problems. For convective heat transfer phenomenon, Guo et al. [11,12] and Tao et al. [13] presented the field synergy principle, which has been validated with numerous examples [14–16]. The field synergy principle suggests that for a given set of constraints, an optimum velocity field exists, which optimizes the synergy between the temperature gradient and the velocity field, to maximate the heat transfer rate. For convective mass transfer phenomenon, Mo et al. [17] used field synergy theory to analysis the removal of volatile organic compounds (VOCs) by photocatalytic oxidation reactors and showed that the average angle between the velocity vectors and the mass concentration gradients can influence the convective mass transfer rate in the reactor. Therefore, optimization of the synergy between the contaminant concentration gradient and the velocity field is also critical for maximizing the decontamination of indoor air in ventilation systems.

In addition, Guo et al. [18] defined a heat transfer potential capacity dissipation based on the essence of heat transfer phenomenon. Then the least dissipation principle for the heat transport potential capacity was developed to enhance the heat conduction efficiency for heat conduction optimization. Meng [19] derived the convective heat transfer field synergy equation by seeking the extremum of the heat transfer potential capacity dissipation for a specified viscous dissipation utilizing the variational principle. The solution of the convective heat transfer field synergy equation gives the optimized velocity field which increases the overall heat transfer rate.

Based on the analogy between heat and mass transfer, this paper applies the field synergy principle to convection mass transfer in ventilation systems to improve the overall decontamination capability of ventilation systems. The relationship between the ventilation decontamination capability and the field synergy is analyzed. The mass transfer potential capacity dissipation function is defined. Then the convective mass transfer field synergy equation is obtained by utilizing thermodynamics variation theory to provide a framework for optimizing ventilation arrangements. Numerical examples are provided to verify the applicability of the theory to ventilation system designs.

2. Field synergy principle and field synergy equation

2.1. Field synergy principle and field synergy equation in convective heat transfer processes [11–13,19]

For two-dimensional boundary layer flows and heat transfer along a plate, integrating the energy conservation equation along the thermal boundary layer with the boundary condition at the outer edge of the thermal boundary layer being $(\partial T/\partial y)_{\delta_{t,x}} = 0$ gives

$$\int_0^{\delta_{t,x}} \rho c_{\mathrm{p}}(\vec{U} \cdot \nabla T)\mathrm{d}y = -\lambda \frac{\partial T}{\partial y}\bigg|_w. \tag{1}$$

The right side is the heat flux between the solid wall and the fluid, while the left side is the dot product between the velocity vector and the temperature gradient, which can be written as:

$$\int_0^{\delta_{t,x}} \rho c_{\mathrm{p}}(\vec{U} \cdot \nabla T)\mathrm{d}y = \int_0^{\delta_{t,x}} \rho c_{\mathrm{p}}|\vec{U}||\nabla T|\cos\beta \mathrm{d}y, \tag{2}$$

where β is the angle between the velocity vector and the temperature gradient. Therefore, the convective heat transfer rate is influenced not only by the magnitude of the velocity and the temperature gradient but also by the angle between the velocity vector and the temperature gradient. In other words, the convective heat transfer rate is influenced by the synergy between the velocity vectors and the temperature gradients. Furthermore, Tao et al. [13] extended the field synergy principle to three-dimensional convective heat transfer problems and validated its accuracy and applicability.

Heat transfer is an irreversible process. When heat is transported from higher temperatures to lower temperatures, the heat transfer capacity will always be reduced, which was defined as the heat transfer potential capacity dissipation by Guo et al. [18]. The heat transfer potential capacity dissipation function is defined as:

$$Z_{\mathrm{q}} = \frac{1}{2}\lambda \nabla T \cdot \nabla T. \tag{3}$$

For steady-state laminar convection heat transfer processes without internal heat source, Meng [19] derived the convective heat transfer field synergy equation by seeking the extremum of the heat transfer potential capacity dissipation using the variational principle for specified constraints including energy conservation, mass conservation and a specified viscous dissipation to enhance the capability of convection heat transfer systems. The synergy equation is:

$$\mu\nabla^2 U - \rho U \cdot \nabla U - \nabla P + (C_{\Phi} A \nabla T + \rho U \cdot \nabla U) = 0. \tag{4}$$

When the flow field satisfies Eq. (4), the entire convection heat transfer capability is optimized.

2.2. Field synergy principle in convective mass transfer processes

The 3D contaminant concentration conservation equation for steady-state mass diffusion without mass sources can be written as

$$\rho\vec{U} \cdot \nabla Y = \nabla \cdot (\rho D \nabla Y). \tag{5}$$

Integrating this equation over the entire domain Ω:

$$\int_\Omega \rho\vec{U} \cdot \nabla Y \mathrm{d}V = \int_\Omega \nabla \cdot (\rho D \nabla Y)\mathrm{d}V. \tag{6}$$

The volume integration over the domain in Eq. (6) can be transformed to a surface integral using the Green' theorem

$$\int_\Omega \rho\vec{U} \cdot \nabla Y \mathrm{d}V = \int_\Gamma \vec{n} \cdot (\rho D \nabla Y)\mathrm{d}S. \tag{7}$$

For ventilation systems, the domain boundary can be divided into contaminant emitting surfaces, surface without mass transfer, air inlets and air outlets. Thus Eq. (7) can be written as

$$\begin{aligned}\int_\Omega \rho\vec{U} \cdot \nabla Y \mathrm{d}V = &\int_{\mathrm{cs}} \vec{n} \cdot (\rho D \nabla Y)\mathrm{d}S + \int_{\mathrm{nms}} \vec{n} \cdot (\rho D \nabla Y)\mathrm{d}S \\ &+ \int_{\mathrm{in}} \vec{n} \cdot (\rho D \nabla Y)\mathrm{d}S + \int_{\mathrm{out}} \vec{n} \cdot (\rho D \nabla Y)\mathrm{d}S.\end{aligned} \tag{8}$$

The first term on the right side is the mass transfer between the contamination source surface and the air, which is the decontamination rate in ventilation systems. On surfaces without mass transfer, the contaminant concentration gradient is zero, so the second integral is zero. The third and fourth terms are the axial diffusion of contaminants at the outlet and inlet, respectively, where the air velocity is high and the contaminant concentration gradient is relatively small, so the axial diffusion of the contaminants at the inlet and outlet may be neglected. Therefore, Eq. (8) can be simplified

$$\begin{aligned}\int_\Omega \rho\vec{U} \cdot \nabla Y \mathrm{d}V &= \int_\Omega \rho|\vec{U}||\nabla Y|\cos\gamma \mathrm{d}V \\ &= \int_{\mathrm{cs}} \vec{n} \cdot (\rho D \nabla Y)\mathrm{d}S,\end{aligned} \tag{9}$$

where γ is the angle between the velocity vector and the concentration gradient. As seen from Eq. (9), the integral of the density times the dot product of the velocity vector and the concentration gradient over the entire domains equal to the overall ventilation system decontamination rate ($\dot{m}$).

For decontamination, V is the room volume and S_{cs} is the surface area emitting contaminants. A characteristic length can then be defined as:

$$L = \frac{V}{S_{\mathrm{cs}}}. \tag{10}$$

Introduce the dimensionless variables:

$$\overline{\overline{U}} = \frac{\vec{U}}{U_{\mathrm{in}}}, \nabla\overline{Y} = \frac{\nabla Y}{(Y_{\mathrm{cs}} - Y_{\mathrm{in}})/L}. \tag{11}$$

Eq. (9) can be written in dimensionless form as:

$$Sh = ReSc\frac{\int_\Omega \overline{\overline{U}} \cdot \nabla\overline{Y}\mathrm{d}V}{V}, \tag{12}$$

where Sh, Re and Sc represent the Sherwood number, the Reynolds number and the Schmidt number. Eq. (12) show that the Sherwood number depends not only on the Reynolds number and the Schmidt number but also on the volume-average value of $\overline{\overline{U}} \cdot \nabla\overline{Y}$. This value is defined as the mass transfer field synergy number which represents the synergy between the velocity vector and the contaminant concentration over the entire volume. For decontamination ventilation, the fluid is air and the Schmidt number is constant. Hence, the various ways for increasing the overall strength of the convective mass transfer can be classified into: (1) increasing the Reynolds number which means increasing the fresh air flow rates and (2) increasing the mass transfer field synergy number by changing ventilation arrangement. For a given fresh air flow rates, the Reynolds number is constant, so the convective mass transfer capability is influenced only by the mass transfer field synergy number. The field synergy number can be increased by comparing velocity fields for various ventilation arrangements to select the largest one. However, this will not likely maximize the field synergy number because it does not consider the essence of the convective mass transfer problem.

2.3. Field synergy equation for convective mass transfer processes

Heat transfer is heat diffusion caused by a temperature gradient while mass transfer is mass diffusion caused by a concentration gradient, which is analogous to heat transfer. When mass is transported from a higher concentration to a lower concentration, the mass transfer capacity is also always reduced. Therefore, the mass transfer potential capacity dissipation function can be defined as:

$$Z_{\mathrm{m}} = \frac{1}{2}\rho D\nabla Y \cdot \nabla Y. \tag{13}$$

For steady-state, constant property and incompressible convective mass transfer without mass sources, the optimized velocity field can be obtained by seeking the extremum of the mass transfer potential capacity dissipation function for specified constraints, which is a typical variational problem in mathematics. A Lagrange function [20,21] can be constructed for a given set of constraints such as the continuity equation, species equation and constant viscous dissipation

$$\Pi = \int\int\int_{\Omega}\left[\frac{1}{2}\rho D\nabla Y \cdot \nabla Y + C_0\Phi + A(\rho D\nabla \cdot \nabla Y - \rho U \cdot \nabla Y) + B\nabla \cdot \rho\vec{U}\right]\mathrm{d}V, \tag{14}$$

where A, B and C, are Lagrange multiplicators. Because of the different types of the constraints, A and B vary with position, while C_0 is constant for a given constant viscous dissipation. Φ is viscous dissipation function which is expressed as:

$$\Phi = \mu\left[2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{\partial w}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2\right]. \tag{15}$$

The variational of Eq. (14) with respect to the mass fraction Y is:

$$-\rho\vec{U} \cdot \nabla A = \rho D\nabla \cdot (\nabla A) - \rho D\nabla \cdot (\nabla Y). \tag{16}$$

The variational of Eq. (14) with respect to the velocity vector $\vec{U}$ is:

$$\mu\nabla^2\vec{U} + \frac{\rho}{2C_0}A\nabla Y + \frac{1}{2C_0}\nabla B = 0. \tag{17}$$

The variational of Eq. (14) with respect to A is the contaminant conservation equation

$$\rho\vec{U} \cdot \nabla Y = \rho D\nabla \cdot \nabla Y. \tag{18}$$

The variational of Eq. (14) with respect to B is the continuity equation

$$\nabla \cdot \rho\vec{U} = 0. \tag{19}$$

Eqs. (16)–(19) have four unknown variables and four governing equations, so the unknown variables can be found for a given set of boundary conditions. The air flow must also satisfactorily meet the momentum equation

$$\rho\vec{U} \cdot \nabla\vec{U} = -\nabla P + \mu\nabla^2\vec{U} + \vec{F}. \tag{20}$$

Comparison of Eqs. (17) and (20) gives the follow equations

$$B = -2C_0P, \tag{21}$$

$$\vec{F} = C_\Phi A\nabla Y + \rho\vec{U} \cdot \nabla\vec{U}, \tag{22}$$

where C_Φ is related to the viscous dissipation

$$C_\Phi = \frac{\rho}{2C_0}. \tag{23}$$

Substituting Eqs. (21) and (22) into Eq. (20) gives:

$$\rho\vec{U} \cdot \nabla\vec{U} = -\nabla P + \mu\nabla^2\vec{U} + (C_\Phi A\nabla Y + \rho\vec{U} \cdot \nabla\vec{U}). \tag{24}$$

Eq. (24) is defined as the convective mass transfer field synergy equation, which is similar to the momentum equation with an additional volume force $\vec{F}$. This force changes the mass transfer field synergy, so that the entire convective mass transfer capability is optimized. This additional volume force can be divided into the additional inertial force $F_{\mathrm{U}} = \rho U \cdot \nabla U$, related to the velocity, and the additional concentration gradient force, $F_{\mathrm{Y}} = C_\Phi A\nabla Y$, related to the species concentration.

For cases without the addition concentration gradient force, the convective mass transfer field synergy equation can be simplified to:

$$0 = -\nabla P + \mu\nabla^2 U. \tag{25}$$

As shown by Eq. (25), the additional inertial force counteracts the inertial force in the fluid flow process, which is similar to flows without inertial force. Because flows without inertial force have a smaller viscous dissipation than any other incompressible flow in the same region with the same values of the velocity vector everywhere on the boundary of the region [22], fluid flows with this additional inertial force have the minimum viscous dissipation for given boundary conditions. Thus, if fluid flows with the additional inertial force as well as the additional concentration gradient force, the viscous dissipations of these fluid flows are larger than the one without additional concentration gradient force. A stronger additional concentration gradient force leads to a larger viscous dissipation. However, the potential effect of the additional concentration gradient force is to drive fluid to flow along the mass flux, and then enhance convective mass transfer. Therefore, the additional concentration gradient volume force not only increases the viscous dissipation, but also enhances convective mass transfer. As shown in Eq. (24), the absolute value of C_Φ determines the magnitude of the additional concentration gradient force. For a given C_Φ, the flow field can be numerically obtain for this specific additional volume force, and then the viscous dissipation as well as the convective mass transfer rate can be calculated. For various values of C_Φ, solving the field synergy equation can obtain different optimal velocity fields. These optimal velocity fields provide a framework for designing ventilation arrangements.

3. Numerical experiment analysis

To illustrate the applicability of field synergy principle for convective mass transfer processes, the decontamination quality was varied by changing the boundary conditions, such as the intake air velocity and the ventilation arrangement. The results were used to analyze the influence of the convective mass transfer field synergy on the overall mass transfer rate. In addition, for a given set of boundary conditions, the convective mass transfer field synergy equation was solved to vary the synergy and change the decontamination capability. The results were all obtained numerically using the commercial software FLUENT 6.0, with the SIMPLEC algorithm for the velocity and pressure linkage. The QUICK scheme was used to discretize the convection and diffusion term. All the flows were assumed to be laminar and steady.

3.1. Analysis of the field synergy

3.1.1. Various inlet air velocities

The two 2D ventilation configurations studied here are presented in Figs. 1 and 2. The dimensions of the rectangular cavity are: $L = 4$ mm, $H = 3$ mm and $W_1 = W_2 = W_3 = W_4 = 0.2$ mm. Air enters the rectangular cavity from the top left corner horizontally in Fig. 1 and vertically in Fig. 2 and exits from the lower right corner. The inlet air has a contaminant mass fraction of 0. The bottom is the contaminant source with a contaminant mass fraction of 0.01, while the left, right and upper surfaces of the cavity all have no mass transfer.

The numerical results are shown in Figs. 3 and 4 for the vertical and horizontal ventilation configurations. With increasing the air inlet velocities, the overall decontamination rate ($\dot{m}$) increased non-linearly, while the field synergy number (S) decreased. The increased air inlet velocity increases the Reynolds number and the surface convective mass transfer coefficient, which enhances the overall decontamination rate. However, the decreasing field synergy number reduces the rate of increase in the decontamination rate. Therefore, increasing the air inlet velocity enhances the decontamination capability, but the decreasing field synergy number reduces the air utilization efficiency.

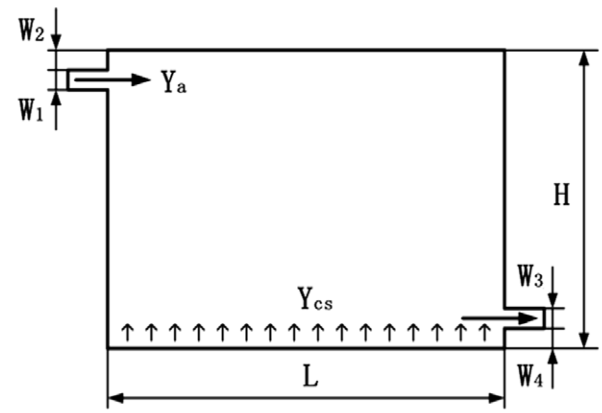

Fig. 1. Ventilation configuration with a horizontal inlet at the top left corner.

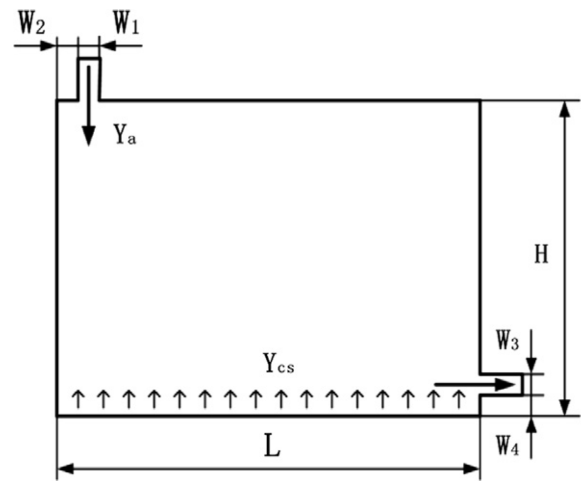

Fig. 2. Ventilation configuration with a vertical inlet at the top left corner.

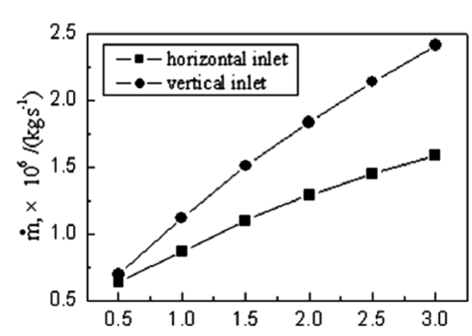

Fig. 3. Variation of decontamination rate for horizontal and vertical inlets.

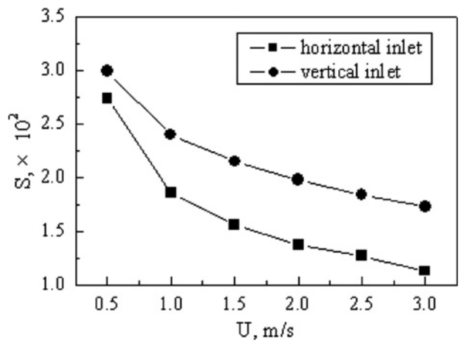

Fig. 4. Variation of field synergy numbers for horizontal and vertical inlets.

3.1.2. Different ventilation types

The overall decontamination rate and mass transfer field synergy for various ventilation types are compared, including a horizontal inlet at the lower left corner (type A, Fig. 5), a vertical inlet at the top left corner (type B, Fig. 2), a horizontal inlet at the top right corner (type C, Fig. 6), a horizontal inlet at the top left corner (type D, Fig. 1) and a vertical inlet at the top right corner (type E, Fig. 7). The boundary conditions and the values of L, H, W_1, W_2, W_3 and W_4 are the same for all five types. The air intake velocities are 1 m s^{-1} or 2 m s^{-1}.

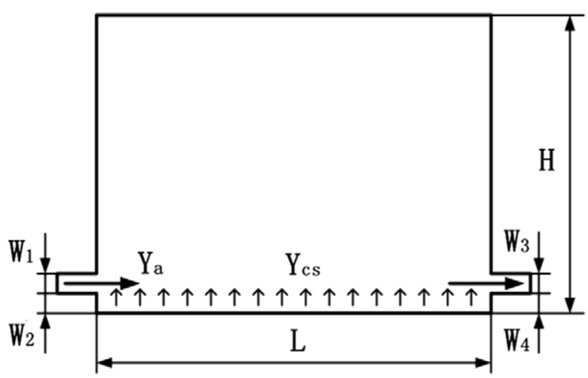

Fig. 5. Ventilation arrangement with a horizontal inlet at the lower left corner.

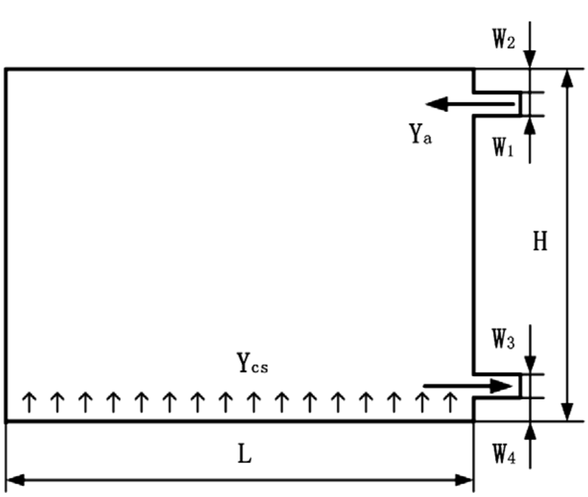

Fig. 6. Ventilation arrangement with a horizontal inlet at the top right corner.

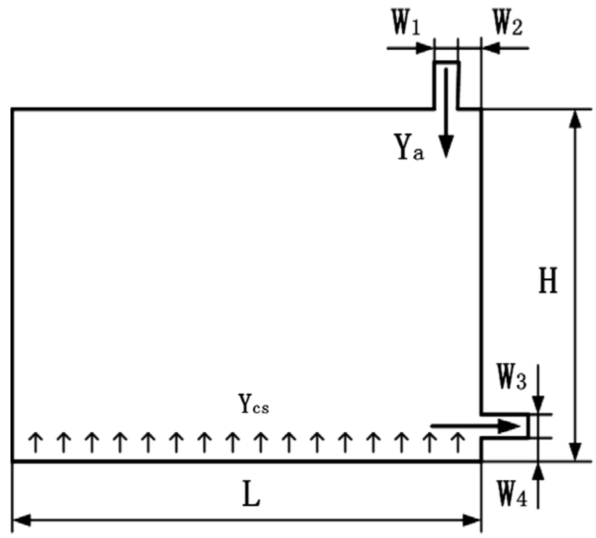

Fig. 7. Ventilation arrangement with a vertical inlet at the top right corner.

The numerical results in Figs. 8 and 9 show that for the same air inlet velocity, both the overall decontamination rate and the mass transfer field synergy number decrease from the highest in type A to B, C, D, and the lowest in type E. For a given air inlet velocity, the Reynolds number is constant, so the overall decontamination rate is only

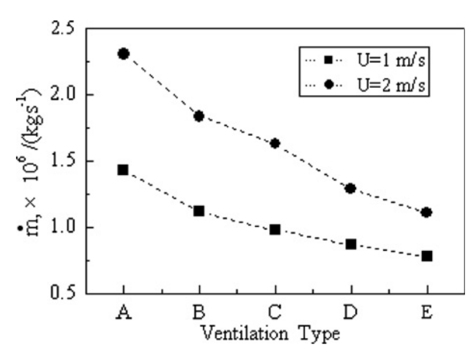

Fig. 8. Decontamination rates for various ventilation arrangements.

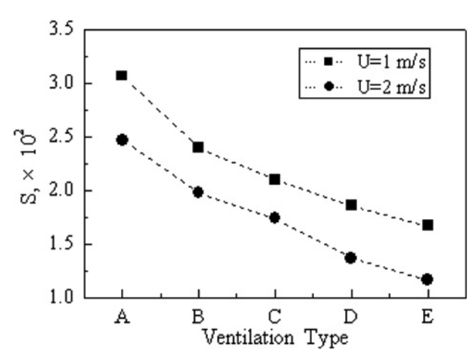

Fig. 9. Field synergy numbers for various ventilation arrangements.

influenced by the mass transfer field synergy number. Therefore, the better ventilation arrangement can be obtained by comparing various velocity fields for various ventilation arrangements and selecting the arrangement with largest mass transfer field synergy number. However, this does not consider the essence of the convective mass transfer physics.

3.2. Validation and application of the field synergy equation

As analyzed in the second part of this paper, the solution of the convective mass transfer field synergy equation can be analyzed to improve the field synergy, so as to improve the decontamination rate.

The ventilation system with a horizontal inlet at the top left corner was selected to analyze how additional forces affect the velocity field and the decontamination rate. Numerical results for the original velocity vectors and contaminant mass fraction contours without additional volume forces in the rectangular cavity with the $2\,\mathrm{m\,s^{-1}}$ intake velocity are presented in Fig. 10. The air entering the cavity at the inlet creates a clockwise eddy. The velocity vectors and the mass fraction contours are almost parallel over most of the computational domain, which means that the velocity vectors and the local concentration gradients are nearly perpendicular to each other, leading to a large angle between them and a small dot product in Eq. (11). In addition, the velocities along the contamination surface are smaller than that at the inlet. Based on the field synergy principle given in Eq. (11), the synergy is relatively bad because the dot product is small. The field synergy number for this example is 1.37×10^{-2} while the overall decontamination rate is $1.29 \times 10^{-6}\,\mathrm{kg\,s^{-1}}$.

The numerical solutions with different constant C_Φ (corresponding to certain viscous dissipation) result in different flow patterns. In this paper, the range of C_Φ is from 0 to -5×10^5 for solving the field synergy equation in the cavity. For the case of $C_\Phi = 0$, the flow field can be obtained as shown in Fig. 11. After entering the rectangle cavity from the inlet, the air is dispersed along the upper and left surfaces. The magnitudes of the velocity and the velocity gradient are both relatively small, and there is not any jet or eddy in the cavity. For this case, both the viscous dissipation and the convective mass transfer rate are small.

By decreasing the value of C_Φ, the fluid flow direction changes along the concentration gradient gradually. Fig. 12 shows the velocity vectors and mass fraction contours in the cavity for the case of $C_\Phi = -5 \times 10^5$. After

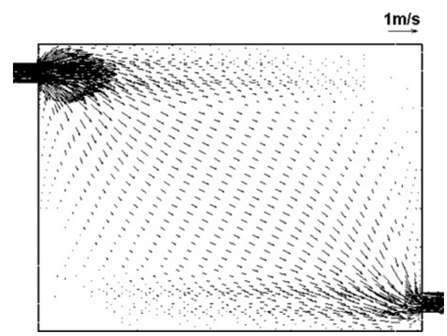

Fig. 11. Optimized velocity vectors for the case of $C_\Phi = 0$.

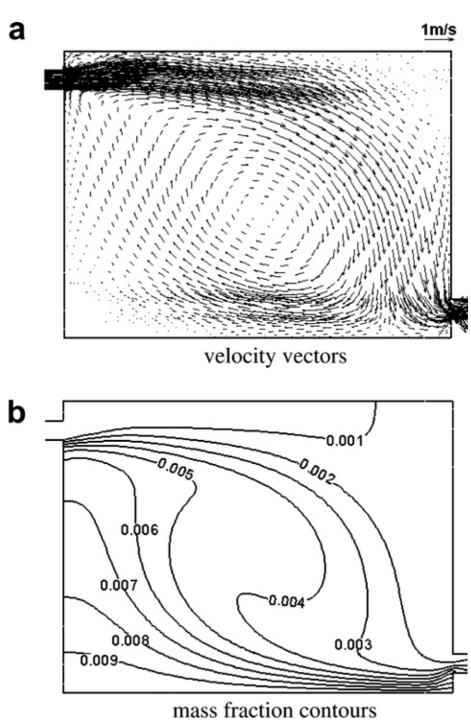

Fig. 10. Flow results without additional volume forces.

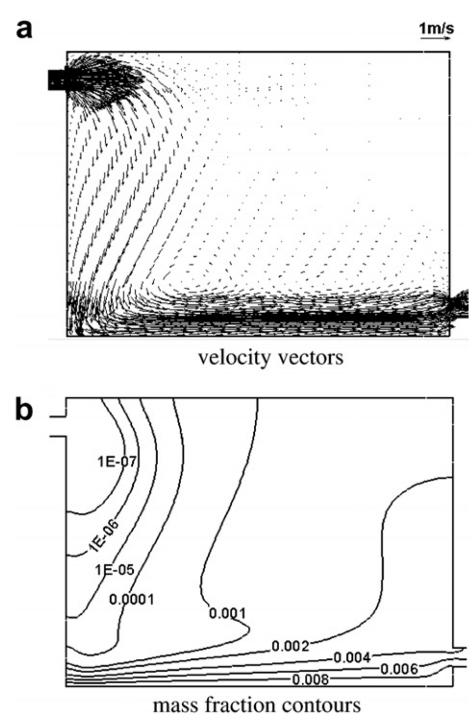

Fig. 12. Optimized results for the case of $C_\Phi = -5 \times 10^5$.

entering the rectangle cavity from the inlet, the air is deflexed so that it immediately flows down the left wall and then towards the outlet along the contaminant surface. The magnitudes of the velocities along the contamination surface are almost equal to that at the inlet. The velocity vectors and the mass fraction contours are almost perpendicular at the lower left corner of the cavity, which means that the velocity vectors and the local concentration gradients are nearly parallel to each other. The contaminant concentration gradient of is quite large. Then using the field synergy concept, the synergy between the velocity vectors and the concentration gradients is better than in the original one without additional forces. The field synergy number for this case is 3.34×10^{-2} with an overall decontamination rate of $3.15 \times 10^{-6}\,\mathrm{kg\,s^{-1}}$, which are both 2.44 times the original value. Therefore, the solution of the field synergy equation can be analyzed to increase the mass transfer field synergy and the overall decontamination rate.

Although the optimal velocity field obtained from the convective mass transfer field synergy equation with additional volume force differs from the actual velocity field without additional volume forces, the optimal flow pattern can be approximated in actual applications by engineering technique, including varying the inlet position or configuration, to enhance the ventilation decontamination capability. As shown in Fig. 12a, the left wall has no mass transfer, so the air downflow here contributes little for enhancing the decontamination. Therefore, the horizontal inlet at the top left corner should be moved to the lower left corner, so that the air flow along the contaminant surface is similar to the optimized flow field obtained from the field synergy equation. This analysis also explains why the mass transfer field synergy and the overall contamination rate are largest for the type A ventilation system, as shown in Figs. 8 and 9.

4. Conclusions

The field synergy principle has been used to analyze convective mass transfer to improve the overall decontamination rate of indoor ventilation systems. In decontamination ventilation processes, the overall system decontamination capability can be enhanced by increasing the air inlet velocity or by enlarging the synergy between the velocity vectors and the contaminant concentration gradients. However, although increases of the air inlet velocity were found to improve the decontamination rate, the inlet velocity increases also reduced the field synergy number which leads a reduction in the air utilization efficiency. The air utilization efficiency and the overall decontamination rate can be increased by increasing the mass transfer field synergy number for a given air inlet velocity.

A method was derived to improve the field synergy based on the essence of convective mass transfer using the mass transfer potential capacity dissipation function for mass transfer analyses. The convective mass transfer field synergy equation was obtained by seeking the extremum of the capacity potential dissipation function for a given set of constraints. The field synergy equation is similar to the momentum equation with an additional volume force. The solution of the synergy equation gives the optimized velocity field which increases the synergy and the overall decontamination rate.

Although the optimal flow field obtained from the convective mass transfer field synergy equation will differ from practical flow fields in some aspects, the optimized velocity field provides guidelines to flow fields that will improve the ventilation decontamination rate in practical applications.

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