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The extremum principle of mass entransy dissipation and its application to decontamination ventilation designs in space station cabins

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In terms of the analogy between mass and heat transfer phenomena, a new physical quantity, i.e. mass entransy, is introduced to represent the ability of an object for transferring mass to outside. Meanwhile, the mass entransy dissipation occurs during mass transfer processes as an alternative to measure the mass transfer irreversibility. Then the concepts of mass entransy and its dissipation are used to develop the extremum principle of mass entransy dissipation and the corresponding method for convective mass transfer optimization, based on which an Euler's equation has been deduced as the optimization equation for the fluid flow to obtain the best convective mass transfer performance with some specific constraints. As an example, the ventilation process for removing gaseous pollutants in a space station cabin with a uniform air supply system has been optimized to reduce the energy consumption of the ventilation system and decrease the contaminant concentration in the cabin. By solving the optimization equation, an optimal air velocity distribution with the best decontamination performance for a given viscous dissipation is firstly obtained. With the guide of this optimal velocity field, a suitable concentrated air supply system with appropriate air inlet position and width has been designed to replace the uniform air supply system, which leads to the averaged and the maximum contaminant concentrations in the cabin been decreased by 75% and 60%, respectively, and the contaminant concentration near the contaminant source surface been decreased by 50%, while the viscous dissipation been reduced by 30% simultaneously.

convective mass transfer, mass entransy dissipation, space station, decontamination ventilation, optimization

Because of the micro-gravity environment in space, air flow in space station cabins caused by natural convection decreases greatly, the only way adopted to promote air flow for removing the contaminant diffused from persons and facilities in space station is mechanical ventilation. Thus, ventilation system determines the decontamination performance in cabins. Meanwhile, since ventilation systems own a certain mass, take up a certain volume and consume electric energy, how to design a suitable ventilation system is critical for decreasing the contaminant concentration, lessening the electric energy consumption, lightening the ventilation system weight, and reducing the manufacture and running cost.

Hofacker et al.[1] numerically simulated the air velocity and temperature fields in the European HERMES aerospaceplane cabin and analyzed the heat transfer performance of the ventilation system with narrow slot inlets. Chang et al.[2] studied the variation range of air velocity in the cabin with different air supply velocities. In refs. [3−5], the air velocity and temperature fields in cabins with various air supply systems, including uniform air inlet, concentrated air inlet and oblique air inlet, were analyzed. By comparing these air supply systems, they found that the heat transfer performance of the

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concentrated air supply system was the best. However, the aforementioned studies mainly focused on the analysis of convective heat transfer processes, while there were little researches for decontamination ventilation design in cabins. On the other hand, for decontamination process with mechanical ventilation system in above ground structures, Chen et al.[6–10] obtained the ventilation system with the optimal decontamination performance by comparing the indoor contaminant concentration with various air flow rates and different geometries, sizes and positions of openings for a given set of constraints, e.g. the geometry of room, the number of persons and the property of contaminant source. However, most technologies were developed empirically or semi-empirically. They could only compare a very limited number of ventilation schemes to select a better one, so they probably did not find an optimal solution. Most important, they hardly aim to the relation between the velocity and contaminant concentration fields during optimization process, so it is difficulty to find the best velocity field with the optimal decontamination performance.

Decontamination ventilation is a convective mass transfer process essentially. In the interest of developing a general approach for optimizing convective mass transfer process, Chen et al.[11] defined the function of mass transfer potential capacity dissipation and deduced the field synergy mass transfer equation by seeking the extremum of the mass potential capacity dissipation with a constant viscous dissipation. Solving the field synergy equation numerically with a given set of constraints gave the optimal flow field theoretically, which has significantly better mass transfer performance for a given pressure drop. Based on this, Chen et al.[12] optimized the geometry of a photocatalytic oxidation reactor to improve its contaminant removal efficiency. However, in refs. [11, 12], other than the expression, the physical meaning of the mass transfer potential capacity dissipation was not formulated, or which capacity of an object been dissipated was not pointed out. Meanwhile, the optimization method was only developed theoretically, while the detailed optimization procedure for practical engineering application was not presented.

In terms of the analogy between mass and heat transfer processes, which are both governed by the linear transport laws, the concepts of entransy and its dissipation are extended to mass transfer analysis in this contribution, the physical qualities for describing the mass transfer ability of an object and measuring the irreversibility during mass transfer process are introduced. And then both the general method and the detailed procedures for optimizing convective mass transfer process are developed. Finally, with the aforementioned method, a ventilation process for removing gaseous pollutants in a space station cabin is optimized to reduce the energy consumption of the ventilation system and decrease the contamination concentration in the cabin.

1 Mass entransy and its dissipation

1.1 The definition of mass entransy

When mass or heat transferred in an object with a certain, not very large, macroscopic concentration or temperature gradient, this physical phenomenon will be described by Fick's law or Fourier's law:

$$q_{\mathrm{m}} = -\rho D \frac{\mathrm{d}Y}{\mathrm{d}n}, \tag{1}$$

$$q_{\mathrm{h}} = -\lambda \frac{\mathrm{d}T}{\mathrm{d}n}, \tag{2}$$

where q_{m}, ρ, D, and Y are the mass flow rate, the density , the mass diffusion coefficient and the species mass fraction, respectively, while q_{h}, λ, T are the heat flow rate, the thermal conductivity and the temperature, respectively.

When there existing electric potential gradient in conductor, the relation between the electric current density and the potential will be described by the Ohm's law:

$$q_e = -k_e \frac{\mathrm{d}U_e}{\mathrm{d}n}, \tag{3}$$

where q_e, k_e, and U_e are the electric current, the electric conductivity and the electric potential, respectively. As shown in eqs. (1), (2) and (3), Fick's law, Fourier's law and Ohm's law all reflect the general rule of diffusion process. That is, during mass, heat and electric transfer processes, all the transfer rates are proportional to the gradient of their corresponding physical quantities, which are viewed as a general flux promoted by a general force, and the general flux is linear with the general force. Therefore, it could be concluded that all these phenomena are analogous.

Based on the analogy between electrical and thermal systems, Guo et al.[13] defined an appropriate quantity, E_{vh}, to describe the heat transfer ability for an object:

$$E_{\mathrm{vh}} = \frac{1}{2} Q_{\mathrm{vh}} T = \frac{1}{2} \rho V c_{\mathrm{p}} T^2, \tag{4}$$

where V and C_p are the volume and the specific heat of an object, respectively. Meanwhile, the temperature, T, is an intensive quantity, while the internal energy, $\rho V c_p T$, is an extensive quantity. Analogous to the electrical potential energy of a capacitor, this physical quantity, E_{vh}, has the "thermal potential energy" meaning, which is named entransy by Guo et al[13].

For mass transfer process, the mass fraction of a component in a mixture is an intensive quantity, while the total mass of a component, ρVY, is an extensive quantity. In terms of the analogy between mass, heat and electric transfer phenomena, herein a new physical quantity, named mass entransy, E_{vm}, is introduced to represent the ability of a component for transferring mass to outside, which has the "concentration potential energy" meaning. Taken the statue with zero concentration as the zero point of this potential energy, the expression of mass entransy is

$$E_{vm} = \frac{1}{2} Q_{vm} Y = \frac{1}{2} \rho V Y^2 , \quad (5)$$

where Q_{vm} is the total mass of a component in a mixture, $Q_{vm} = \rho VY$.

The mass entransy of a component per unit volume mixture, e_{vm}, is

$$e_{vm} = \frac{1}{2} \rho Y^2 . \quad (6)$$

In addition, since the mixture density and the component concentration are both state parameters, the mass entransy is also a state parameter.

1.2 The mass dissipation during mass diffusion

For mass diffusion without a mass source, the species conservation equation is

$$\rho \frac{\partial Y}{\partial t} = -\nabla \cdot q_m , \quad (7)$$

where t is the time. Multiplying both sides of eq. (7) by the mass fraction of the component gives the mass entransy balance equation.

$$\rho Y \frac{\partial Y}{\partial t} = -\nabla \cdot \left(q_m Y \right) + q_m \cdot \nabla Y . \quad (8)$$

The left term in eq. (8) is the time variation of the mass entransy of a component per unit volume mixture. The first term on the right is the mass entransy transfer associated with the component diffusion while the second term on the right is the local rate of mass entransy dissipation, which represents the irreversible loss induced by the concentration gradient during mass diffusion, and thus is the measurement of the irreversibility of mass diffusion. The mass entransy balance equation can then be rewritten as

$$\frac{\partial e_{vm}}{\partial t} = -\nabla \cdot \dot{e}_m - \phi_m , \quad (9)$$

where $\dot{e}_m = q_m Y$ is the mass entransy flux. ϕ_m is the mass dissipation function:

$$\phi_m = -q_m \cdot \nabla Y = \rho D \left| \nabla Y \right|^2 . \quad (10)$$

1.3 The mass dissipation during convective mass transfer

For convective mass transfer without a mass source, the species conservation equation is

$$\rho U \cdot \nabla Y = \nabla \cdot \left(\rho D \nabla Y \right) , \quad (11)$$

where U is the velocity vector.

Multiplying both sides of eq. (11) by the mass fraction of the component is the mass entransy balance equation for convective mass transfer:

$$\rho U \cdot \nabla \left(Y^2 / 2 \right) = \nabla \cdot \left(\rho D Y \nabla Y \right) - \rho D \left| \nabla Y \right|^2 . \quad (12)$$

The left term is the mass entransy transfer of a component induced by mixture flow. The first term on the right is the mass entransy transfer induced by component diffusion while the second term on the right is the local dissipation rate of mass entransy of a component during its diffusion, which is the measurement of the irreversibility of convective mass transfer. Thus, eq. (12) can then be rewritten as

$$U \cdot \nabla e_{vm} = -\nabla \cdot \left(\dot{e}_m \right) - \phi_m , \quad (13)$$

where ϕ_m, the same as shown in eq. (10), is the mass entransy dissipation during convective mass transfer, which illustrates that the measurements of irreversibility for both mass diffusion and convective mass transfer are the same. This is because convective mass transfer essentially is the mass diffusion accompanied with fluid flow, and mass diffusion is the root of the irreversibility of mass transfer. By the way, in refs. [11, 12], the mass entransy dissipation was called the mass transfer potential capacity dissipation.

2 The extremum principle of mass entransy dissipation

For convective mass transfer, due to viscosity, mechanical energy will be consumed, so if we want to optimize the whole convective mass transfer performance, viscous dissipation should be considered. Thus, for steady state convective mass transfer without a mass source, the optimization objective is to find a velocity field, which has the extremum of mass entransy dissipation for a given set of constraints, where the optimization object is the velocity field, and the optimization criterion is the extremum of mass entransy dissipation, which expressed by variational form is

$$\delta \iiint_{\Omega} \phi_{\mathrm{m}} \mathrm{d}V = \delta \iiint_{\Omega} \rho D \left| \nabla Y \right|^2 \mathrm{d}V = 0 . \tag{14}$$

The constraints include a fixed viscous dissipation during fluid flow, i.e. a constant pumping power, species conservation equation, as shown in eq. (11), and continuity equation:

$$\nabla \cdot \rho U = 0 . \tag{15}$$

This is a typical functional extremum problem. The constraints can be removed by using the Lagrange multipliers method to construct a function

$$\Pi = \iiint_{\Omega} \begin{bmatrix} \rho D \left| \nabla Y \right|^2 + C_0 \phi_{\mathrm{mom}} \\ + A\left(\rho D \nabla \cdot \nabla Y - \rho U \cdot \nabla Y \right) + B \nabla \cdot \rho U \end{bmatrix} \mathrm{d}V , \tag{16}$$

where A, B and C_0, are the Lagrange multiplicators. Because of the different types of the constraints, A and B will vary with position, while C_0 is constant for a constant viscous dissipation. ϕ_{mom} is the viscous dissipation.

The variation of eq. (16) with respect to A, B and the mass fraction, Y, are the species conservation equation, the continuity equation and

$$-\rho U \cdot \nabla A = \rho D \nabla \cdot \nabla A - 2 \rho D \nabla \cdot \nabla Y , \tag{17}$$

where, for prescribed boundary concentration and mass flux, the boundary condition of the variable A are $A_{\mathrm{b}} = 0$ and $\left(\partial A / \partial n \right)_{\mathrm{b}} = 2 \left(\partial Y / \partial n \right)_{\mathrm{b}}$, respectively.

The variation of eq. (16) with respect to the velocity vector U is

$$\rho U \cdot \nabla U = -\nabla P + \mu \nabla^2 U + \left(C_{\Phi} A \nabla Y + \rho U \cdot \nabla U \right) , \tag{18}$$

where C_{Φ} is a constant related to the viscous dissipation:

$$C_{\Phi} = \frac{\rho}{2 C_0} . \tag{19}$$

Eq. (18) is the Euler's equation, essentially the momentum equation with a special additional volume force, by which the fluid velocity pattern is adjusted to lead to an optimal component concentration field with the extremum of mass entransy dissipation to maximum the convective mass transfer coefficient for fixed viscous dissipation during a convective mass transfer process.

Although the optimal velocity field obtained by solving the continuity equation, the species conservation equation, eqs. (17) and (18) simultaneously 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. Thus, the main purpose of eq. (18) is to obtain the optimal velocity distribution to give guidance for designing and implementing various convective mass transfer systems. In the follow paragraph, as an example, the ventilation process for removing gaseous pollutants with the uniform air supply system in a space station cabin will be optimized to show the application of the extremum principle of mass entransy dissipation and decrease the contaminant concentration in the cabin. The implementary steps are briefly described as follows:

(1) For the original ventilation system, solve the continuity equation, the species conservation equation and the momentum equation without the additional volume force simultaneously to obtain the original velocity and contaminant concentration fields in the cabin;

(2) Solve the continuity equation, the species conservation equation and eqs. (17) and (18) to obtain the optimized velocity and contaminant concentration fields with the original ventilation system;

(3) Compare the original and optimized velocity and concentration fields to determine the improvement for the original ventilation system, e.g. varying the position or the structure of openings, for obtaining a velocity fields approximating to the optimal one;

(4) For the improved ventilation system, repeat steps 1 and 2 gradually;

(5) Compare the velocity and concentration fields before and after optimization again, and then analyze their individual similarity to determine whether it is necessary to further modify the improved ventilation system. If the optimized velocity and concentration fields are similar to the original ones, the optimization procedure is completed. Otherwise, we need to further improve the ventilation system.

3 The physical model for decontamination ventilation process in a space station cabin

The 2-D space station cabin with uniform air supply system is studied in this paper as shown in Figure 1.

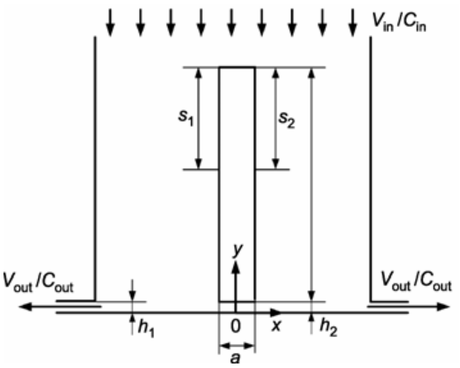

Figure 1 Sketch of the space station cabin with uniform air supply system.

Both the length and the width of the cabin in x and y directions are 2 m, the height of the air outlets, h_1, is 0.1 m. There is a rectangle partition in the center of the cabin in x direction, which is take as the simplified mannequin with the dimensions of: a = 0.3 m, b = 1.7 m. The space below the partition, h_2, is 0.1 m. Air enters the cabin vertically on the top and exits from the lower corners. The intake air velocity is 0.01 m/s with the contaminant concentration of zero. The top of the partition, S_1 and S_2, with the heights of 0.7 m is the contamination source surface with the gaseous pollutant diffusion rate of 2×10^{-6} kg/m^2, while the other surfaces of the cabin have no contaminant diffusion. The density and the viscosity of the air are 1.225 kg/m^3 and 1.7894×10^{-5} kg/(m·s). The diffusion coefficient of the gaseous pollutant, D, in the air is 1.65×10^{-5} m^2/s.

A mesh with the total number of 120000, which has 350 grids in both x and y directions, is chosen as the main computation mesh as shown in Figure 2. The mesh is more condense near the wall, the partition and the openings, where more steep velocity gradient is expected. The minimum and maximum sizes of the grids are 0.5 mm and 0.8 mm, respectively.

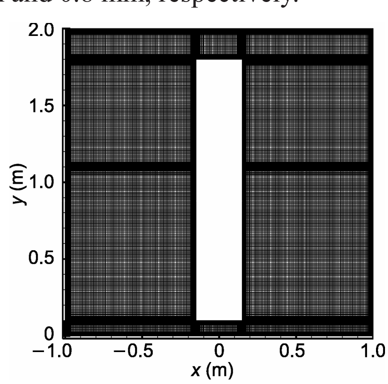

Figure 2 Computation meshes of the cabin with uniform air supply system.

For simplicity, air flow in the cabin is assumed as a steady-state laminar flow with a uniform velocity at the inlet and a uniform pressure at the outlets. The CFD program, FLUENT 6.0, is used to solve the governing equations together with the boundary conditions. The velocity and pressure are linked using the SIMPLEC algorithm. The pressure term in the momentum equation is discretized using the PRESTO! Scheme while the convection and diffusion terms are discretized using the first order upwind scheme. The user defined function (UDF) is used for adding the additional volume force in the momentum equation.

4 Optimization procedures and discussions

Step 1: Analyze the decontamination performance of the original ventilation system

Figures 3(a) and (b) are the original air flow path lines and the contaminant mass fraction contours in the cabin with the uniform air supply system. After entering the cabin from the inlet, the air creates a piston flow near the left and right surfaces of the cabin. Whereas, because of the impediment of the partition, the air can not flow down along the partition, which means that the air velocity is very small near the contaminant source surfaces. In addition, most of the air exits the cabin from the outlets directly without removing the contaminant, which leads to the poor convective mass transfer performance. For this case, the viscous dissipation rate, ϕ_{mom}, and the mass entransy dissipation rate, ϕ_m, in the cabin are 1.03×10^{-5} W and 1.82×10^{-8} kg/s, respectively. The mass fraction of the contaminant near the partition is about 0.5%, the maximum and average mass fractions of the contaminant in the cabin are 0.93% and 0.04%, respectively.

Step 2: Calculate the optimal velocity field and its decontamination performance with the uniform air supply system

Figures 4(a) and (b) are the optimized air flow path lines and the optimized contaminant mass fraction contours in the cabin with the uniform air supply system by solving the continuity equation, the species conservation equation, eqs. (17) and (18) simultaneously. Herein, in order to obtain an air velocity field with the same viscous dissipation rate as the original one, the parameter, C_Φ, associated with the viscous dissipation rate, equals to 1×10^4. After entering in the cabin from the inlet, the air above the partition flows down along the partition,

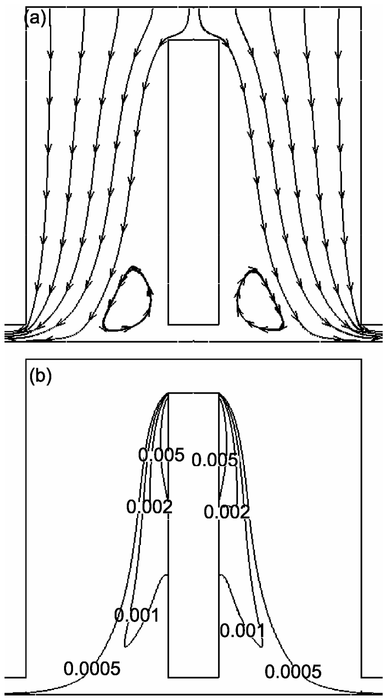

Figure 3 Original results with the uniform air supply system. (a) Air flow path lines; (b) contaminant mass fraction contours.

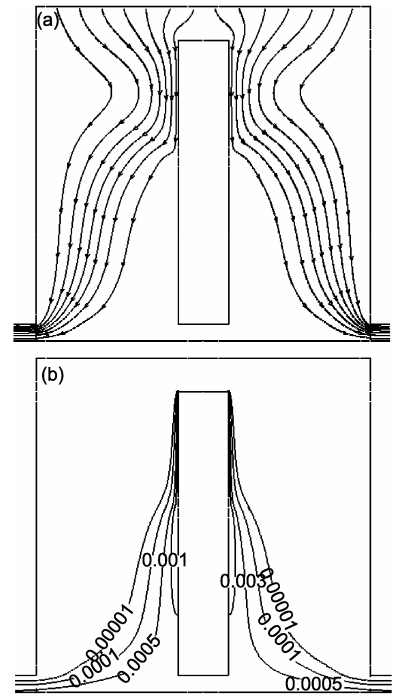

Figure 4 Optimized results with the uniform air supply system (C_Φ = 1×10^4). (a) Air flow path lines; (b) contaminant mass fraction contours.

while the other air is deflected to the contaminant surface and then towards to the outlets along the contaminant source surface. As shown in Figure 4(b), the contaminant mass fraction near the partition is about 0.1%, the maximum and average contaminant mass fractions in the cabin are 0.22% and 0.01%, respectively, while the viscous dissipation rate and the mass entransy dissipation rate in the cabin are 1.13×10^{-5} W and 3.26×10^{-9} kg/s. Table 1 lists the decontamination ventilation performances in the cabin before and after optimization. Compared with the original results, the mass entransy dissipation rate is decreased 82%, the contaminant mass fraction both in the cabin and near the contaminant source surface are decreased by about 75%.

Table 1 The decontamination ventilation performances before and after optimization with the uniform air supply system

	Original	Optimized
Viscous dissipation Φ_{mom} (W)	1.03×10^{-5}	1.13×10^{-5}
Mass entransy dissipation Φ_m (kg/s)	1.82×10^{-8}	0.33×10^{-8}
Contaminant mass fraction near the partition C_w	0.5%	0.1%
Averaged contaminant mass fraction C_{ave}	0.04%	0.01%
Maximum contaminant mass fraction C_{max}	0.93%	0.22%

Step 3: Improve the ventilation system

The optimal flow field, as shown in Figure 4(a), is an ideal state, induced by an suppositional volume force, where the air is deflected to the contaminant surface and then towards to the outlet along the contaminant source surface. Whereas, it is nearly impossible to add a suitable additional volume force in practical engineering, which is the same as calculated in eq. (18). Herein, the uniform air supply system can be modified to the concentrated air supply system to make air flow down along the contaminant surfaces directly.

Figure 5 is the air velocity distribution at the height of y = 1.5 m. The maximum air velocity near the contaminant source surface is about five times the one at the inlet and the air velocity is higher in the area closed to the contaminant source with the space of 0 to 0.25 m. Thus, for the concentrated air supply system, as shown

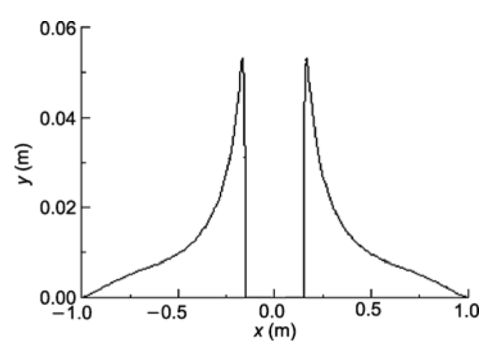

Figure 5 Air velocity distribution at the height of y = 1.5 m.

in Figure 6, the air inlets can be placed in the two areas of x = –0.4 m—–0.15 m and x = 0.15 m—0.4 m. The air supply velocity is 0.04 m/s to keep the same air mass flow rate, while other parameters keep constant.

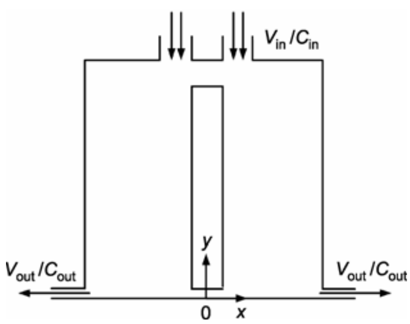

Figure 6 Sketch of the space station cabin with the concentrated air supply system.

Step 4: Analyze the decontamination performance of the concentrated air supply system

Figure 7 is the computation meshes for the improved ventilation system. The total number of the grids is 160000, which are both about 400 grids in x and y directions. The minimum and maximum sizes of the grids are 0.5 mm and 0.8 mm, respectively.

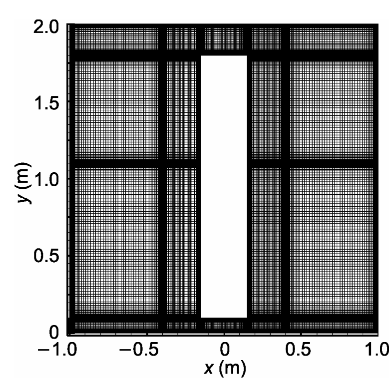

Figure 7 Computation meshes of the cabin with concentrated air supply system.

Figures 8(a) and (b) are the original air flow path lines and the contaminant mass fraction contours in the cabin with the concentrated air supply system. After entering the cabin, the air flows down along the left and right surfaces of the partition to the bottom of the cabin and then exits the cabin from the air outlets. Compared with the uniform air supply system, the air velocity near the contaminant source surface is higher, which will improve the convective mass transfer performance. For this case, the time rates of the viscous dissipation and mass entransy dissipation in the cabin are 7.32×10^{-6} W and 6.28×10^{-9} kg/s, respectively, while, as shown in Figure 8(b), the contaminant mass fraction near the partition is about 0.2%, the maximum and averaged contaminant mass fraction in the cabin are 0.47% and 0.01%, respectively. As listed in Table 2, compared to the original results with the uniform air supply system, the maximum contaminant mass fraction both in the cabin and near the contaminant source surface are decreased by 50 %. The average contaminant mass fraction in the cabin is decreased by 75 %. Furthermore, the time rates of the vis-

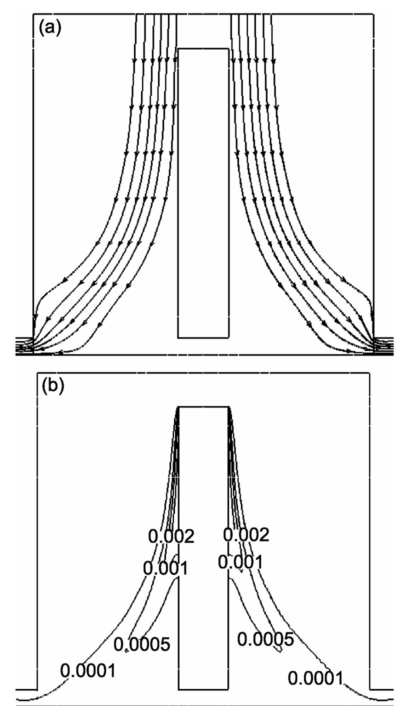

Figure 8 Original results with the concentrated air supply system. (a) Air flow path lines; (b) contaminant mass fraction contours.

Table 2 The decontamination ventilation performances before and after improvement

	Uniform air supply system	Concentrated air supply system
Viscous dissipation Φ_{mom} (W)	1.03×10^{-5}	0.73×10^{-5}
Mass entransy dissipation Φ_{m} (kg/s)	1.82×10^{-8}	0.63×10^{-8}
Contaminant mass fraction near the partition C_w	0.5%	0.2%
Averaged contaminant mass fraction C_{ave}	0.04%	0.01%
Maximum contaminant mass fraction C_{max}	0.93%	0.47%

cous dissipation and mass entransy dissipation are decreased by 30 % and 65%, respectively, at the same time.

Step 5: Calculate the optimal velocity field and its decontamination performance with the concentrated air supply system

For the concentrated air supply system as shown in Figure 6, utilizing the extremum principle of mass entransy dissipation again for the case of C_{Φ} = 1×10^4 gives the optimal air flow pattern and contaminant mass fraction contours in the cabin as shown in Figures 9(a) and (b). The time rates of the viscous dissipation and mass entransy dissipation in the cabin are 1.22×10^{-5} W and 3.26×10^{-9} kg/s, respectively, while, as shown in Figure 9(b), the contaminant mass fraction near the partition is about 0.1%, the maximum and averaged contaminant mass fraction in the cabin are 0.22% and 0.01%, respectively.

Step 6: Compare and analyze the original and the optimized results with the concentrated air supply system

For concentrated air supply system, comparing the optimized results with the original ones, as shown in Figures 8 and 9, it is obviously found that both the flow patterns and the contaminant concentration distributions are similar. As listed in Table 3, for the results before and after optimization with the concentrated air supply system, the averaged contaminant concentrations in the cabin are the same, and the other parameters for estimating the decontamination performance are similar. Thus, it can be concluded that the original decontamination performance with the concentrated air supply system is approach to the optimized result, that is, this concentrated air supply system is the optimal one with the best performance in practical engineering applications. In addition, as listed in Table 2, compared to the results with the uniform air supply system, not only the viscous dissipation during air flow in the cabin is reduce by 30%, but also the decontamination performance of the ventilation system is enhanced, e.g. the averaged and the maximum contaminant concentration in the cabin are decreased by 75% and 50%, respectively.

In a word, the aforementioned procedures illustrate that, for a given set of constraints, utilizing the extremum principle of mass entransy dissipation will maximum the convective mass transfer performance during decontamination ventilation process and finally decrease the contaminant concentration. In addition, for coinstantaneous heat and mass transfer optimization, due to different engineering application, the optimization objectives of these transfer processes consist of several cases including increasing the heat, mass or enthalpy transfer performance, so it is needed to choose a suitable optimization criterion according to different objectives. If we need to improve the mass transfer performance, the extremum principle of mass entransy dissipation developed in this paper should be used, while if we need to improve the enthalpy transfer performance, we may need to adopt the corresponding extremum principle of enthalpy entransy dissipation.

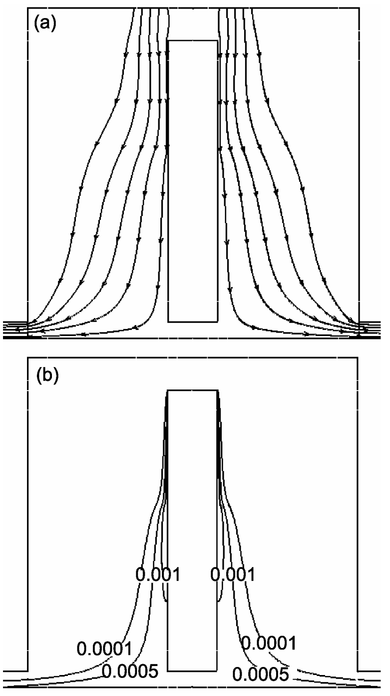

Figure 9 Optimized results with the concentrated air supply system (C_{Φ} = 1×10^4). (a) Air flow path lines; (b) contaminant mass fraction contours.

Table 3 The decontamination ventilation performances before and after optimization with the concentrated air supply system

	Original	Optimized
Viscous dissipation Φ_{mom} (W)	0.73×10^{-5}	1.22×10^{-5}
Mass entransy dissipation Φ_m (kg/s)	0.63×10^{-8}	0.33×10^{-8}
Contaminant mass fraction near the partition C_w	0.2%	0.1%
Averaged contaminant mass fraction C_{ave}	0.01%	0.01%
Maximum contaminant mass fraction C_{max}	0.47%	0.22%

5 Conclusions

In terms of the analogy between mass, heat and electric transfer phenomena and similar to the definition of entransy for heat transfer, the concept of mass entransy was introduced in this paper to represent the ability of a component for transferring mass to outside, which has the “concentration potential energy” meaning. Meanwhile, during mass transfer, the mount of a component is conserved while the mass entransy of this component will be dissipated. The mass entransy dissipation is an alternative for measuring the irreversibility of mass transfer.

For convective mass transfer optimization, the extremum principle of mass entransy dissipation was developed. With the constraints of mass conservation, species conservation and fixed viscous dissipation, an Euler’s equation, essentially the momentum equation with a special additional volume force, was obtained by seeking the extremum of mass entransy dissipation during convective mass transfer process utilizing the variational method. Solving this optimization equation for a given set of constraints will obtain a velocity distribution with the best convective mass transfer performance, and then to give guidance for designing and implementing various convective mass transfer systems.

For the ventilation process for removing gaseous pollutants in a space station cabin with a uniform air supply system, the velocity field with the best decontamination performance was obtained theoretically based on the extremum principle of mass entransy dissipation. With the guide of this optimal flow patterns, a suitable concentrated air supply system with appropriate air inlet position and width has been designed to replace the uniform air supply system, which not only reduces the viscous dissipation during air flow in the cabin by 30%, but also enhances the decontamination performance of the ventilation system, e.g. the averaged and the maximum contaminant concentrations in the cabin are decreased by 75% and 50%, respectively.

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