NEW SCALES FOR ASSESSING VENTILATION PERFORMANCE

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ABSTRACT

Several new scales have been developed to quantify fresh air diffusion and contaminant dispersion in ventilated spaces. The local purging effectiveness is proposed for analyzing the individual contribution of each supply opening for a multi-inlet system. The local specific contaminant-accumulating index is defined to indicate the tolerance of a ventilation flow to contaminants. Furthermore, the regional purging flow rate, U_p, is re-embodied in a simple expression different from the previous description. Two U_p-related parameters applicable for characterizing ventilation flows, i.e., the equivalent regional Peclet number and the back-mixing index, are also described. These new scales and their application are discussed and demonstrated by means of numerical simulations. The present new scales appear to be promising for designing, diagnosing and optimizing ventilation systems.

KEYWORDS

ventilation efficiency; *contaminant removal effectiveness*; *numerical simulation*

INTRODUCTION

Ventilation performance is usually addressed either by the efficiency of diffusing fresh air into a space or by the effectiveness of removing contaminants from a space, or by both. Various scales have been explored for indicating *ventilation efficiency* and are used for determining the degree to which fresh air is dispersed, recirculated and mixed within a ventilated space, as well as for determining how ventilating air interacts with pollutants.

The scales for assessing ventilation performance can be either local or global. The local scales are usually able to reveal the detail of ventilation flows at desired locations; the global scales, by contrast, yield general descriptions for a flow system. The quantitative determination of a ventilation scale is, in general, achieved with experimental measurements or numerical simulations. When using a scale to characterize a ventilation flow system, this scale should meet two criteria according to Sandberg (1981): it should be generally able to assess system performance under different operating conditions; and it should be measurable. These two criteria are not always met in practice. Some scales are difficult to measure in experiments, e.g. the local purging flow rate.

On the one hand, many scales have been proven to be available for characterizing ventilation air flows. On the other hand, some scales are usually unsuitable for indicating contaminant dispersion and removal, which depend on not only ventilation flows but also specific contaminant sources. For example, a high local air change index at one position does not promise a low contaminant concentration, which is also related to the contaminant source (e g., its location and strength). A scale that is able to bridge these two aspects, i.e., characterizing air flow (the general) and indicating contaminant dispersion from a specific source (the specific), is thus desired in ventilation applications.

Numerical simulation can usually provide fundamental and local flow structure in a ventilated space. This work therefore concentrates on discussing and developing local scales that can be explored with the aid of numerical simulations. The *local purging effectiveness of inlet*, A_{sp}, is proposed to evaluate the effect of each inlet when delivering fresh air to a location in a multi-inlet flow system. Another new scale is the *local contaminant-accumulating index*, α, which can be used to indicate the capacity of a ventilation flow to account for specific contaminant sources. These local quantities can be derived from the transport equations as given in this study. It is thus convenient to use numerical simulations to determine them. In addition, the regional purging flow rate, U_p, is re-embodied in a simple expression different from the previous description. Two U_p-related parameters, the equivalent regional Peclet number and the back-mixing index, are also described. The applications of these new proposals are demonstrated by using CFD simulations.

NEW VENTILATION SCALES

The scales used to assess ventilation performance can be classified into three groups: a) *Ventilation air diffusing efficiency*: includes scales that indicate how efficiently fresh air has been supplied and delivered; b) *Ventilation effectiveness*: includes scales that evaluate how effectively contaminants have been removed or diluted by ventilating air flows. c) *Specific ventilation effectiveness*: includes scales that evaluate the ability of ventilating air to remove or dilute contaminants for specific applications. Basic ventilation scales include, for example, contaminant concentration, C, local mean age of air, τ, purging flow rate, U_p, and residence time distributions (RTD).

Three methods have usually been used to quantitatively determine these and other ventilation scales (Peng *et al.*, 1997): the experimental method, the compartmental method and the numerical method. The experimental method is usually costly and time-consuming, but often provides results closest to those in practice. The numerical method is the most efficient means of providing local detailed characteristics for both the air flow and the contaminant distribution. The compartmental method (multi-chamber/zone method) provides a tool for analyzing a ventilation system by means of quantifying the regional ventilation performance for various compartments/zones.

Local purging effectiveness of inlet, A. For systems with multiple inlets, It is important to distinguish the respective contribution of each supply opening for ventilation design and optimization. Kato *et al.* (1992) and Murakami (1992) proposed the concept of the contribution ratios of inlet and outlet, r_s and r_e, which can indicate the territories affected by the supply jet and extract sink. They are, however, less useful in recirculating regions of the flow domain. A Markov chain model, which can be used together with the compartmental method, has recently been proposed (Peng and Davidson, 1997). This model is able to yield the transfer probabilities from a supply opening to an interior region and from an interior region to an extract, by which the contribution of each supply and exhaust opening can thus be analyzed.

A new local scale is proposed here to quantitatively clarify the effect of each supply opening for a multi-inlet system. The openings are denoted by $s1$, $s2$, ..., sp, ..., sm. For an arbitrary opening, say sp, its contribution to an arbitrary location within this system is analyzed as follows.

a) The nominal time constant, τ_n, for the flow system is first calculated, $\tau_n = V/Q$, which is the mean age of the air leaving the system through the extract.

b) *Old air* is supplied into the system through each supply opening, e.g. the exhaust air is fed back to all the supply openings. This can be done in numerical calculations by simply setting the boundary condition of the local mean age at each supply opening to τ_n. Solving the transport equation for τ gives the local mean age, τ_{old}, in the system, as the *old air* is supplied. Note that τ_{old} can also be calculated as the sum of τ_n

and the local mean age of air predicted with zero τ-condition at all the supply openings.

c) *Fresh air* is supplied into the system through one specific inlet *sp*, while the old air continues to be supplied through the rest of the inlets. This means that the boundary condition of the local mean age at supply opening *sp* is re-specified as 0 and the boundary conditions for the other supply openings remain the same as at step *b*), i.e. τ_n. The calculated local mean age of air under this condition is denoted as τ_{new}.

The variation between τ_{old} and τ_{new} at any location is therefore *purely* due to the contribution of inlet *sp*. At an arbitrary point, the decrease in local mean air age, i.e. $\delta\tau = (\tau_{old} - \tau_{new})$, indicates the capability of the system to purge the *old air* by supplying fresh air through inlet *sp*. In other words, it reflects the *freshening* ability of the supply opening *sp* to the location in question. The relative decrease in local mean age at an arbitrary point is defined here as the *local purging effectiveness* of inlet *sp*, A_{sp}. It thus yields

$$A_{sp} = \frac{\delta\tau}{\tau_{old}} = \frac{(\tau_{old} - \tau_{new})}{\tau_{old}} \qquad (1)$$

At the supply opening considered, the local purging effectiveness is equal to unity, and to zero for other inlets. A large A_{sp} means a large capability of the supply opening *sp* to diffuse fresh air into a location for purging or diluting the contaminant there. This scale can thus indicate the effect of a specific supply opening in a multi-inlet ventilation system. The local purging effectiveness of a specific inlet can be measured with tracer experiments by altering the induced tracer concentration at the inlet considered. When using the "reverse-tracing" flow, Eq. (1) can also be used to indicate the effect of an exhaust opening for systems with multiple outlets.

Equation (1) provides an approach for analyzing ventilation air flows, termed here the *age-variation analysis*. The use of this method in conjunction with numerical simulation is convenient. The principle involved in this method is straightforward: the age difference, $\delta\tau$, at one location reveals the effect of the factor changed to induce this variation. Further, the age variation actually obeys a transport equation

$$\nabla \cdot [u(\delta\tau)] = \nabla \cdot [D\nabla(\delta\tau)] \qquad (2)$$

The boundary condition for the inlet considered, say *sp*, should be $\delta\tau_{sp} = \tau_n$, and 0 for the other inlets.

Local specific contaminant-accumulating index, α. Many of the existing ventilation scales have been used to quantify either ventilating air flows (by indicating the ventilation air diffusing efficiency) or contaminant removal/dilution (by indicating the ventilation effectiveness) in a ventilation system. In a specific situation, a scale used as a general index (indicating ventilation air diffusing efficiency or ventilation effectiveness) can be inconsistent with a scale used for indicating specific ventilation effectiveness. For example, a location with a low mean age of air can be a location with a high contaminant concentration, since the contaminant distribution is related not only to the air flow but also to the property of the contaminant source. Attempts are thus made in this work to develop an scale for assessing the capability of a ventilation flow to tolerate the contaminant source in a specific situation. This scale should function as a bridge between the general scale and the specific scale. In other words, it should be able to reflect how an existing ventilation air flow and a specific contaminant source interact on each other.

The contaminant concentration is a straightforward index that indicates the contaminant dispersion within a system for a specific situation. However, this indication is not sufficient to characterize the potential and general capability of the ventilation flow to dilute/remove contaminants. The local contaminant level caused by a specific source is not capable of indicating the local *freshness* of the ventilating air itself, which is usually represented with the local mean age of the air. A new local parameter termed the *local age-integrated exposure*, γ, is proposed as

$$\gamma = \int_0^\tau C(t)dt \tag{3}$$

Equation (3) shows that γ expresses the local accumulation of the contaminant at an arbitrary position over a time equal to the local mean age of the air passing this position. This parameter thus reflects the diluted/removed amount of contaminant at a position when the air has *grown up* to the local mean age (representing freshness) τ, or simply the total exposure to the contaminant over a time period of τ. A value of γ that is too large suggests, therefore, that the contaminant is *overloaded* by the air with an age of τ at the location considered. By comparing this index with a value specified for limiting the time-integrated exposure, a scale can be obtained for evaluating the capacity of an air flow to dilute/remove the contaminant in a ventilated zone. A low value of γ implies either that a small amount of contaminant has been transported to the position in question or that the air flow has been quickly supplied to this position, or both.

The local age-integrated exposure is measurable in practice. First, the local mean age of the air at an arbitrary point is detected by tracer experiments. The concentration sequence of the contaminant is then recorded at the same position, with the specific contaminant source switched on. The area under the concentration curve during the time period 0-τ is then the value of γ.

When using numerical methods, a transport equation for this quantity can be readily derived (Peng *et al.*, 1997) as

$$\begin{aligned} &\nabla\cdot(u\gamma) = \\ &\nabla\cdot(D\nabla\gamma) - 2D\,[\nabla\tau\cdot\nabla C(\tau)] + S_c\tau \end{aligned} \tag{4}$$

where $C(\tau)$ is the concentration at the time equal to the local mean age, τ. Eq. (3) represents the *start-up* accumulation of the contaminant at an arbitrary location. In practice, the accumulation at steady state is of more importance and interest. Equation (3), therefore, becomes $\gamma = C(\infty)\tau$, and the corresponding transport equation takes the following form

$$\begin{aligned} &\nabla\cdot(u\gamma) = \nabla\cdot(D\nabla\gamma) - \\ &2D\,[\nabla\tau\cdot\nabla C(\infty)] + C(\infty) + S_c\tau \end{aligned} \tag{5}$$

This equation can be solved numerically. The boundary condition of γ at the inlet is zero, and its first derivative is assumed to be zero normal to the wall surface and the outlet.

The mean exposure of the whole space to contaminants during one air change is $<C>\tau_n$ with $<C>$ as the mean room concentration. This mean nominal-time-integrated exposure can then be used to normalize the age-integrated exposure, γ. The logarithm (to the base 10) of this normalized quantity is used to define the *local specific contaminant-accumulating index*, α, giving

$$\alpha = \log\left(\frac{\gamma}{\tau_n < C >}\right) \tag{6}$$

When $\alpha = 0$, then $\gamma = (\tau_n <C>)$; $\gamma < (\tau_n <C>)$, as $\alpha < 0$; and $\gamma > (\tau_n <C>)$ as $\alpha > 0$. A negative α indicates a small amount of contaminant accumulation and thus implies a large contaminant-diluting capability at the location considered. For complete mixing, α is zero, which forms the basic scale of this quantity.

When the steady-state concentration is used for γ in Eq. (3), Equation (6) can be further expressed as

$$\alpha = \log\left(\frac{\varepsilon_c}{\varepsilon_p \varepsilon_{ap}}\right) \qquad (7)$$

where ε_c is the contaminant-removal effectiveness, $\varepsilon_c = C_e/\langle C \rangle$, ε_p is the local air change index, $\varepsilon_p = \tau_n/\tau_p$, and ε_{ap} is the local air quality index, $\varepsilon_{ap} = C_e/C_p$. Equation (7) shows that α refers to both the delivering of fresh air to a location and the removal of contaminants from this location.

The local specific contaminant-accumulating index, α, is a scale combining the effects of both the specific source (through concentration of contaminant) and the ventilation air flow (through local mean age of air). This index is thus able to reflect the interaction of a specific contaminant source and the ventilation flow. It can be used as a general scale to indicate the ventilation performance under different situations and as a scale to bridge the ventilation air diffusing efficiency (or ventilation effectiveness) and specific ventilation effectiveness.

Back-mixing index/probability, β_p. Peng and Davidson (1997) showed that, for an arbitrary region p within a flow system, the total air flow rate passing through it, or the turnover flow rate, W_p, is composed of two parts, including the purging flow rate, U_p, and the residual turnover flow rate, R_p. This gives

$$W_p = U_p + R_p \qquad (8)$$

The residual turnover flow rate, R_p, is the remaining net flow rate at which the air leaving region p may return back. A back-mixing index or probability, β_p, can thus be defined in terms of R_p and W_p. This gives

$$\beta_p = \frac{R_p}{W_p} = 1 - \frac{U_p}{W_p} \qquad (9)$$

The back-mixing index indicates the probability of the air rejoining p after leaving it. This index, therefore, reflects the degree of air recirculation in region p. It is thus applicable for quantifying the regional air mixing.

Equivalent regional Peclet number, α_p. Zvirin and Shinnar (1976) originally proposed this concept, which is expressed as

$$\alpha_p = \frac{2V}{\delta V_p}\frac{U_p}{W_p} = \frac{2V}{\delta V_p}(1 - \beta_p) \qquad (10)$$

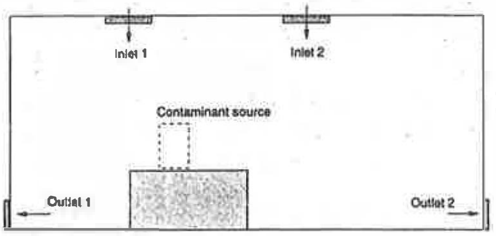
where δV_p is the local volume of region p and V is the total volume of the flow system. W_p expresses the exchanging ability of a region with its surroundings. The quantity U_p/W_p thus indicates the fraction of purging air flow in the turnover flow rate passing through region p, see also Peng and Davidson (1997). α_p can be used as an indication of the uniformity of mixing. It can also be used to represent the segregation between the flow in the region considered and the ideal plug flow. Note that α_p is a parameter that depends on the volume of the region considered.

The application of the two U_p-related parameters, β_p and α_p, was demonstrated by Peng and Davidson (1997). In the next section, only the use of the other new scales is discussed.

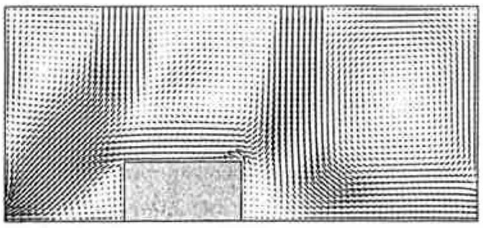
APPLICATION AND DISCUSSION

For the purpose of demonstrating the use of the new scales, a two-dimensional ventilation flow is analyzed, as shown in Fig. 1a. This ventilation flow system has two supply openings in the ceiling and two exhaust outlets at floor level. A block is used to simulate the working platform, and a passive contaminant source is uniformly distributed above this platform. The nominal time constant, τ_n, is 168 seconds, and the turnover time of contaminant, τ_t, is 158 seconds.

The air flow is simulated with the conventional two-equation turbulence k-ε model, in conjunction with wall functions. The resultant velocity field, as shown in Fig. 1b, is then used to solve the transport equations for the contaminant concentration C, the local mean age of air τ, the local age-integrated exposure γ at steady state, Eq. (5), and the age variation, Eq. (2).



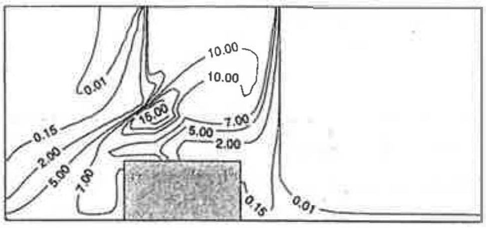
a) Configuration of flow system.



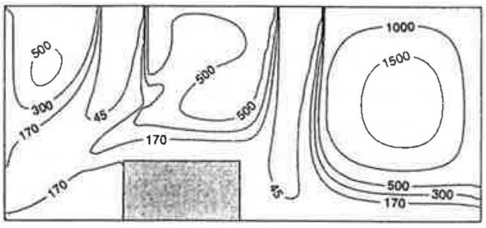
b) Air flow pattern.

Fig. 1 The ventilation flow system used for demonstration.

Figures 2a and 2b show the calculated distributions of the local contaminant concentration and the local mean age of the air. The flow pattern in the space is rather complicated and consists of several recirculating regions. As a result of air convection, the contaminant above the platform has apparently been entrained into three recirculating regions: two regions between the inlets and one behind the platform. The concentrations there are thus particularly high. As expected, the local mean age of the air in all the recirculating regions is much higher than τ_n, since the fresh air is not directly delivered into these zones. Note that, in the recirculating regions on the left and right upper corners, the local mean air ages are rather high, but the contaminant concentrations in these regions are very low. The contaminant source in this case is isolated from these two regions by the fresh inflow diffused through the supply openings in the ceiling.



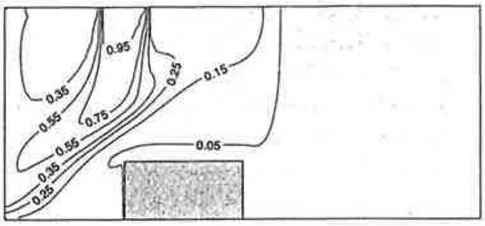
a) Contaminant concentration $C(\infty)$.



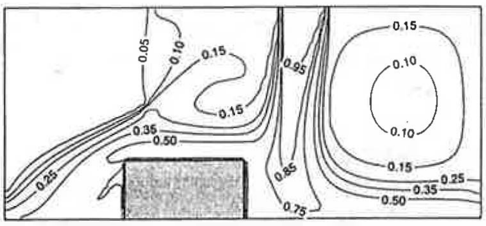
b) Local mean age of air τ (s).

Fig. 2 Computed distributions of contaminant concentration and local mean air age.

Figures 3a and 3b show the spatial distributions of the local purging effectiveness for the two supply openings, A_{s1} and A_{s2}. The effects of the two supply openings, inlet 1 ($s1$) and inlet 2 ($s2$), are clear. There is always a high purging effectiveness within the territories of the supply jets. The contaminant source above the platform is purged or diluted mainly by the air from inlet 2, which has a much higher purging effectiveness than inlet 1. This scale is also capable of indicating the influence on the recirculating regions. The more fresh air reaching a region, the larger is the purging effectiveness there. A high local age usually corresponds to a low purging effectiveness. The local purging effectiveness indicates the capability of the considered supply opening to deliver fresh air to a location, and to dilute or remove contaminants from a location. A very small value, e.g. 0.05, can be used to approximately estimate the boundary the fresh air has reached. The local purging effectiveness is able to reflect the contribution of each supply opening to a position. In other words, this scale indicates the ability of a specific supply opening to replace contaminated air at a location with fresh air.

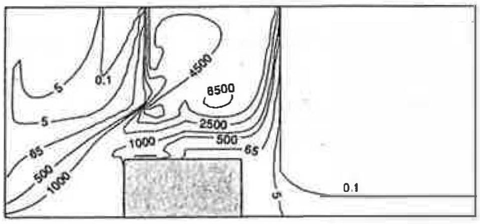


a) A_{s1} for inlet 1.

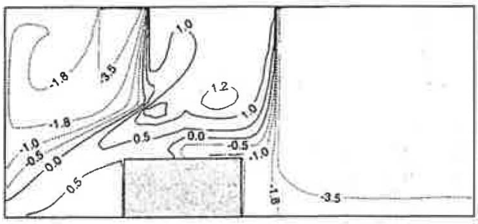


b) A_{s2} for inlet 2.

Fig. 3. Distributions of local purging effectiveness, A_{s1} and A_{s2}.



a) Age-integrated exposure, γ, (mg s/m^2).



b) Contaminant-accumulating index, α.

Fig. 4 Calculated distributions for γ and α.

The spatial distributions of the age-integrated exposure, γ, and the specific contaminant-accumulating index, α, are given in Fig. 4a and Fig. 4b. The dotted lines in Fig. 4b correspond to negative values of α. The two recirculating regions, on the upper left-hand side and right-hand side, have negative α values due to the low concentration (see Fig. 2a), although the local mean age there is rather high (see Fig. 2b). The region enclosed by the zero solid contour line in Fig. 4b is the domain with high exposure to the contaminant and the old air.

CONCLUSIONS

The scales used in practice for characterizing ventilation performance can be classified into three groups: *ventilation air diffusing efficiency*, which indicates the capacity of providing fresh air to occupants; *ventilation effectiveness*, which indicates the capacity to remove contaminants from ventilated space; and *specific ventilation effectiveness*, which indicates the capacity to deal with specific situations. Attempts have been made to develop new ventilation scales to account for these aspects.

Numerical simulations can often provide details on local air flow structure and contaminant dispersion. Several local ventilation scales, which can be calculated with numerical methods, have been proposed. The local purging effectiveness of an inlet, A_{sp}, can be used to indicate the individual contribution of each supply opening for a multi-inlet flow system. This quantity reflects the capability of an supply opening to purge the old air at a location by delivering fresh air there. The same concept can be used to assess the effects of an exhaust opening by using the so-called "reverse-tracing air flow" for a multi-outlet system.

The local specific contaminant-accumulating index, α, or the age-integrated exposure, γ, has been proposed as a scale to combine the general index, τ, with the concentration of contaminant produced by a specific source. This index can be used to assess the ability of a ventilation flow system to tolerate contaminants produced by specific sources. It can also be used to indicate the regions where the air is *young* (low age) but contaminated (high concentration) from a specific source or *vice versa*. This scale, as a general index, is thus capable of reflecting the interaction between the ventilation flow and a specific contaminant source.

The new scales proposed here, A_{sp} and α, are both experimentally measurable and numerically computable. The age variation (to obtain A_{sp}) and the age-integrated exposure (to obtain α) are governed by transport equations, which have been derived in this work. They can thus be conveniently analyzed by numerical simulations. The age-variation analysis appears to be useful to indicate the influence of a single input in a multi-input flow system. This method has been used to define A_{sp}.

These new scales are applicable for quantifying indoor air flows and contaminant dispersion, and thus for assessing ventilation performance. They can be used for designing, diagnosing and optimizing ventilation flow systems.

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