PERFORMANCE EVALUATION OF A DISPLACEMENT VENTILATION SYSTEM FOR IMPROVING INDOOR AIR QUALITY: A NUMERICAL STUDY

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ABSTRACT

To evaluate the performance of a ventilation system, the local mean age of air has usually been used to estimate how efficiently fresh air is diffused to a desired location. However, this index alone is often not sufficient to assess the local air quality that is also associated with the property of the contaminant source in a ventilated space. Several new indices have been proposed recently, which enable the use of numerical simulation and appear to be appropriate scales for assessing mixing ventilation systems.

These scales are implemented in this work to evaluate the performance of a displacement ventilation system in a workshop for improving indoor air quality. CFD techniques are used to investigate the influence of heat and contaminant sources on the local air quality in the occupied zone. The impact of displacement ventilation on indoor air quality is discussed.

INTRODUCTION

The primary objective of a ventilation system is to improve indoor air quality. This concerns the effectiveness of the system in removing/diluting contaminants in a ventilated space. It is well known that inadequate ventilation is a common denominator in buildings with troublesome air quality that often causes sick-building syndrome (SBS). The prevalence of SBS problems is closely associated with room air motion upon which the contaminant distribution is identified. The contamination level is controlled by dilution and mixture with outdoor and/or other make-up fresh air. The assessment of indoor air quality can thus be accounted for, to a certain extent, by tracing the ventilation airflow pattern.

It is generally recognised that a displacement ventilation system is more efficient than a mixing system in delivering fresh air to the room occupants. In some comparative studies it has been shown that displacement ventilation enables a higher local air exchange in the occupied zone than mixing ventilation does as using the same air supply rate, see e.g. [1, 2]. The performance of displacement ventilation relies largely on the thermal plume created by heat sources, such as lamps and occupants. The presence of a plume due to the occupant may have significant impact on the evaluation of air quality in the active occupied zone [1, 3].

A displacement ventilation flow, by its nature, is often characterised by stable thermal stratification. Such a flow feature often makes the passive scalar quantities vertically stratified (particularly in the occupied zone), for example, the contaminant concentration and the local mean age of the air, which have been commonly used to evaluate ventilation performance. Recently, several new scales have been proposed and applied to the assessment of mixing ventilation [4]. These scales have been defined in terms of the contaminant concentration and the local mean age of air. They can thus be explored through numerical simulations as demonstrated in [4], where these scales showed promising capabilities of evaluating the performance of mixing ventilation [4]. In a previous study [3], the layout of a displacement ventilation system and the operating conditions in a material-processing workshop were optimised by analysing numerically the personal exposure to contaminants (in the breathing zone) and to the supplied cold air. In this work, the new scales are implemented to evaluate that ventilation system by means of numerical simulations. One of the main purposes here is to identify how well these scales can reflect the results as optimised in [3] and to show their abilities in evaluating a displacement ventilation system for improving air quality. Based on the result, the impact of displacement ventilation on indoor air quality is discussed.

THE LAYOUT OF THE WORKSHOP VENTILATION

The sketch of the workshop is shown in Fig. 1. It has dimensions of 8 m × 3.6 m × 6 m. Material is processed on a platform with dimensions of 1.8 m × 0.8 m × 1.2 m, releasing contaminants at a rate of 10 mg/s from the surface. The heat gain from two lamps hung 0.5 m above the platform is 120 W. The back wall is towards the outdoors, having a heat loss of 0.4 kW in winter time. Fresh air is supplied through a 0.6 m × 0.8 m opening on a side wall, and the extract opening is located below the ceiling on the opposite wall. Other details on the layout of the workshop can be found in [3].

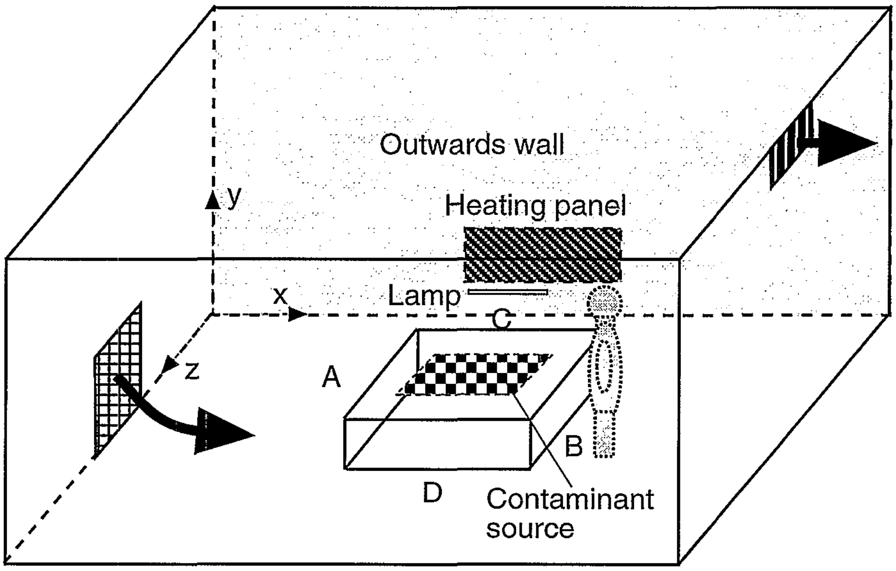


Figure 1. Sketch of the workshop ventilated by displacement.

A standing worker (1.7 m in height) is simulated on a moderate activity level (releasing heat of 50 W/m^2). Four positions beside the platform (A, B, C and D) are available for the worker when processing the material. A convective heating panel (1.7 kW) with an area of 1.2 m × 0.6 m may be installed on either the opposite side wall or the outward back wall. By using three indices, the contaminant concentration in the breathing zone, the percentage of dissatisfied occupants due to draft and the temperature difference between the occupant's neck and feet levels, the ventilation layout for the workshop has been optimised as follows [3]:

- the air supply conditions are: the air change per hour ACH = 3 and T_{in} = 20 °C;
- the heating panel is installed on the outwards back wall;
- the operating position is selected at position B.

THEORY

The airflow in the workshop is simulated using the two-equation turbulence k-ε model. Finite volume method is employed to discretise the differential equation system. The distributions of the passive contaminant and the local mean age of air are calculated by solving the transport equations for the concentration, C, and the local mean age of air, τ.

The scales used here to evaluate the system are the purging effectiveness of inlet, A, the local specific contaminant-accumulating index, α, and the local air quality index, $\varepsilon_{ap} = C_e/C_p$. The distributions of the temperature, the contaminant concentration and the local mean age of air are also compared in cases with and without the worker simulated at position B.

The local purging effectiveness of inlet was originally devised to distinguish the individual contribution of an inlet for systems with multiple supply openings. It is defined as

$$A = \frac{\delta\tau}{\tau_{old}} = \frac{(\tau_{old} - \tau_{new})}{\tau_{old}} \quad \text{....(1)}$$

where τ_{old} is computed by specifying an *old* age, e.g., a nominal time constant, $\tau_n = V/Q$, at the inlet (old air is supplied), τ_{new} is obtained by specifying zero age at the inlet (fresh air is supplied). The use of this scale is to investigate how well the local old air is purged and/or diluted by the fresh air from the supply opening. A high value of A implies a large local *freshening* capability at the location considered and a close connection to the air supplying.

The local specific contaminant-accumulating index, α, is derived from the local age-integrated exposure, $\gamma = \int_0^\tau C(t)dt$. At a steady state, $\gamma = C\tau$, the index α is defined as

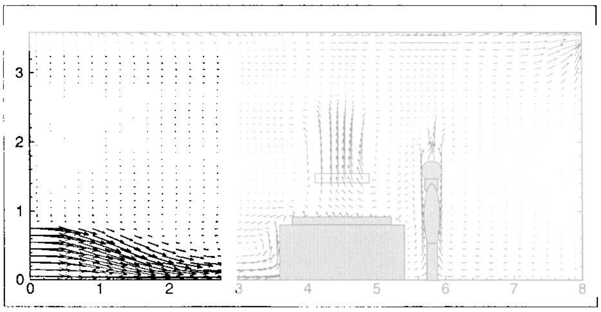
$$\alpha = \log\left(\frac{\gamma}{\tau_n < C >}\right) \quad \text{....(2)}$$

where $<C>$ is the mean room concentration. As α becomes zero, the local mixture is equivalent to a complete mixing; a negative α indicates a small amount of contaminant accumulation and thus a large contaminant-diluting capability at the location. It has shown that the age variation, $\delta\tau$, and the age-integrated exposure, γ, are governed by their respective transport equations [3]. It is thus convenient to explore these scales in numerical simulations. In addition, the local air quality index, ε_{ap}, is employed to indicate the local (at an arbitrary location P) contaminant level (C_p) in comparison with the one at the extract opening (C_e)

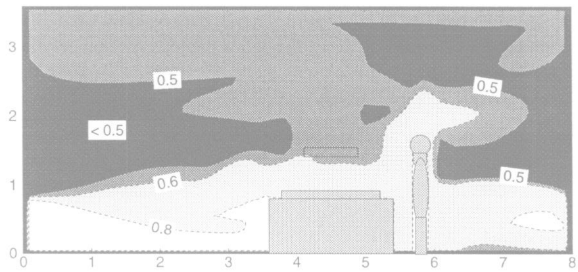
RESULTS

In this section, the above scales are used to evaluate the operating conditions as optimised in [3] for the ventilated workshop. To investigate the effect of the thermal plume induced by the worker (simulated as a heat source), the scales are compared in two cases with and without the worker standing at position B.

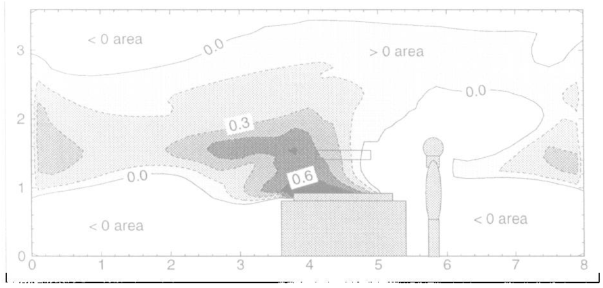
In theory, ventilation by displacement gives two zones separated by a stratification front: a lower zone with unidirectional flow and an upper zone with recirculating air motion. In practice, it is often hard to indicate the height of the stratification front by observing only the flow field. The flow in the lower zone is often characterised also by local recirculation due to, e.g., obstacles, particularly when the upward convection entailed by a heat source is not intensive enough. Other quantities are then used to identify the front height. Since the fresh air is directly supplied to the lower zone, where the flow tends to be dominated by a somewhat unidirectional pattern, quantities that are capable of indicating an ideal complete mixing can then be employed to distinguish the stratification height. For a complete mixing, the quantities C and τ are equal to C_e and τ_n everywhere, respectively, while the corresponding values are A = 0.5, $\alpha = 0$ and ε_{ap} = 1.0 referring to the scales used here. In the lower zone, one should then have $A > 0.5$, $\alpha < 0$ and $\varepsilon_{ap} > 1.0$, respectively.



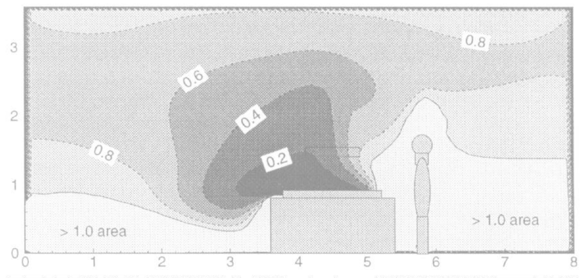
a). Velocity field



b). Local purging effectiveness of inlet, A



c). Local contaminant-accumulating index, α



d). Local air quality index, ε_{ap}

Figure 2. Distributions of ventilation flow and indices on the vertical central section (z = W/2) cross the worker's breathing zone.

Fig. 2 shows the flow pattern and the distributions of A, α and ε_{ap}, on the central section in the z-direction. The plume formed around the worker brings up fresh air, and renders a better air quality in the breathing zone than that with an ideal complete mixing as indicated by the scales. The plume due to the lamp entrains some fresh air from the upward convection flow in front of the worker. A part of the air then flows over the platform and slightly pushes the contaminant towards the left part of the upper zone as shown in Fig. 2 c) and d). Owing to such a flow feature, the local purging effectiveness above the platform becomes relatively large (see Fig. 2 b)), in spite of a rather high contaminant concentration around the pollution source. Near the ceiling the scales exhibit acceptable values, because the heating panel on the back wall raises supplied fresh air from the lower zone up to the ceiling and diffuses it over the ceiling surface.

In order to investigate the effect of the worker (simulated as a heat source), the vertical distributions for several quantities are illustrated in Fig. 3 at a position of 2 m from the supply opening and fairly far from position. Comparing both cases with and without the presence of the worker, the distributions of the temperature, the concentration, the local age (normalised by τ_n), A, α and ε_{ap} are only slightly changed at this position, where the stratification height is identified to be rather low between y/H = 0.2 and 0.4.

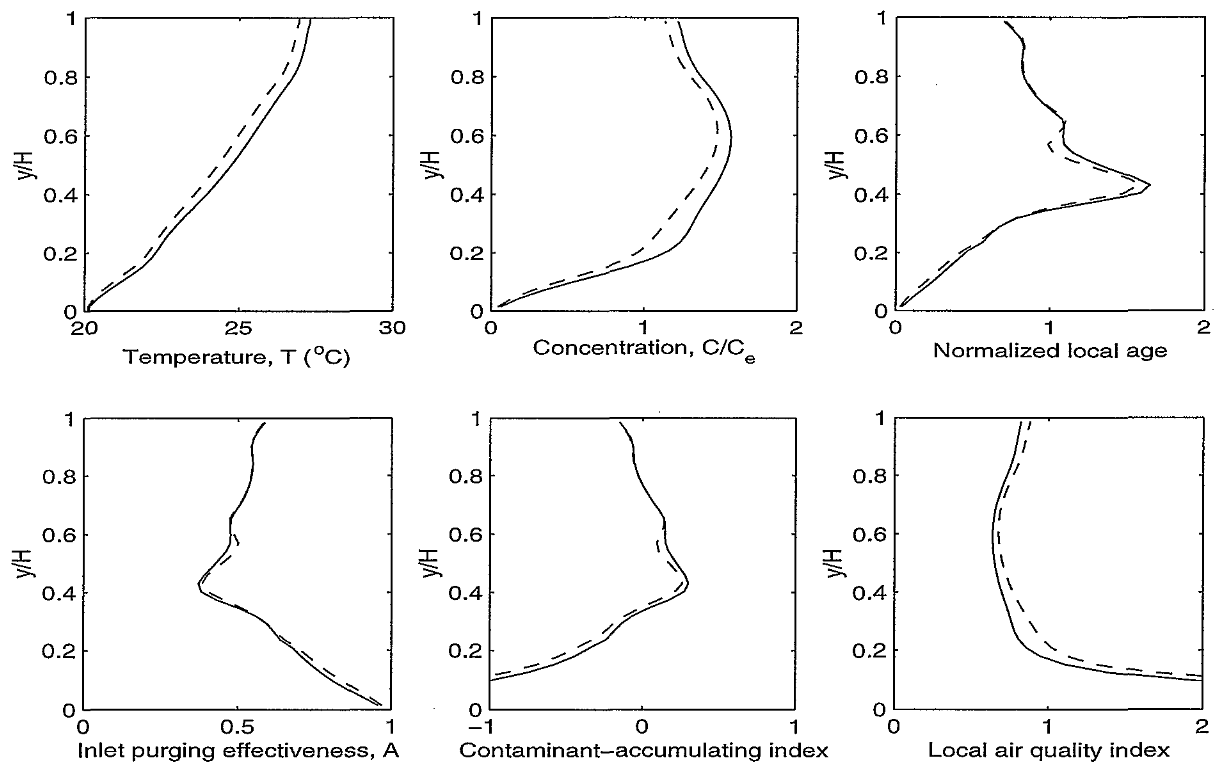


Figure 3. Vertical distributions of different quantities at a position of 2 m from the supply opening (between Position A and the inlet). ——— with a worker simulated at position B, – – – without a worker at position B.

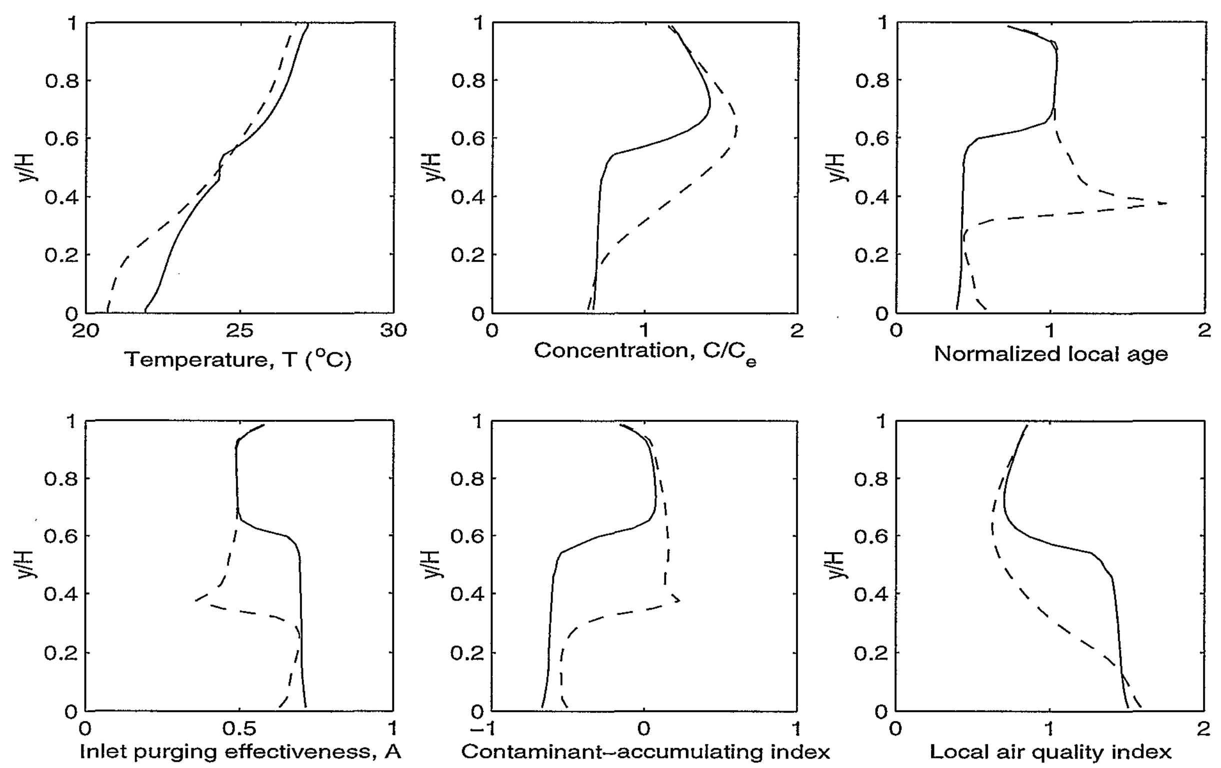


Figure 4. Vertical distributions of different quantities at a location through the breathing zone of the worker at position B (same legend as in Fig. 3).

In the region around position B, however, substantial difference is made due to the plume entailed by the worker, as shown in Fig. 4. In general, the stratification front is raised up to about $y/H \approx 0.6$. And the air quality in the worker's active zone is largely improved, showing a high local purging effectiveness and a large air quality index, as well as a small contaminant-accumulating index as compared with the case of which no worker is simulated. The scales used here are indeed very promising indices to evaluate the performance of a displacement ventilation system. This is also reflected in Fig. 2, where the region having scale values better than those for a complete mixing is bounded with a solid contour line, see Fig. 2 b), c) and d). It is noted that scales that are only associated with the airflow pattern, such as the local mean age of air and the local purging effectiveness, might be less informative to assess the air quality in the presence of a specific contaminant source in the room. One of the most relevant scales is the index α, which is able to indicate the local contamination level and to assess how well the local contaminated air is replaced with the fresh air.

CONCLUSIONS

A displacement ventilation system for a workshop is numerically studied by using several ventilation scales in view of the air quality in the worker's active zone, particularly in the breathing zone. All the scales used in this work are shown to be relevant indices to identify the stratification level between the lower zone and upper zone.

The local purging effectiveness of inlet, A, is a promising scale to identify the contribution of fresh air diffusion from a supply opening to an arbitrary location. Like the mean age of air, however, it might be less informative in assessing the air quality in regions surrounding specific contaminant sources. Nevertheless, a high A value implies that the local contaminant can be efficiently replaced by the fresh air.

The local contaminant-accumulating index, α, is the most relevant scale to evaluate the airflow in combination with the contaminant distribution related to indoor air quality. A small α means a low contaminant level and/or a large local freshening capability of the supplied air.

The presence of the worker as a heat source may essentially enhance the stratification level in the worker's active zone where the scale values identify an unidirection-dominated flow and indicate a generally better air quality than with a complete mixing. It should be noted that the area of the lower zone with a large stratification height is often limited due to the limited intensity of the plume created by a human body. Caution must then be taken for other regions where heat sources are weak or absent.

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