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Calculation of Ventilation Effectiveness using Steady State Concentration Distributions and Turbulent Airflow Patterns in a Half Scale Office Building

Hwataik Han
Department of Mechanics and Design
Kook Min University
Seoul 136-702, Korea

ABSTRACT

A numerical procedure is introduced to calculate local ventilation effectiveness using the definitions of local decay rate and local mean age. A low Reynolds number κ–ε model is implemented to calculate steady state turbulent velocity distributions, and a step-down method is used to calculate transient concentration distributions. Simulations are carried out for several different values of air change rates and several different diffuser angles in a two-dimensional model of a half scale office room. The results show that the local ventilation effectiveness within a room could vary significantly from one location to another. It is numerically proved that the local mean age distribution obtained from the transient calculation is equivalent to the steady state concentration distribution with homogeneously distributed contaminant sources.

Key words: Room Airflow, Contamination Control, Turbulence, Ventilation Effectiveness

INTRODUCTION

Ventilation systems should remove pollutants generated in an occupied space efficiently and supply fresh air to occupants in the space adequately. Many empirical methods and guidelines developed for designing ventilation systems are based on factors such as nominal air change rates or a minimum quantity of air per person or per unit floor area under the assumption of instantaneous homogeneous mixing of air within a ventilated space (ASHRAE 1991).

Various definitions of ventilation effectiveness based on theoretical aspects and experimental measurements of them have been reported. Sandberg (1983) has proposed a definition of ventilation efficiency based on the concept of age and residence time, and has reported experimental results. Skaret and Mathisen (1983) have proposed a two-zone mixing model to describe the concept of ventilation effectiveness and have verified them experimentally. A literature survey shows that most of the works related to ventilation effectiveness are experimental.

In order to predict the effectiveness of a ventilation system, complete information of indoor air movement should be obtained. It is the objective of the present study to provide a numerical procedure to predict the ventilation effectiveness using the turbulent airlfow modeling by adopting the definitions of local decay rate and local mean age. It is aimed to verify numerically the theoretical relationships on various parameters of ventilation effectiveness.

ANALYSIS

Model Configurations

The half-scale model ventilation chamber constructed in the Thermal Environmental Laboratory at the University of Minnesota has been chosen for the present numerical study. Details of the construction of the chamber are explained in Kuehn et. al (1991). The configuration of the chamber is shown in Figure 1 along with a grid pattern for the calculation domain. There are fine grids near solid walls, and more or less uniform in the middle of the chamber. The number of grids in the x-direction is 28 and the number of grid in the y-direction is 22.

Steady State Flow Field

The airflow in the chamber is modeled as a steady state two-dimensional flow. The mean velocity distributions are calculated by solving the continuity and the momentum equations in a Cartesian coordinate. The turbulent quantities are calculated using the low-Reynolds number $\kappa-\varepsilon$ turbulent model as outlined by Jones and Launder (1973). No wall functions are required to establish boundary conditions for ε as required by the ordinary $\kappa-\varepsilon$ formulation. This is a significant advantage for internal air flows which may encounter a variety of obstacles.

The boundary conditions of $\kappa=0$ and $\varepsilon=0$ are applied on solid surfaces. The turbulent intensity of the incoming air is assumed to be 1%. The solutions for the above $\kappa-\varepsilon$ equations along with the continuity and the momentum equations have been obtained with a control volume finite difference computer code that is based on SIMPLE algorithm (Patankar 1980).

Transient Concentration Distributions

In order to determine the transient concentration distribution, a step-down method is utilized in the present calculations. The initial concentration distribution in the chamber is maintained at a uniform concentration of value 1.0 at all locations. At time zero, fresh outside air of zero concentration is supplied to the chamber, and the concentration is allowed to decay transiently. The flow field is assumed to be steady throughout the calculations and not to be affected by the changes in the concentration distributions. Small time steps are utilized in the beginning of the calculation when the concentration change is great. There is no concentration gradients on the solid wall surfaces. The turbulent Schmidt number is assumed to be unity.

Ventilation Effectiveness

Local decay rate. When the mixing is complete, the concentration is uniform in the chamber. For the step-down method the concentration in the chamber decays exponentially. When the mixing is not complete, the decay rate is not uniform throughout the chamber. The transient concentration distributions at the grid locations are calculated and the slops of the logarithm of the concentration versus time for all the grid points are calculated using the least square fit to get the local decay rates.

$$\lambda = -\frac{1}{t}\ln[\frac{c(t)}{c_o}] \tag{1}$$

Local mean age. The age of a fluid element is defined as the time elapsed since the fluid element entered the room (Sandberg 1983). The population of air molecules may be characterized by their statistical cumulative age distribution, $\Phi(\tau)$, and corresponding frequency distribution, $\phi(\tau)$. The cumulative distribution is non-dimensional and its magnitude gives the fraction of the considered population with an age less than or equal to τ. The local mean age is the first moment of the age distribution, which is the average of the frequency distribution function weighted by its age. It can be rewritten in terms of the cumulative distribution function.

For a step-down procedure, the complement of the cumulative distribution function, $(1-\Phi(\tau))$, is equal to the concentration divided by the initial concentration (Sandberg 1983). The local mean age may be taken as the area under the concentration versus time curve for the local point over the initial concentration. This measure takes into account all information in the dilution process.

$$\mu_{\phi} = \int_0^{\infty} \phi(\tau) \cdot \tau \, d\tau = \int_0^{\infty} (1 - \Phi(\tau)) \, d\tau = \frac{\int_0^{\infty} c(t) \, dt}{c_0} \tag{2}$$

Steady state concentration distribution and local mean age. The governing equation for a steady state concentration distribution with uniformly distributed contaminant sources has the identical form with the transient concentration equation integrated with respect to t for a step-down procedure with respect to the following terms.

$$\frac{c_{\infty}}{\dot{m}} = \frac{\int_0^{\infty} c(t) \, dt}{c_0} \tag{3}$$

The solution of the transient equation, i.e. the area under the concentration curve divided by the initial concentration should be the same with the solution of the equation for the steady state concentration distribution, c_{∞} divided by the source strength, $\dot{m}$, when a contaminant source is distributed in the room uniformly. The initial concentration distribution in a transient procedure is 'geometrically similar' to the pollution source distribution in a steady state condition (Sandberg 1983). Therefore, the local mean age can be calculated either by the area under the concentration curve in the transient step-down procedure or by the steady state concentration distribution with contaminant sources uniformly distributed in the calculation domain.

RESULTS AND DISCUSSIONS

Figure 2a shows the steady state streamline pattern when the nominal air change rate is 92 ACH. There is a large recirculation across the entire chamber and there is a local recirculation at the corner near the diffuser. The transient concentration distributions at time=10, 20, 30, 50, 100 sec are shown in Figure 2bcdef. The concentration decreases rapidly underneath the diffuser and in the regions near the streamlines starting from the diffuser. The decrease of the concentration is relatively slow in the middle of the large recirculation zone and at the corners of the chamber.

The concentration decays at several locations in the chamber are shown in Figure 3. The average room concentration is superimposed in the figure, which can be obtained by averaging the concentration distribution in the chamber or can be obtained from the total contaminants escaped through the exhaust up to the present time. The straight bold line indicates the constant decay of concentration in the chamber in case of complete mixing. The concentration curves show non-linear decays during the first 20-30 seconds, and the decay rates remain relatively constant regardless of the location after the initial transients diminish. The local decay rates are obtained by fitting the concentration-time curves at all locations. The isopleth of the local decay rate is shown in Figure 4a. The decay rate does not vary considerably from one location to another except the control volumes right next to the diffuser. Note that the nominal decay rate is 1/(39 sec) when the mixing is complete. The slop of the concentration curve does not seem to be a good measure to determine the local ventilation effectiveness.

The local mean age, i.e. the area under the concentration curve, indicates the cumulative amount of contaminant present at the location. Since the initial uniform concentration is 1.0, the area under the curve has the dimension of seconds. The distributions of the local mean age are shown in Figure 4b. The mean age varies from 10 sec to 70 sec from one location to another. The steady state concentration distribution has been obtained when the contaminant sources are present uniformly throughout the chamber. The contaminant source has a strength of 1 kg/s per unit mass of air. As was shown previously, the steady state concentration distribution is identical with the local mean age distribution obtained from the transient analysis. Slight differences near the walls are caused due to the boundary conditions not decorated.

Transient concentration measurements are conducted in most of the experimental studies on ventilation effectiveness, whereas numerical computations can be performed with relative ease in steady state calculations than in transient calculations. It is suggested to use the steady state concentration procedure to obtain local mean age distributions, since it provides a faster convergence and it requires less memory capacity than the transient step-down method.

CONCLUSIONS

- The ventilation effectiveness based on the definitions of local mean age and decay rate has been obtained from the transient and steady state concentration distributions and the turbulent airflow patterns in a half-scale office chamber. Defining ventilation effectiveness using the local mean age concept appears to be better than using the definition based on local decay rate.

- Ventilation effectiveness defined by the local mean age varies by more than one order of magnitude throughout the chamber. Hence design methods based on nominal air change rate may not be satisfactory in meeting ventilation objectives in some cases.

- The steady state concentration distribution with a contaminant source distributed uniformly in the chamber is proved numerically to be identical with the local mean age distribution calculated from the transient analysis. It is suggested to use the steady state approach in obtaining the local mean age, since the steady state calculation needs less computation time and memory space.

- The numerical method developed in the present study can be used in predicting the effectiveness of real ventilation systems. The effects of various ventilation factors such as nominal air change rate, location of intakes and exhausts, and nature of sources can be determined in designing effective ventilation systems.

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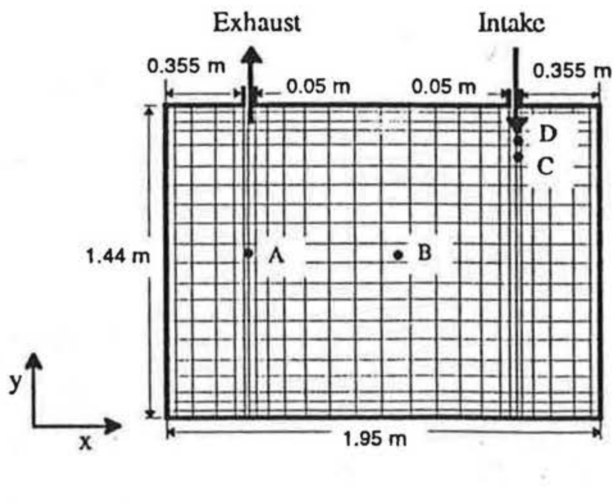

Figure 1. Configuration of the ventilation chamber shown with grid patterns for the present numerical stud

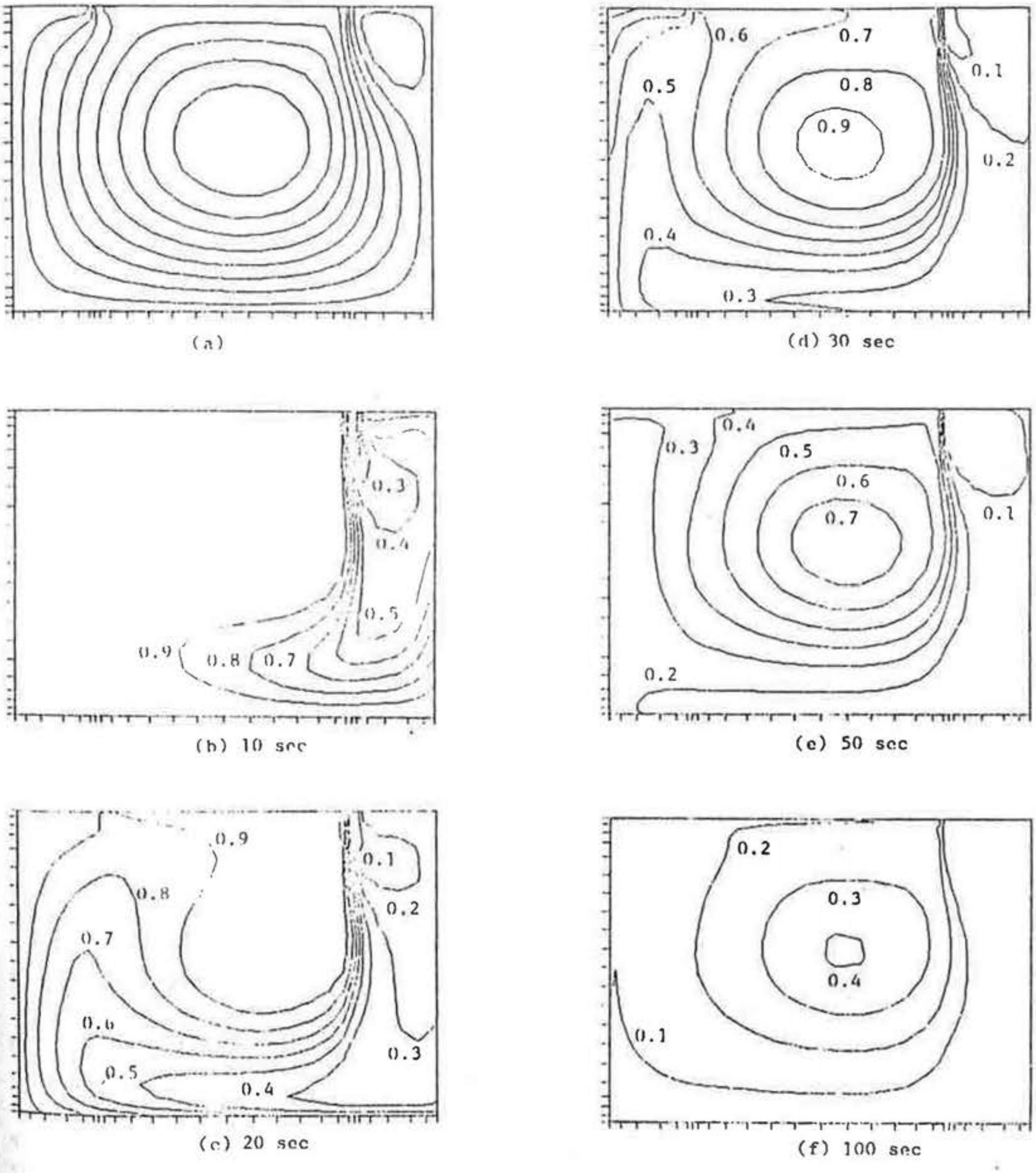

Figure 2. Streamline pattern and transient concentration distributions at 10, 20, 30, 50 and 100 sec after a step-down procedure started.

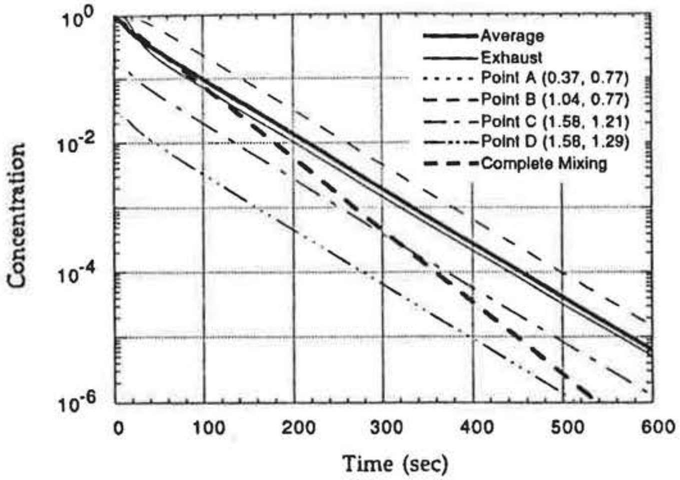

Figure 3. Transient concentration decays at various locations.

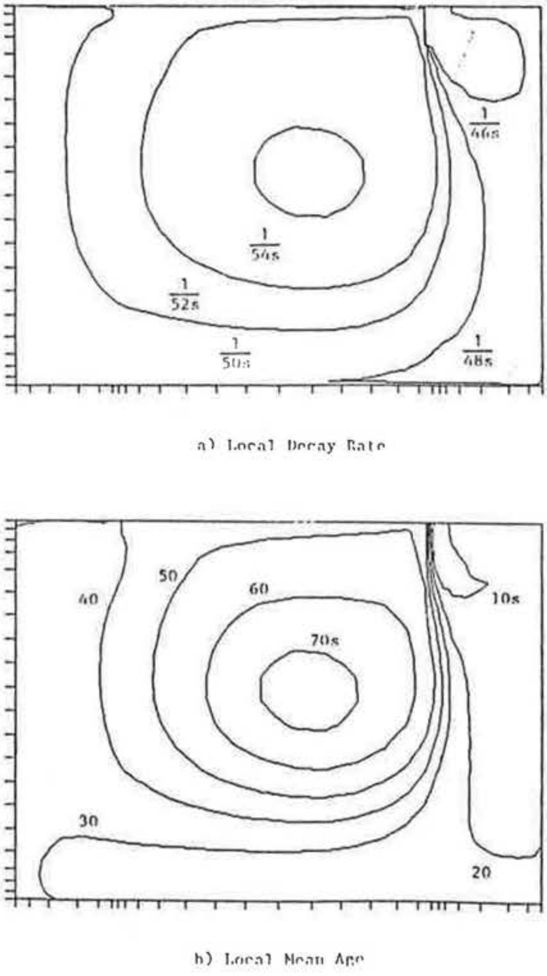

Figure 4. Distributions of local decay rate and local mean age.