6027

International Symposium on Room Air Convection and Ventilation Effectiveness
University of Tokyo, July 22 – 24, 1992

Ventilation Efficiency in a Two-Dimensional Enclosure with a Supply Outlet in the Ceiling or in the Floor

Shin-ichiro NAGANO and Toru MIMA
Technical Research Institute, FUJITA CORPORATION
74, Odana-cho, Kouhoku-ku, Yokohama-shi, 223, Japan

ABSTRACT

The ventilation efficiency in a two-dimensional enclosure with one supply outlet and two exhaust inlets is investigated. Using a standard k-ε model, the effects of changes in Reynolds number (hereinafter "Re") based on the supply outlet width on the average room concentration and the average breathing zone concentration are investigated. Under conditions that the ventilation efficiency is regarded as improving with the reduction of average room concentration and average breathing zone concentration, the ceiling supply outlet system is more effective than the floor supply outlet system. The best efficiency is achieved at Re≧ 100 with both one supply outlet and two exhaust inlets located in the ceiling.

KEYWORDS Ventilation Efficiency, Numerical Simulation, Room Airflow

INTRODUCTION

In recent years the floor supply outlet system have been adopted in air conditioning systems in order to achieve a more comfortable thermal environment in office spaces. This system has better energy efficiency than the ceiling supply outlet system since direct temperature control of the occupied zone is possible. However, from the viewpoint of an air quality, the floor supply outlet system may cause a deterioration in air quality by lifting dust from the dust generation and accumulation floor zone into the office users' breathing zone. It is important to know which system can ensure the cleanest air quality. In order to simplify the problem, this study considers a two-dimensional room configuration at a uniform temperature, with one supply outlet and two exhaust inlets.

NUMERICAL ANALYSIS METHOD

The floor supply outlet and ceiling exhaust inlet type in room configuration Type 1 and the analysis mesh used are shown in Figure 1. The room users' breathing zone is designated (▨). Regarding sources of pollutants, the case of a source in proximity to a floor surface (designated (▒)), and that of a uniform source throughout the room space were considered (Kato and Murakami 1988). As shown in Figure 2, six types of room configuration were investigated depending on the layout of one supply outlet and two exhaust inlets. The degree of pollutant diffusion was investigated into cases with Re of 5 to 10000 as shown in Table 1.

Table 1 Analysis Conditions at Re of 5 to 10000

Re	Supply outlet velocity (m/s)	Exhaust inlet velocity (m/s)	Air exchange rate (1/h)
5	0.0003	0.00015	0.0216
10	0.0006	0.0003	0.0432
50	0.003	0.0015	0.216
100	0.006	0.003	0.432
500	0.03	0.015	2.16
1000	0.06	0.03	4.32
2500	0.15	0.075	10.8
5000	0.3	0.15	21.6
10000	0.6	0.3	43.2

NOTE : $Re=U_{out} L_o/\nu$

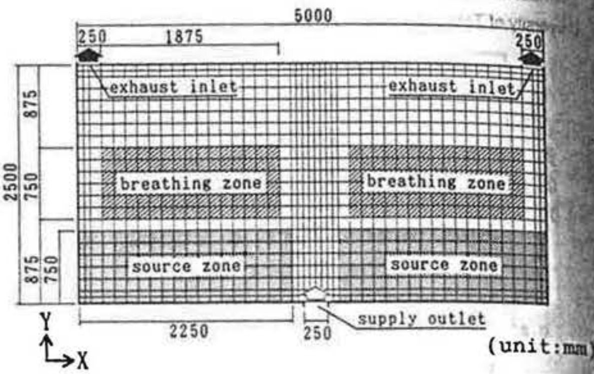

Figure 1 Two-Dimensional Enclosure with Defined Breathing Zone and Source Zone, and Mesh Dividing System (46(X)x22(Y)meshes) Used, in Case of Type 1 with One Supply Outlet in the Floor and Two Exhaust Inlets in the Ceiling

The flow analysis was performed by using a standard k-ε model. The basic equations are is indicated in Table 2. Boundary conditions are shown in Table 3. In each source zone the instantaneous uniform diffusion concentration was set at unity. It was judged that the ventilation efficiency was improved as the average breathing zone concentration decreased. For the isothermal calculations, it was found that the results of flow analysis for Types 1 to 3 could be substituted for those of Types 4 to 6 by inversion of the layout.

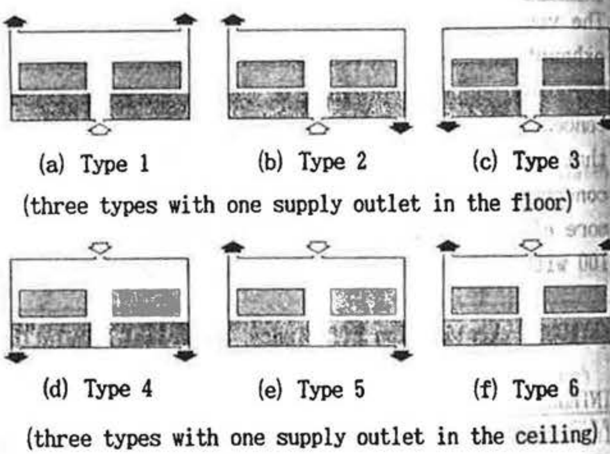

Figure 2 Arrangement of One Supply Outlet and Two Exhaust Inlets for Six Types Investigated

ANALYTICAL RESULTS

Flow Analysis Results at Re=5000

The airflow distributions at Re=5000 are shown in Figure 3. In Type 1 (Figure 3(a)), the floor jet impinges on the ceiling surface and flows along horizontally following the ceiling surface. In Type 3 (Figure 3(c)), after the floor jet has impinged on the ceiling, the airflow breaks away from ceiling surface and the recirculating flow is established in the internal corners formed by the ceiling and walls. Compared with Type 1, the airflow velocity over the floor surface is reduced. The airflow field of Type 2 (Figure 3(b)) appears as a combination of the airflow fields of Types 1 and 3.

Results of Concentration Analysis at Re=5000

Figure 4 shows the concentration distributions in each type at Re=5000 and a source generating at a steady state in the proximity to a floor surface. Overall, Types 1 to 3 have larger areas of high concentration than Types 4 to 6. In Figure 5, the results of the average breathing zone concentration C_b and the average room concentration C_r in each type are shown. The breathing zone concentration decreases in order of Types 1 to 6, indicating that the ventilation efficiency increases in the same order. In each type, the average breathing zone concentration is greater than the average room concentration. Average breathing zone and room concentrations of Types 2 and 5 are almost equal to the average values of those in Type 1 and 3, and 4 and 6 respectively.

The Effect of Varying Re on Cases where a Source Is Generated in the Floor Surface Zone

Average room and breathing zone concentrations for each type with varied Re are shown in Figure 6(a) and (b). The trends in variation of average room and breathing zone concentration are similar, but the difference between average breathing zone and room concentrations in each type differs depending on Re. Looking at the average breathing zone concentration, the value at $Re \gtrsim 2500$ decreases in order of Types 1 to 6, and thus the ventilation efficiency also increases in this order. Regardless of Re, Type 1 normally has the highest value. The lowest value among all cases is that of Type 3 at $Re \lesssim 50$, and Type 6 at $Re \gtrsim 100$. At $Re \gtrsim 500$, with the exception of the case of Type 4 at Re=1000, the ceiling supply outlet system (Types 4 to 6) offers better ventilation efficiency than the floor supply outlet system (Types 1 to 3). From the above results it is concluded that Type 1 has the worst ventilation efficiency regardless of Re value. Optimum ventilation efficiency is obtained with Type 3 at $Re \lesssim 50$,

Table 2 k-ε Two-Equation Turbulence Model

$$\frac{\partial U_i}{\partial X_i} = 0 \qquad (1)$$

$$\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial X_j} = -\frac{\partial}{\partial X_i}\left(\frac{P}{\rho} + \frac{2}{3}k\right) + \frac{\partial}{\partial X_j}\left\{(\nu + \nu_t)\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right)\right\} \qquad (2)$$

$$\frac{\partial k}{\partial t} + \frac{\partial k U_i}{\partial X_j} = \frac{\partial}{\partial X_j}\left[\left(\nu + \frac{\nu_t}{\sigma_1}\right)\frac{\partial k}{\partial X_j}\right] + P_k - \varepsilon \qquad (3)$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial \varepsilon U_i}{\partial X_j} = \frac{\partial}{\partial X_j}\left[\left(\nu + \frac{\nu_t}{\sigma_2}\right)\frac{\partial \varepsilon}{\partial X_j}\right] + C_1\frac{\varepsilon}{k}P_k - C_2\frac{\varepsilon}{k} \qquad (4)$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \qquad (5)$$

$$\frac{\partial C}{\partial t} + \frac{\partial C U_j}{\partial X_j} = \frac{\partial}{\partial X_j}\left[\left(\frac{\nu}{S_c} + \frac{\nu_t}{\sigma_3}\right)\frac{\partial C}{\partial X_j}\right] + C_s \qquad (6)$$

Here, $$P_k = 2\nu_t\left\{\frac{1}{2}\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right)\right\}^2 \qquad (7)$$

$\sigma_1=1.0, \sigma_2=1.3, \sigma_3=1.0, C_\mu=0.09, C_1=1.44, C_2=1.92, S_c=1.0$

Table 3 Boundary Conditions and Finite-Difference Scheme

(1) Supply Outlet	$U_t=0.0, U_n=U_{out}, k_o=0.005\cdot U_{out}^2$ (m^2/s^2), $\varepsilon_o=L_o\cdot k_o^{1/2}$ (m^2/s^3), $C=0.0$ subscript t, n: tangential and normal direction with respect to outlet surface U_{out}: supply outlet velocity (:Table 1), L_o: supply outlet width (=0.25m)
(2) Exhaust Inlet	$U_t=0.0$, $U_n=U_{in}$, $\partial k/\partial n=0.0$, $\partial\varepsilon/\partial n=0.0$, $\partial C/\partial n=0.0$ U_{in}: exhaust inlet velocity (:Table 1)
(3) Wall Surface	$\frac{U_t\cdot(C_\mu^{1/2}\cdot k)^{1/2}}{(\tau_w/\rho)} = \frac{1}{\kappa}\ln\left[\frac{E\cdot h\cdot(C_\mu^{1/2}\cdot k)^{1/2}}{\nu}\right]$ ① $\left\{(\nu+\nu_t)\frac{\partial U}{\partial n}\right\}_{WALL} = \frac{\tau_w}{\rho}$ ② $\bar{\varepsilon} = \frac{C_\mu^{3/4}\cdot k^{3/2}}{\kappa\cdot h}\cdot\ln\left[\frac{E\cdot h\cdot(C_\mu^{1/2}\cdot k)^{1/2}}{\nu}\right]$ ③ $\varepsilon_1 = \frac{C_\mu^{3/4}\cdot k^{3/2}}{\kappa\cdot h}$ ④ $U_n=0.0$, $\partial k/\partial n=0.0$, $\partial C/\partial n=0.0$ h: distance from wall surface to the center of the near-wall cell $\kappa=0.4$, $E=9.0$, $\nu=0.15\times10^{-4}$ (m^2/s)
(4) Finite Difference Scheme	Space differential: 1) QUICK scheme : momentum equation 2) First-order upwind scheme : transport equations for k, ε and C 3) Centered differential scheme for all others Time differential: Adams-Bashforth scheme with second-order accuracy

NOTE: This simulation is performed using full-scale physical parameters.
③ is for the boundary condition for k-equation and ④ is that for ε-equation.

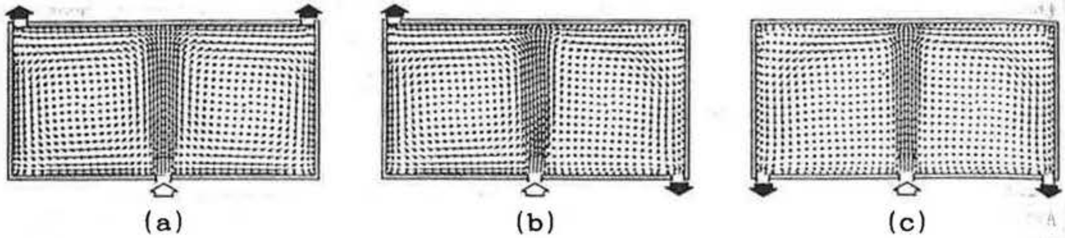

Figure 3 Airflow Fields in Each Type at Re=5000 : (a) Type 1 (or Type 4 with reversed floor and ceiling) ; (b) Type 2 (or Type 5 with reversed floor and ceiling) ; (c) Type 3 (or Type 6 with reversed floor and ceiling)

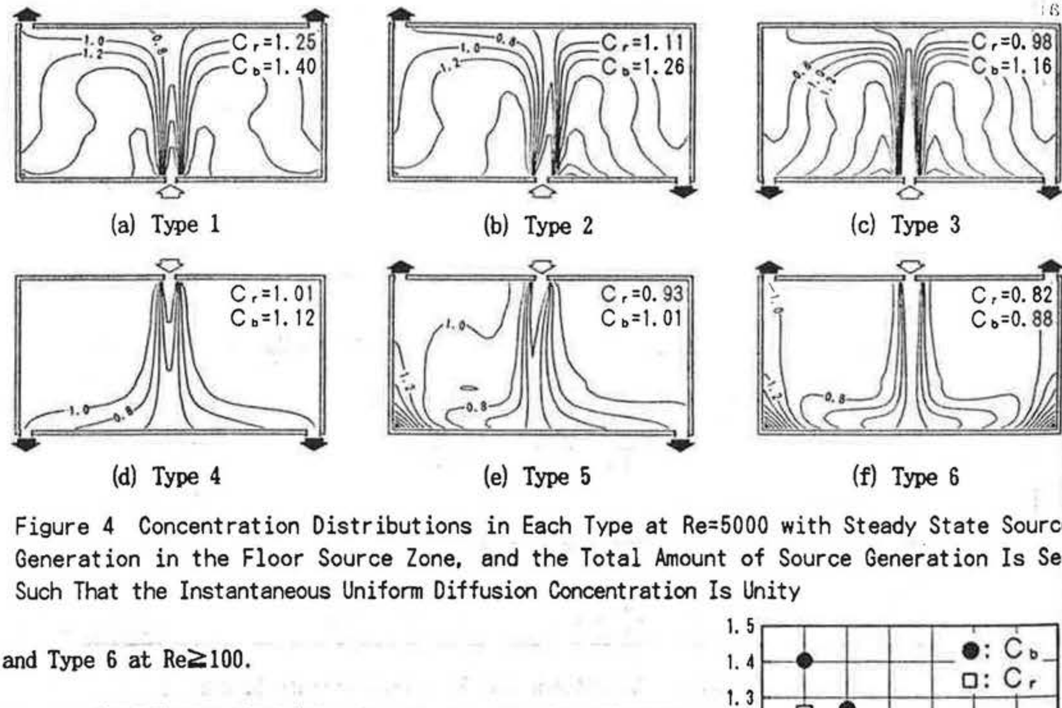

Figure 4 Concentration Distributions in Each Type at Re=5000 with Steady State Source Generation in the Floor Source Zone, and the Total Amount of Source Generation Is Set Such That the Instantaneous Uniform Diffusion Concentration Is Unity

and Type 6 at Re≧100.

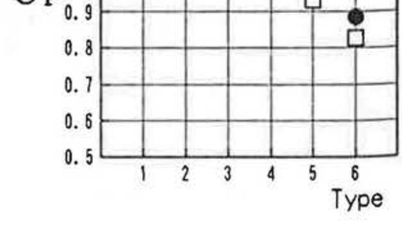

Figure 5 Comparison Between Average Room Concentration C_r and Average Breathing Zone Concentration C_b in Each Type

The Effect of Varying Re on Cases where a Uniform Source Is Generated in the Whole Room

In order to study the effect of different layouts of one supply outlet and two exhaust inlets, the average room and breathing zone concentrations were investigated into each type under a uniform source generation in the whole room. This is shown in Figure 7. In this case, the results of Types 1 to 3 are the same as those of Types 4 to 6, and discussion will therefore be limited to Types 1 to 3. For Types 1 and 2, average room and breathing zone concentrations increase up to Re=500, and tend to decrease over this. In contrast, Type 3 shows a gentle

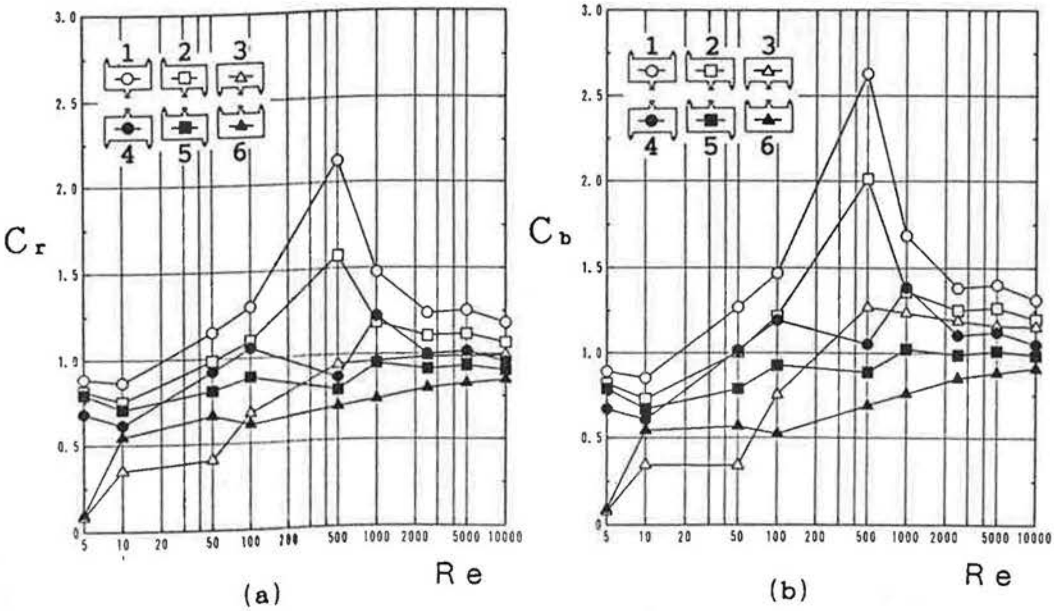

Figure 6 Effect of Changes in Re, for the Case where a Source Is Generated in the Floor Surface Zone : (a) effect of changes in Re on average room concentration C_r ; (b) effect of changes in Re on average breathing zone concentration C_b

continuous increase throughout the range of Re under consideration. In each type, the average breathing zone concentrations are higher than the average room concentrations as stated above. Average room and breathing zone concentrations for Type 2 are almost equal to the Type 1 values up to Re=10, whereas Type 3 has values lower than these. At Re between 50 and 500, the Type 2 values are close to Type 1. At Re≧1000, the Type 2 values finally become nearly equal to the average values of Types 1 and 3. Regarding the influence of varying Re values, the values at Re≦500 show a large difference between Types, but at Re>500 this difference becomes small. In the case of a uniform source generation in the whole room, the worst efficiency was the ceiling exhaust inlet type of the floor supply outlet system (Type 1), and the floor exhaust inlet type of the ceiling supply outlet system (Type 4).

DISCUSSION

As shown in Figure 7, the variations of average breathing zone and room concentrations with Re have the difference between Type 3 and Types 1 and 2. In order to study this, the effect of change in Re on the ratio of room average $\overline{\nu_t}$ to ν is shown in Figure 8. The $\overline{\nu_t}/\nu$ ratio for Type 3 has a very small value at Re between 5 and 100, and at Re≧100 it shows an increase with values almost equal to Types 1 and 2. At low Re between 5 and 10, the coefficient of viscosity $(\nu+\overline{\nu_t})$ in Type 3 is about 4 times that of Types 1 and 2, and this is thought to have influenced the average concentrations. Although not mentioned in this report, while the circulating flow was established in the room at Re≧10 in Types 1 and 2, in Type 3 it was not established if Re≦50. Though the formation of a circulation seems to have a great influence on the $\overline{\nu_t}$ value, more detailed investigation should be employed by a low Reynolds number k-ε model (e.g. Lage et al. 1991).

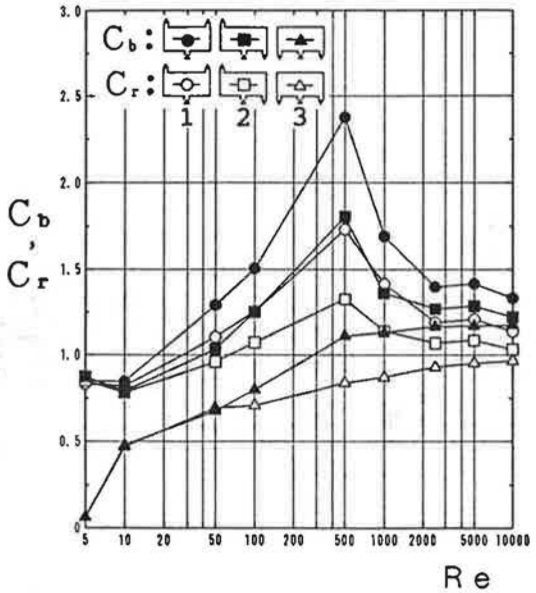

Figure 7 Variation of Average Room and Breathing Zone Concentrations (C_r & C_b) with Re, for the Case where a Uniform Source Is Generated in the Whole Room

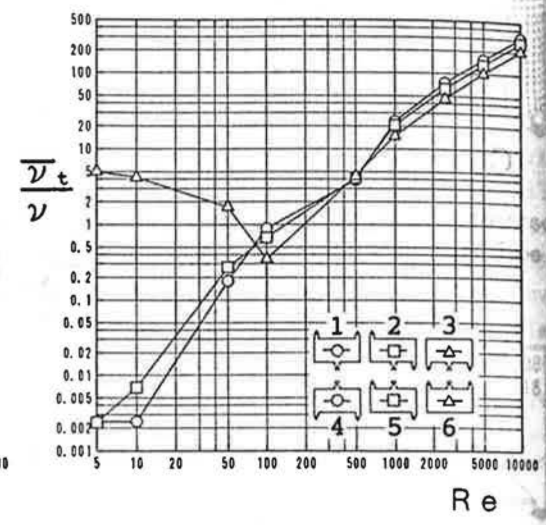

Figure 8 Variation of Ratio of Room Average $\overline{\nu_t}$ Value to ν with Re

CONCLUSIONS

The ventilation efficiency of the floor or ceiling supply outlet systems have been investigated into the case of a two-dimensional isothermal enclosure by using a standard k-ε model. The following conclusions may be drawn.

(1) At Re≧500, with the exception of the case at Re=1000, the ceiling supply outlet system offers better ventilation efficiency than the floor supply outlet system.

(2) Judging from the ventilation efficiency in the breathing zone, the worst arrangement is the floor supply outlet and ceiling exhaust inlet type, and the best is the floor supply outlet and floor exhaust inlet type at Re≦50 and the ceiling supply outlet and ceiling exhaust inlet type at Re≧100.

(3) In cases where a uniform source is generated in the whole room, the average breathing zone concentration is usually greater than the average room concentration.

NOMENCLATURE

C:average concentration, C_s:concentration source term, C_b:average breathing zone concentration C_r:average room concentration, k:turbulence energy, ε:dissipation rate, L_0:supply outlet width P:mean pressure, ρ:fluid density, ν_t:turbulence kinematic viscosity, ν:kinematic viscosity

REFERENCES

Kato, S and S. Murakami 1988. New ventilation efficiency scales based on spatial distribution of contaminant concentration aided by numerical simulation. ASHRAE Transactions, Vol.94, Part 2, pp.309-330

Lage, J.L.; A. Bejan; and R. Anderson 1991. Efficiency of transient contaminant removal from a slot ventilated enclosure. Int. J. Heat Mass Transfer, Vol 34, No.10, pp.2603-2615