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Poster 9

NUMERICAL SIMULATION OF INDOOR TURBULENT AIR FLOWS CAUSED BY CROSS-VENTILATION AND ITS MODEL EXPERIMENTS

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SYNOPSIS

Since thermal comfort on human body is influenced by the local air flow speed, it is needed to estimate the distribution of air flow speed in a room for the "effective ventilation". Numerical solution of the equations for the motion of 3-dimensional turbulent air flow and model experiments are conducted for this purpose. The experiment model is a single room model house with 2 windows on the opposite walls. It is actually ventilated by the natural wind. Non-directivity thermistor anemometers are used to measured the 3-dimensional distribution of indoor air flow speed. Several kinds of numerical simulation are carried out on the similar space to the experiment model. Two kinds of mathematical turbulence model are adopted, one is the k-ε 2-equation model, and the other is the Large Eddy Simulation. Two kinds of pseudorandom number are used as the turbulence component of the velocity on the inflowing opening boundary in the LES. The distributions of scalar speed in the sections which are perpendicular to axes of the numerical simulation results are compared with those of the experiment results. They are not entirely corresponding, however, the same tendencies are found.

1. INTRODUCTION

Cross-ventilation is here regarded as natural ventilation through relatively large openings, for instance windows and doors widely opened. It probably makes an adequate air flow rate in a room, and such a air flow often brings about comfortable thermal environment in the warm season[1]. It is one of the simplest and the most effective cooling means without air-conditioning. Although thermal comfort on a human body consists of a lot of factors, as air temperature, humidity and radiation, the thermal effect of cross-ventilation depends upon the air flow speed in the vicinity of the human body[2]. However, it is almost impossible to control the air flow speed caused by cross- ventilation in detail. Therefore, it is necessary to predict the distribution of air flow speed in a room in various cases in the step of planning a dwelling house for the "effective ventilation".

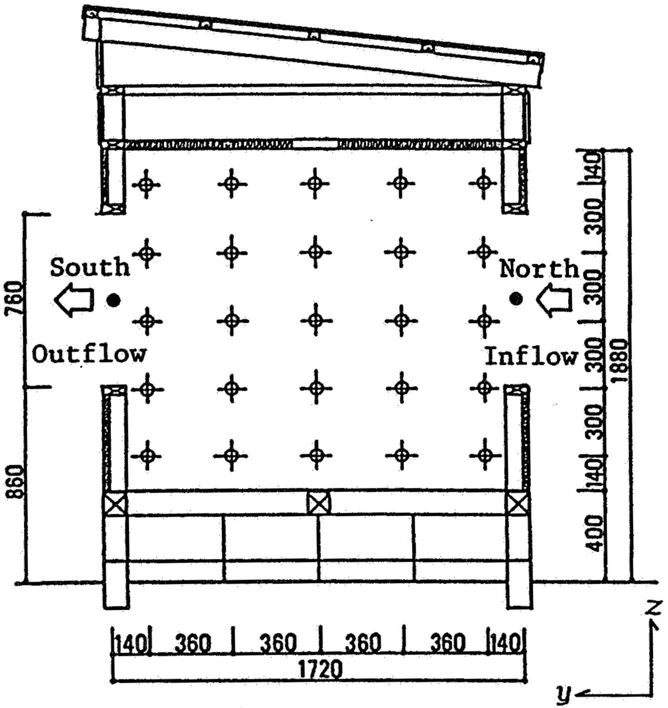
The development of the large capacity and high speed super-computer makes numerical simulation the dominant method for the prediction of the air flow distribution in a room instead of the model experiment. However, there are still some problems left in the numerical simulation. Turbulence is one of the most important problems, and the indoor air flow is almost always regarded as turbulence. The mathematical turbulence model is needed, because the direct simulation of turbulence is impossible or nonsense from the viewpoint of its cost performance. There are two kinds of turbulence model which are recognized practically accurate in various engineering field. One is the k-ε 2-equation model[3] (k-ε model), and the other is the Large Eddy Simulation (LES)[4]. Both of them are tested for the simulation of a air flow caused by cross-ventilation in this paper.

The similarity between the result of numerical simulation and the actual flow phenomenon is another important problem of numerical simulation[5]. It is generally examined by compared with the scaled model experiment, if it is impossible or difficult to measure the turbulent values of the real flow. However, it is also difficult to reproduce the large scale turbulence as the natural wind by the wind tunnel or so on. Cross-ventilation is the very air flow which is influenced by the natural wind directly. Therefore, the model house, which is built on the ground and is naturally ventilated, is used for the model experiments to examine the results of the numerical simulation in this paper. There are few documents on the distribution of the air flow in a house which is naturally ventilated[6,7]. Grasping the air flow distribution caused by cross-ventilation itself is one of the purpose of this paper as its numerical simulation.

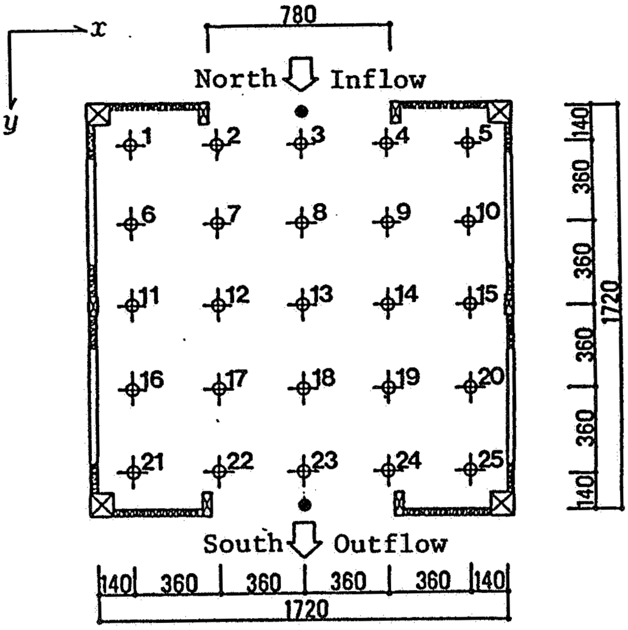
2. MODEL EXPERIMENTS

2.1 Experiment Procedure

The experiment model built on the ground is used for measuring indoor air flow speed caused by cross-ventilation. Its section and plan are shown in Fig. 1 (a), (b), respectively, with the axes of coordinate that is fixed on the model. It has two openings oppositely on its southern and northern wall. They are the same shape of a square, and fixed at the same position in the wall. They are relatively large openings to the whole dimensions of the wall. When the main direction of the wind is north, in other words, the wind direction is perpendicular to the openings, the measurements are carried out. Five non-directivity thermistor anemometers are used to measure the distribution of the indoor air flow speed. These anemometers are fixed on a stand to be situated at measurement heights which are shown in Fig. 1 (a). The stand is moved on the measurement points from No.1 to No.25 by turns which are shown in Fig. 1 (b). Therefore, the measurement points are set on the grid that divide the room space into 5x5x5, and the total number of the measurement points amounts to 125. The air flow speed are measured for 150 seconds at each measurement point. It takes about 80 minutes for a series of the measurement including the moving time. The wind speeds at the centre of the inflowing and the outflowing openings are constantly measured by a 3-dimensional ultrasonic anemometer and a non-directivity thermistor anemometer, respectively. The wind speed and direction above the roof of the model are measured at the height of 4.5m from the ground level by a 3-cup anemometer and an arrow-shaped vane, respectively, as the natural wind data which is not influenced by the model itself. All the data are recorded at the intervals of 2 seconds, and their mean values are found from 60 data.



(a) Section



(b) Plan

Fig. 1. Experiment model with measurement points of indoor air flow velocity (dimensions in mm)

2.2 Experiment Results

The changes on standing of the wind vector above the roof and the wind vector at the inflowing opening on x-y plane and y-z plane measured by 3-dimensional ultrasonic anemometer are shown in Fig. 2 (a), (b) and (c), respectively. The wind directions at the inflowing opening correspond to the wind directions above the roof, the wind speeds at the inflowing opening are about half as much as those above the roof as shown in Fig. 2 (a) and (b). Moreover, it is obvious that the natural wind which flows into the inflowing opening is almost horizontal as shown in Fig. 2 (c). The correlation between the mean inflowing wind speeds and the mean wind speeds above the roof is shown in Fig. 3. The inflowing wind speeds are correlated with the wind speeds above the roof with the high correlation coefficient of 0.91. The correlation between the mean inflowing wind speeds and the mean outflowing wind speeds are shown in Fig. 4. Although those values are scattered somewhat widely, the outflowing flux is nearly equal to the inflowing flux, because the inclination of the regression line is about 45 . The correlations between the mean wind speeds of two openings and their standard deviations are shown in Fig. 5 and Fig. 6. The standard deviations of the inflowing and the outflowing wind speed correspond to their mean values to some extent. Both the inclination value of the regression line of Fig. 5 and that of Fig. 6, which indicate the means of the turbulence intensity at the inflowing opening and at the outflowing opening, are the same value of 36%.

3. NUMERICAL SIMULATION

3.1 Governing Equations of the k-ε Model

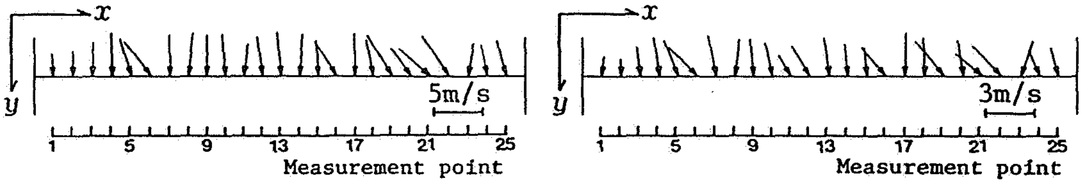
The air flow in a room caused by cross-ventilation is regarded as the incompressible isothermal turbulent flow. It is expressed by the continuity equation and the Navier-Stokes (N-S) equations. The ensemble mean of the turbulence is here the objective value to be simulated. The ensemble mean of the continuity equation is as follows:

$$\frac{\partial U_i}{\partial x_i}=0 \tag{1}$$

where, U_i is the mean velocity component of x_i direction, i is the tensor, $x_1=x$, $x_2=y$ and $x_3=z$. The ensemble mean of the N-S equations become the Reynolds equations with the Reynolds stress term. The Reynolds stress is modelled by the turbulent kinetic energy, k, and the product of the eddy viscosity, ν_t, and the differentials of the mean velocity.

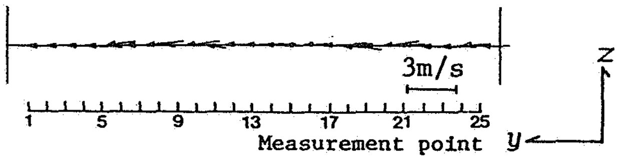
$$\frac{\partial U_i}{\partial t}+\frac{\partial}{\partial x_j}(U_iU_j)=-\frac{\partial \Pi}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\nu_t\cdot E_{ij}+\frac{1}{Re}\frac{\partial U_i}{\partial x_j}\right) \tag{2}$$

$$E_{ij}=\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i} \tag{3}$$



(a) Wind vector above the roof at the height of 4.5m from the ground

(b) Wind vector on x-y plane measured by 3-dimensional ultrasonic anemometer



(c) Wind vector on y-z plane measured by 3-dimensional ultrasonic anemometer

Fig. 2. Changes on standing of the wind vector above the roof and the inflowing wind vector

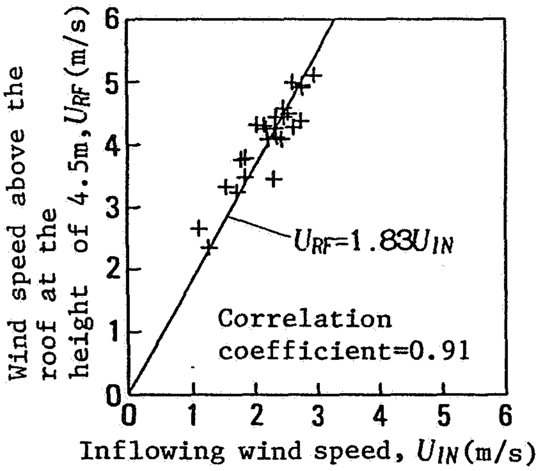


Fig. 3. Correlation between the inflowing wind speeds and the wind speeds above the roof

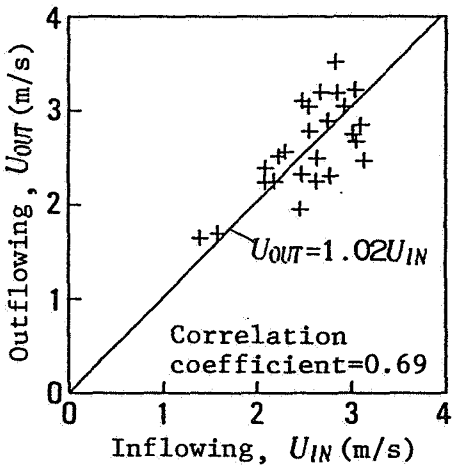


Fig. 4. Correlation between the inflowing wind speeds and outflowing wind speeds

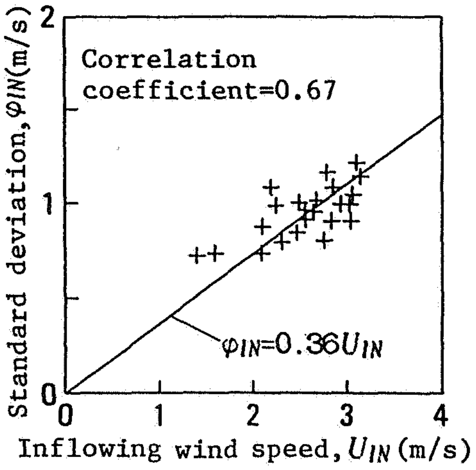


Fig. 5. Correlation between the inflowing wind speeds and their standard deviations

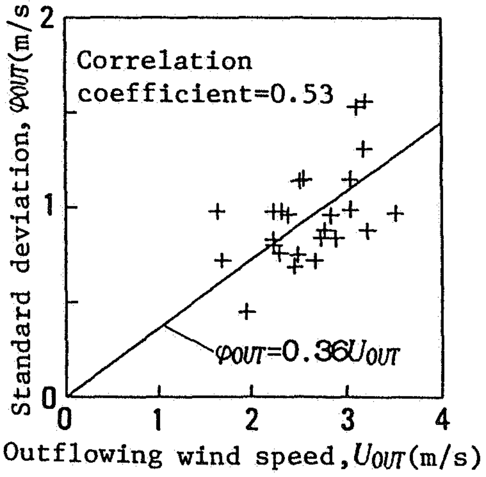


Fig. 6. Correlation between the outflowing wind speeds and their standard deviations

where, t is time, Π is pressure including $(2/3)k$, Re is the Reynolds number. ν_t is found by the algebraical expression of k and the energy dissipation rate, ε, from dimensional analysis.

$$\nu_t=C_D\frac{k^2}{\varepsilon} \tag{4}$$

Then, the equations of k and ε are essential to solve the variables in the mean field. These equations are found from the equations for the fluctuating field.

$$\frac{\partial k}{\partial t}+\frac{\partial}{\partial x_i}(kU_i)=\frac{\partial}{\partial x_i}\left\{\left(\frac{\nu_t}{\sigma_1}+\frac{1}{Re}\right)\frac{\partial k}{\partial x_i}\right\}+\nu_t\cdot E_{ij}\frac{\partial U_i}{\partial x_j}-\varepsilon \tag{5}$$

$$\frac{\partial \varepsilon}{\partial t}+\frac{\partial}{\partial x_i}(\varepsilon U_i)=\frac{\partial}{\partial x_i}\left\{\left(\frac{\nu_t}{\sigma_2}+\frac{1}{Re}\right)\frac{\partial \varepsilon}{\partial x_i}\right\}+C_1\frac{\varepsilon}{k}\nu_t\cdot E_{ij}\frac{\partial U_i}{\partial x_j}-C_2\frac{k\varepsilon}{\nu_t} \tag{6}$$

where, C_D, C_1, C_2, σ_1 *and* σ_2 are constants, and these values used here are 0.09, 1.59, 0.18, 1.0 and 1.3, respectively.

3.2 Governing Equations of the LES

The fundamental equations are the continuity equation and the N-S equations which are the same ones as the $k-\varepsilon$ model, however, the averaging procedure is different. All the equations are filtered out and separated into the grid scale (GS) and the sub-grid scale (SGS) variables. The GS variables are solved directly and the SGS variables are modelled by the GS variables. This filtering operation has much the same meaning as the spatial average, but it is not the same process as the ensemble mean. The filtered continuity equation is the same form as eq. (1).

$$\frac{\partial u_i}{\partial x_i}=0 \tag{7}$$

where, u_i is the GS velocity component of x_i direction. There are three different terms, the cross term, the Leonard term and the SGS Reynolds stress term, from the Reynolds equations. The cross term and the Leonard term are neglected here, and the only SGS Reynolds stress term, which is correspond to the Reynolds stress term in the Reynolds equations but not entirely equal to that, is modelled by the product of the SGS eddy viscosity, ν_{SGS}, and the differentials of the GS velocity components.

$$\frac{\partial u_i}{\partial t}+\frac{\partial}{\partial x_j}(u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\nu_{SGS}\cdot e_{ij}+\frac{1}{Re}\frac{\partial u_i}{\partial x_j}\right) \tag{8}$$

$$e_{ij}=\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i} \tag{9}$$

where, p is pressure including the SGS turbulent energy term. ν_{SGS} is modelled from dimensional analysis by the GS velocities[8].

$$\nu_{SGS}=(C_s\cdot\Delta)^2\left\{\frac{(e_{ij})^2}{2}\right\}^{1/2} \tag{10}$$

where, C_s is the Smagorinsky constant, that is here 0.1, Δ is the characteristic width of the filter, which is defined as follows:

$$\Delta=(\Delta x_1 \cdot \Delta x_2 \cdot \Delta x_3)^{1/3} \tag{11}$$

where, Δx_i is the grid width of x_i direction. All the variables used here are non-dimensionalized by the width or height of the openings as the reference length, and the inflowing wind speed as the reference speed. *Re* based on these reference values in the model experiment becomes 10^5.

3.3 Numerical Calculation Procedure

The governing equations mentioned above are transformed into the finite difference equations by the explicit forward differences to the time differentials and the centred differences to the spatial differentials on the staggered grid system. The calculation algorism adopted here is the original MAC method. The grid system is fixed in the objective space which is similar to the experiment model, divided x and y length into 18 equally and z length into 16 equally.

The variables on the inflowing boundary are the given conditions. The tangential velocity components on the inflowing boundary are 0. The normal velocity component in the k−ε model is 1, as the reference speed. As for the LES, three kinds of the normal velocity component are given. One is the constant value, 1, which is the same condition as the k−ε model and it is called "Constant". The others are the normal and the uniform random number, which are called "Normal" and "Uniform", respectively. Their mean values are 1 and their turbulence intensity values are 36% that is the result of the model experiment. The frequency distributions of the given random numbers are shown in Fig. 7. The turbulence intensity in the k−ε model is given by the value of k. That is here 0.2 which is correspond to the turbulence intensity of 36% under the isotropic hypothesis. While ν_{SGS} is calculated directly from the variables on the inflowing opening, ν_t on the inflowing opening is given as follows:

$$\nu_t=k^{1/2} \cdot l \tag{12}$$

where, l is the turbulence length scale, that is 1.0 from the result of the model experiment.

3.4 Boundary Condition

The boundary condition of most variables are given by these values in an external cell. The normal velocity component on the wall is 0. The velocity components tangential to the wall are found from the power law velocity profile as shown in Fig. 8[9,10]. The normal velocity in an external cell of the wall boundary is found from the flux balance in the external cell and the adjacent internal cell. On the outflowing opening, the tangential components are free slip and the normal component is found from the flux balance in the internal cell neighbouring to the outflowing opening as shown in Fig. 9. The boundary conditions

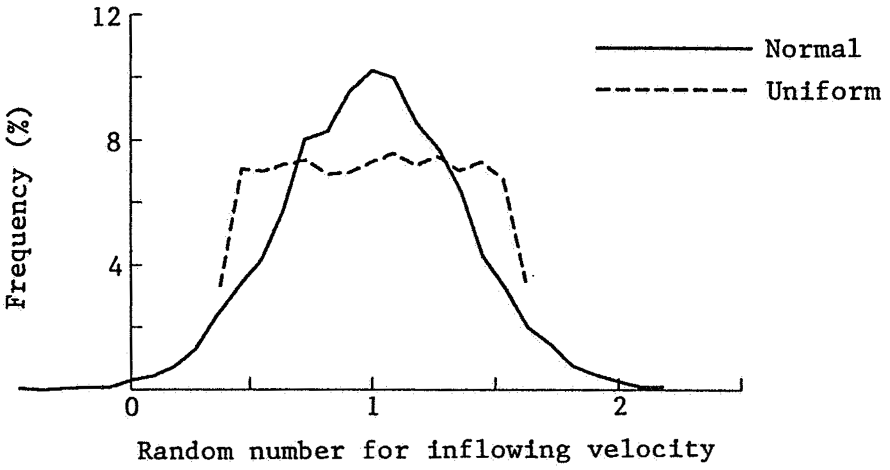


Fig. 7. Frequency distribution of random numbers used for the inflowing boundary in the LES

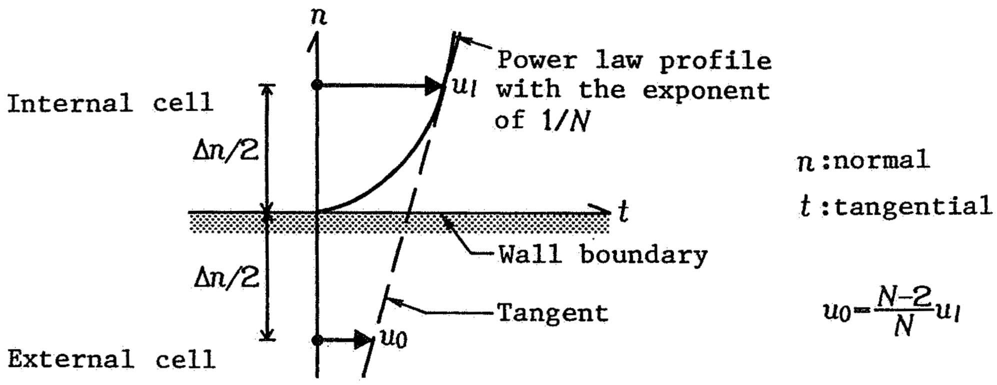
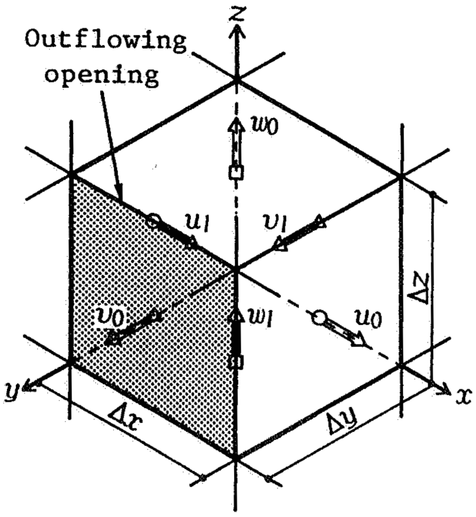


Fig. 8. Boundary condition of the tangential velocity component on the wall



$$v_0=v_l+\frac{\Delta y}{\Delta x}(u_l-u_0)+\frac{\Delta y}{\Delta z}(w_l-w_0)$$

Fig. 9. Boundary condition of the outflowing velocity

of p and Π are found from the basic equations (2) and (8) which are transformed into the difference equations over the velocities on the boundary. The boundary conditions of k, ε and ν_{SGS} on the outflowing opening are free slip. ν_{SGS} and ν_t on the wall are 0. The boundary condition of k on the wall is free slip. The boundary condition of ε is given as follows:

$$\varepsilon = C_D^{\frac{3}{4}} \cdot k^{\frac{3}{2}} \Big/ \left\{ \kappa \left(\frac{\Delta n}{2} \right) \right\} \qquad (13)$$

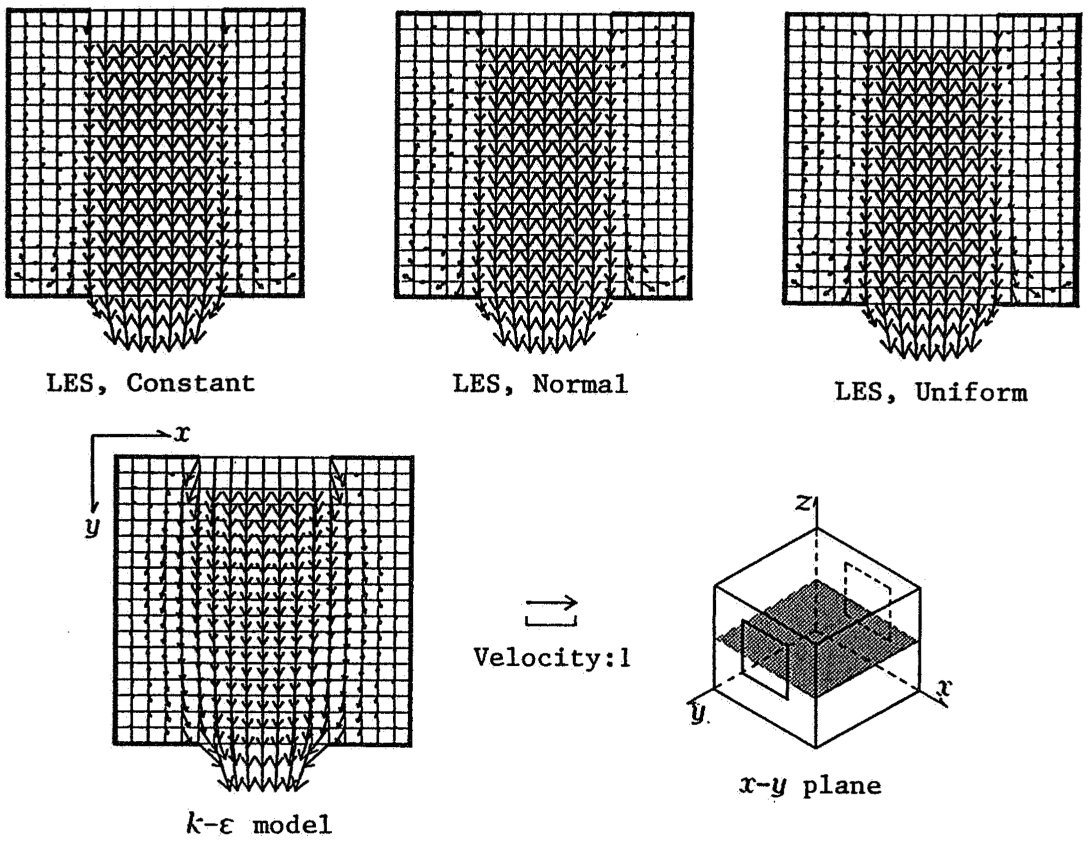
where, κ is the Karman constant, Δn is the grid scale of the normal direction. That is the value of ε in the internal cell adjacent to the wall boundary.

4. COMPARISON BETWEEN MODEL EXPERIMENT AND NUMERICAL SIMULATION

There are four kinds of numerical simulation, one is the k-e model, and the others are the LES. Three kinds of the LES are distinguished by the inflowing boundary condition into the Constant, the Normal and the Uniform. These results are examined, compared with the result of model experiment over the distributions of scalar speed and velocity vector on three sections. These sections are perpendicular to each axis and at the center of the each side length, they are called X-Y plane, Y-Z plane and X-Z plane. The results on the X-Y plane, on the Y-Z plane and on the X-Z plane are shown in Fig. 10, Fig. 11 and Fig. 12 respectively. All the results of the LES are the mean values of 10 time steps.

As for Fig. 10 and Fig. 11, both of them have two openings and there are a lot of common points in the air flow distributions in these section. Therefore, these two sections are examined at the same time. The difference of three kinds of boundary conditions of the LES, particularly the Normal and the Uniform, is not clear. The distributions of the velocity vector by the LES indicate that the air flow passes across the analysis space straightly from the inflowing opening to the outflowing one. The distributions of the scalar speed by the LES in the area from the inflowing opening to the outflowing one are almost uniform. It is regarded as the main flow. The secondary circulations beside the main flow are so weak that contour lines of the scalar speed concentrate to the edges of the two openings. These tendencies do not change by the inflowing boundary. On the other hand, the velocity vectors by the k-e model diffuses right after the inflowing opening gradually, and the scalar speeds by the k-e model decrease up to the centre of the section. They are similar to the results of the model experiments on both sections, although the results of the k-e model keep symmetrical patterns. The distributions of the scalar speed by the model experiments are asymmetric because of the minute fluctuation of the natural wind.

As for Fig. 12, there is little difference, either, between the distributions of the velocity vector by the Normal and that by the Uniform. However, they are a little different from the



LES, Constant

LES, Normal

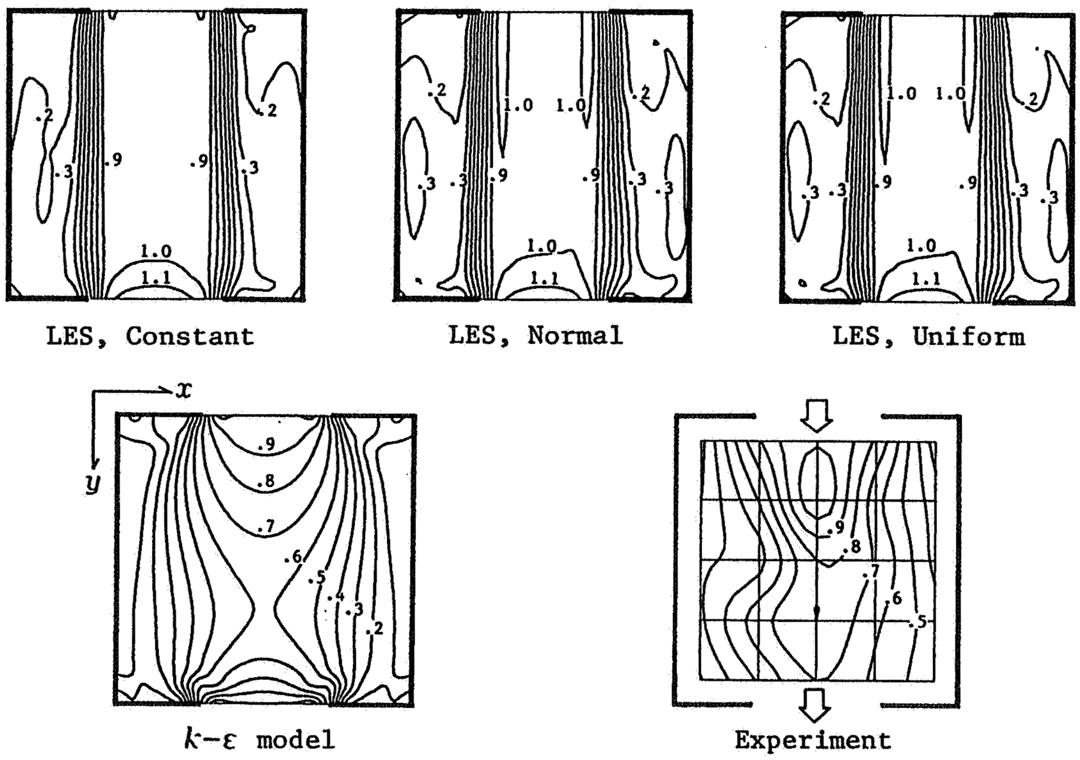
LES, Uniform

k-ε model

Velocity:1

x-y plane

(a) u-v vector on x-y plane



LES, Constant

LES, Normal

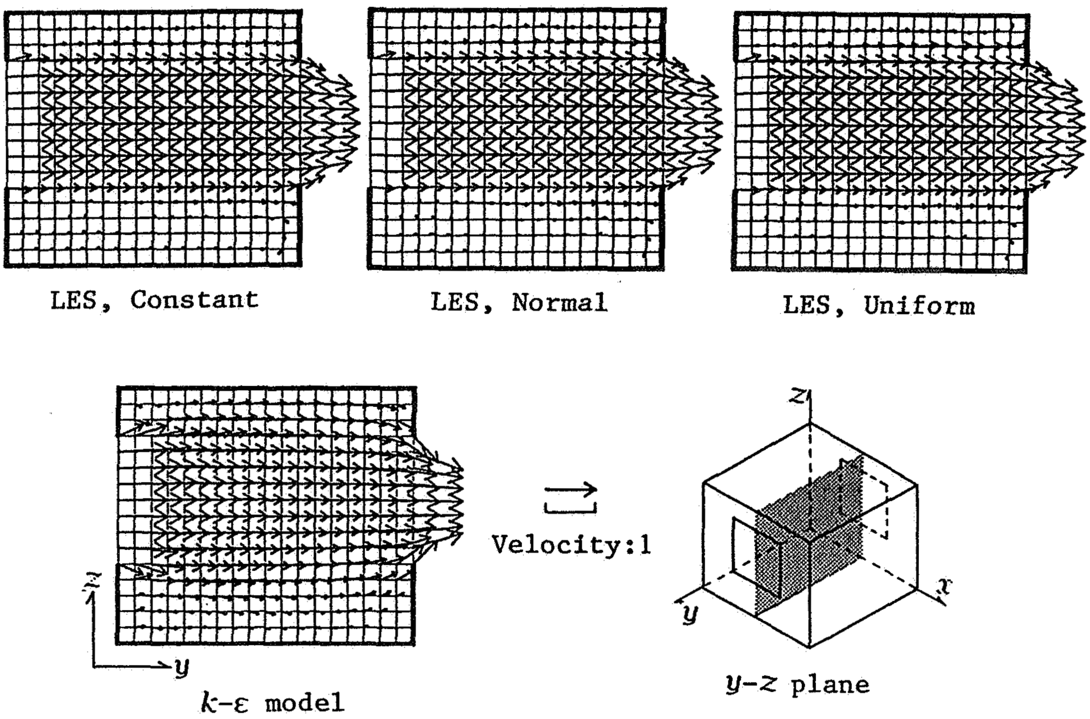
LES, Uniform

k-ε model

Experiment

(b) Scalar speed on x-y plane

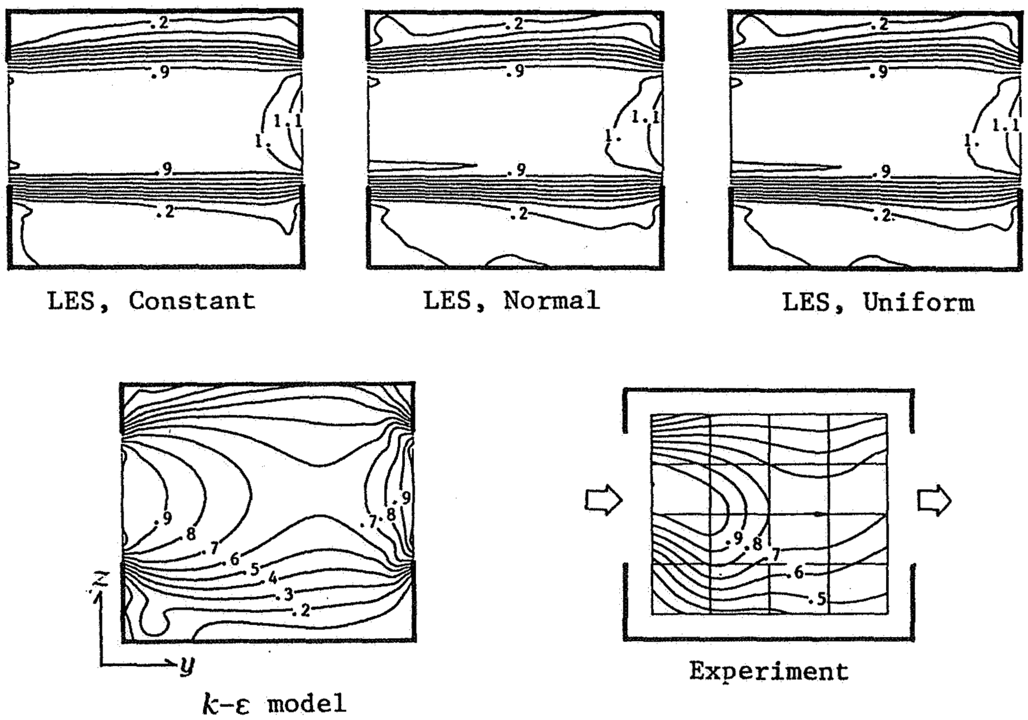
Fig. 10. Distributions of u-v vector and scalar speed on x-y plane



LES, Constant LES, Normal LES, Uniform

k-ε model y-z plane

(a) v-w vector on y-z plane

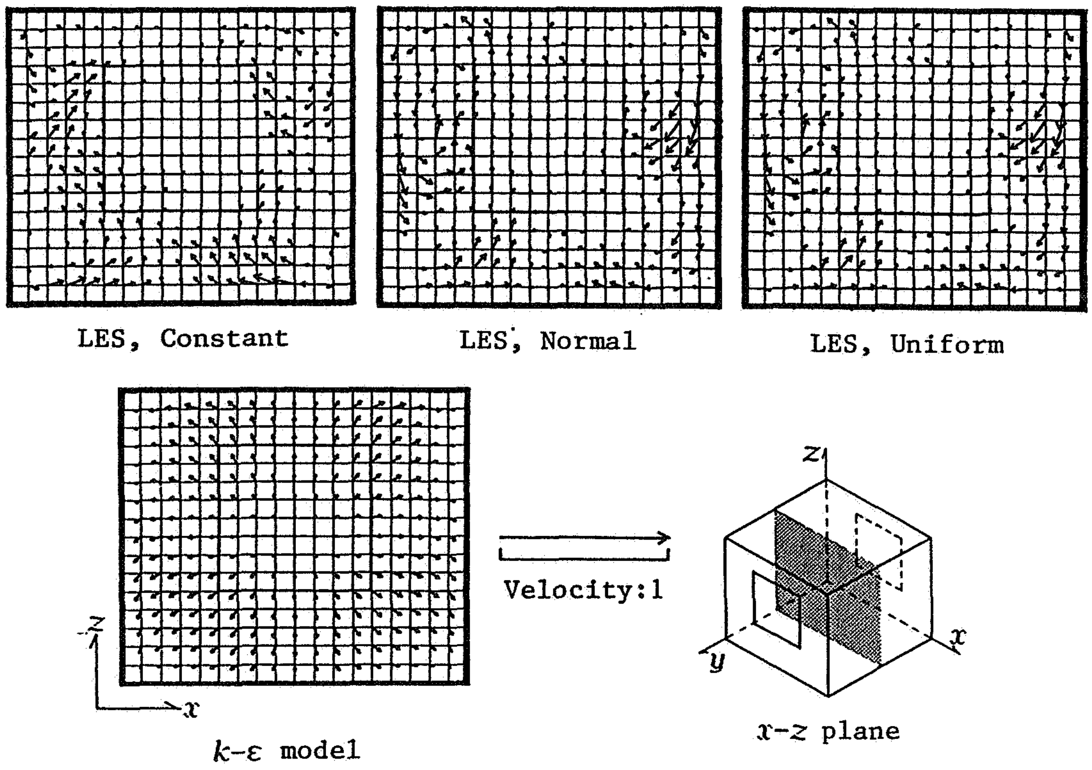


LES, Constant LES, Normal LES, Uniform

k-ε model Experiment

(b) Scalar speed on y-z plane

Fig. 11. Distributions of v-w vector and scalar speed on y-z plane



LES, Constant

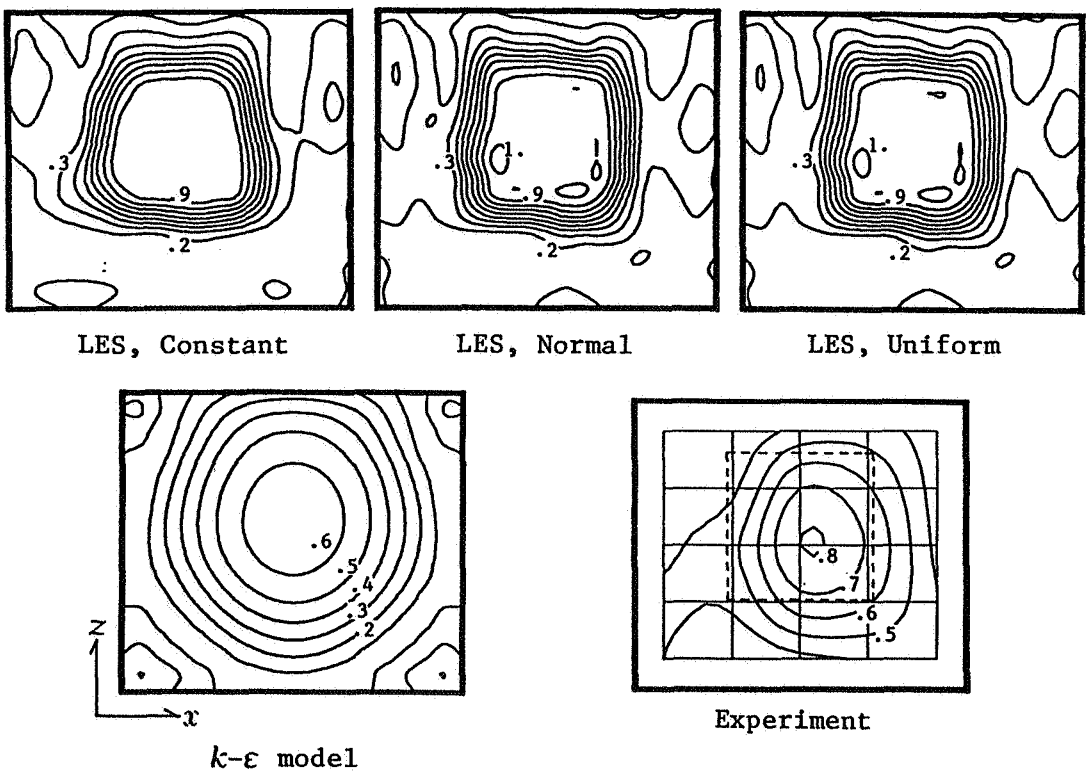
LES, Normal

LES, Uniform

k-ε model

x-z plane

(a) u-w vector on x-z plane



LES, Constant

LES, Normal

LES, Uniform

k-ε model

Experiment

(b) Scalar speed on x-z plane

Fig. 12. Distributions of u-w vector and scalar speed on x-z plane

result by the Constant. The distributions of the velocity vector by the LES indicate the secondary circulations around the main flow, while that by the k-e model indicates the diffusion of the main flow. The distributions of the scalar speed by the LES keep the shape of the opening clearly. On the other hand, the distribution of the scalar speed by the k-ε model show the same tendency as that by the model experiment, although there is a little difference in the values of the contour lines.

5. CONCLUSION

Although there are a lot of documents about the numerical simulation of indoor air flows, those about natural ventilation are limited and those compared with model experiments by the natural wind are more limited. In this paper, four kinds of numerical simulation of turbulent air flow in a room caused by cross-ventilation are carried out, and these results are compared with those of model experiments in the natural wind. There are two major purpose here, one is to grasp the air flow distribution in a model room naturally ventilated, and the other is to simulate such a air flow numerically.

It is difficult to measure the 3-dimensional distribution of air flow speed with a limited number of instruments, because the instruments have to be moved. It takes some long time for a series of the experiments and the measurement data include the long term fluctuation of the natural wind. As for the wind speed, that is eliminated by non-dimensionalization of the mean air flow velocities, as to the wind direction, however, it is impossible. As the stable breeze was blowing in the daytime on the experiment day fortunately, these experiments were able to be carried out under the condition of almost constant wind direction that was perpendicular to the opening. The results of the model experiments seem appropriate distributions of air flow speed.

While this kind of experiment is easy to be influenced by the wind condition, it is necessary to use the large scale turbulence like the natural wind, and it is very difficult to make such a wind artificially in a wind tunnel and so on. Then, numerical simulation is expected as the method to predict the air flow phenomena like this. Two kinds of turbulence model are adopted in the numerical simulation here. However, these models are not refined, they are used in the original and simple form. The boundary conditions on the openings are contrived. On the inflowing boundary, two kinds of random number are used in the LES, the turbulence scale of the model experiments is used in the k-ε model and their turbulence intensity are used in both the model. On the outflowing boundary, the boundary condition that expresses the free outflow is adopted. The outflowing boundary condition well functions, and the flux on both the openings are balanced. However, the inflowing boundary conditions of the LES hardly reform the results. The result of the k-ε model is closer to that of the model experiments than that of the LES, because the random numbers that have no relation spatially and temporally are used as the inflowing turbulence condition in the LES, while the turbulence length scale from the experiment data is given as the inflowing boundary condition of the k–ε model. This result indicates that the turbulence scale or the kinetic eddy viscosity are needed for the inflowing boundary condition and such a boundary condition should be made and given to the LES.

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