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# Two-Dimensional Turbulence Flow Model for a Personal Computer

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## ABSTRACT

*A user-friendly, two-dimensional $k$-$\epsilon$ turbulence model was developed. This turbulence model determines the turbulent flow field, the effective turbulent diffusion coefficient, and the contaminant concentration profiles within an occupied space. The model has been written for a personal computer to compute case results with reasonable accuracy and computational speed (a few minutes). The ventilation effectiveness due to the locations of the supply air duct and the contaminant source were investigated.*

## INTRODUCTION

Over the years software has been developed to compute the airflow distribution and concentration profiles within rooms. Most of these models require either a mainframe or supercomputer (Ishizu and Kaneki 1984; Kurabuchi et al. 1989; Murakami and Kato 1989; Yamamoto et al. 1990). Some of these models were developed for predicting airflow in cleanrooms constructed for the electronics industry (Shanmugavelu et al. 1987; Yamamoto et al. 1988; Busnaina and Abuzeid 1989). However, these models have limited use because of the lack of accessibility to mainframe computers for most engineers. Even the most complex model contains assumptions affecting the accuracy of the prediction and may not adequately account for the details of room configuration, supply/return air duct location, source location, and inflow velocity.

The philosophy guiding the present development is to provide software tools for estimation of airflow distribution and contaminant transport for engineers responsible for indoor air quality. The software is being developed for personal computers, which now are available to almost everyone. Compromises had to be made with respect to the detail of the computations to permit computational times practical for the capacity of personal computers. Fast, direct solution schemes have been incorporated into the model with no iterations needed. Therefore, no computational errors associated with the grid points occurred for these algorithms. For a wide range of practical situations, the capability provided by a personal computer to predict the general behavior of contaminant dispersion in a room is adequate to design the ventilation system or solve sick building problems. In addition, the software is designed specifically to take advantage of the interactive ability of personal computers. This has the advantage of reducing errors in inputing data through the use of menus, and a graphical output reduces the chances of misinterpretation of the results.

Figure 1 depicts a typical room configuration for which the inlet (B) and exhaust (T) dimensions and locations (A), room dimensions (W, H), and the inflow velocity ($U_0$) can be varied. The model is able to predict airflow dynamics and the effective turbulent diffusion coefficient, which are, in turn, incorporated into the particle diffusion model to solve the particle concentration profiles within a significantly shorter computational time (a few minutes). In the present study, the room is in isothermal condition, so buoyancy forces are not taken into account by the model. The qualitative effects of the placement of the supply air duct and the location of the source on contaminant distribution and basic design data for ventilation effectiveness can be obtained.

## USER-FRIENDLY SOFTWARE

This model is written in a highly interactive way with the user controlling the flow of the program. The interactiveness is facilitated by the use of menus that display choices of room configurations and operating parameters. The menus display several lines of text on the screen and a flashing cursor. The user selects an action to be taken by positioning the cursor at the desired location. Examples of operating menus are shown in Figures 2 and 3. When the cursor is positioned, the <Enter> key is pressed to activate the operation. When the computation is completed, all necessary data files are created for contour plotting of streamlines, turbulent kinetic energy distribution,

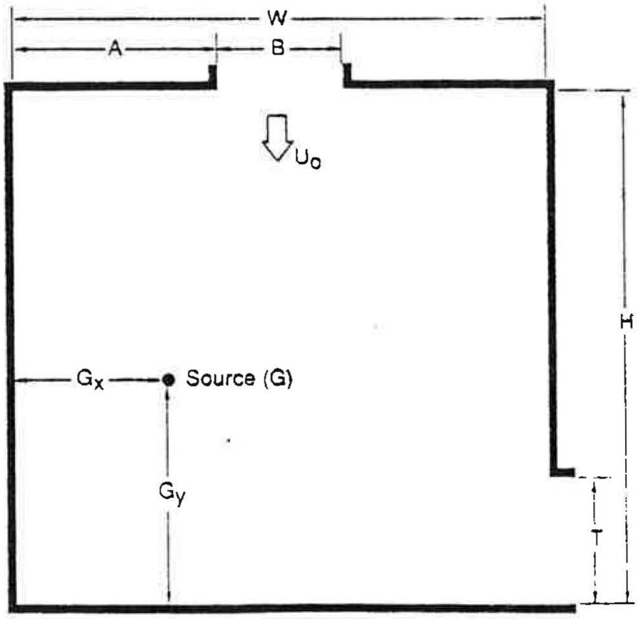

*Figure 1 Room outline and variables*

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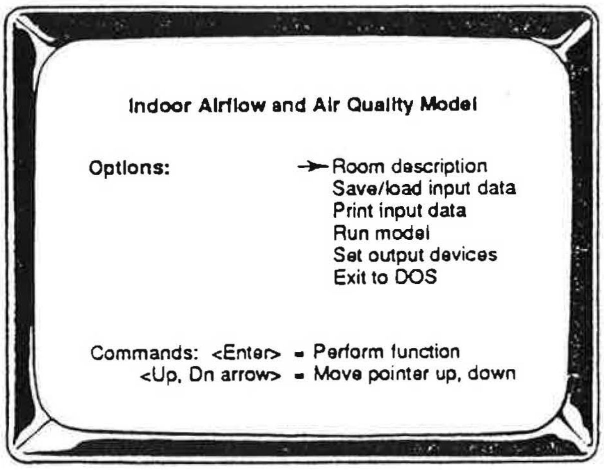
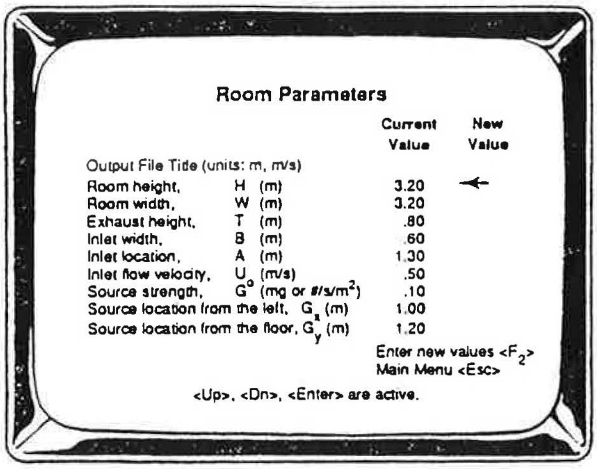


```
Indoor Airflow and Air Quality Model

Options:                    →Room description
                              Save/load input data
                              Print input data
                              Run model
                              Set output devices
                              Exit to DOS

Commands: <Enter>        - Perform function
      <Up, Dn arrow>     - Move pointer up, down
```

*Figure 2 Example of an operating menu for the room*



```
                         Room Parameters
                                                   Current    New
                                                    Value    Value
Output File Tide (units: m, m/s)
Room height,            H  (m)                       3.20      ←
Room width,             W  (m)                       3.20
Exhaust height,         T  (m)                        .80
Inlet width,            B  (m)                        .60
Inlet location,         A  (m)                       1.30
Inlet flow velocity,    Uo (m/s)                      .50
Source strength,        G° (mg or #/s/m²)             .10
Source location from the left,  Gx (m)               1.00
Source location from the floor, Gy (m)               1.20
                                                 Enter new values <F2>
                                                 Main Menu <Esc>
              <Up>, <Dn>, <Enter> are active.
```

*Figure 3 Example of data entry menu*

kinetic dissipation energy rate, contaminant concentration profile, and velocity vector plots. The default values of the room parameters are depicted in Figure 3.

## COMPUTATIONAL SCHEME

Among existing models of turbulence, a new computational scheme was developed to solve a two-dimensional k-ε turbulence model. The Navier-Stokes equations and Reynolds stress equations can be expressed in the form of a vorticity-stream function. The governing equations are reduced to four instead of the five normally used: stream function equation, vorticity equation, turbulent kinetic energy equation, and energy dissipation rate equation. These equations are expressed in a finite difference form and solved simultaneously with appropriate boundary conditions using a microcomputer. When the room configuration and the flow field are specified, then the particle diffusion equation can be solved.

When solving Poisson's equation (the stream function equation), a new solution method, called the "fast direct solution (FDS) method" (Nakamura 1977), is employed instead of a conventional iteration method, such as the successive-overrelaxation method. This FDS method requires no iterations; therefore, no computational errors associated with the selection of the grid size occur. Employing the vorticity-stream function and the FDS method thus reduces the computational time considerably and allows the use of a microcomputer at the starting level of computation. A grid point of 17 × 17 was used for this model. The computational result, using a grid point of 25 × 25, is almost identical to that with 17 × 17. The detailed formulation and computational procedures and the arguments due to the mesh size have been described previously (Baker and Kelso 1990; Yamamoto et al. 1991).

## NUMERICAL RESULTS AND DISCUSSION

Figure 4a shows the airflow streamlines in the room. The supply duct was placed at the center of the ceiling, and the exhaust duct was located at the bottom of the side wall. Two large recirculation zones were observed for both sides of the main airflow path. The strength of flow recirculation was slightly greater for the right-hand side. The strength of recirculation is an index of how strongly contaminants can be entrained and trapped in the recirculation zone. Once contaminants are trapped in such a recirculating zone, they rarely escape from this region unless strong external forces, such as electrostatic force, are present. Clearly, flow recirculation is not a favorable condition. Figure 4b shows the time-averaged velocity distributions. Note that the fluid velocity is nondimensionalized by the inflow velocity of 0.5 m/s.

The distribution of the effective contaminant diffusion coefficients is important because it is the measure of airflow mixing. The contaminant diffusion coefficient consists of the diffusion due to Brownian motion and the diffusion due to the

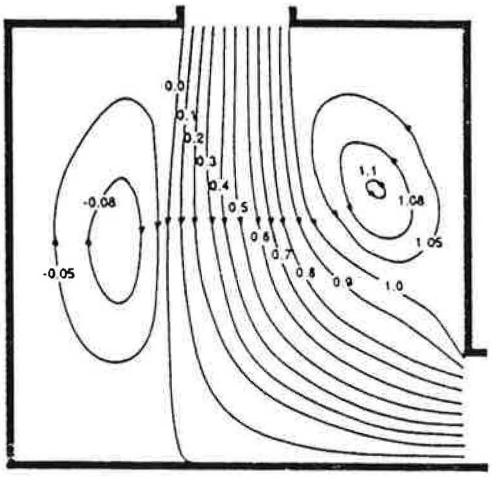


*Figure 4a Airflow streamlines (inflow velocity of 0.5 m/s)*

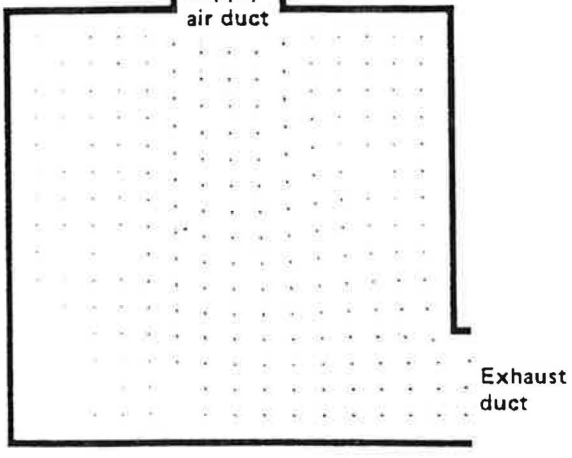


*Figure 4b Time-averaged velocity distributions in the room (inflow velocity of 0.5 m/s)*

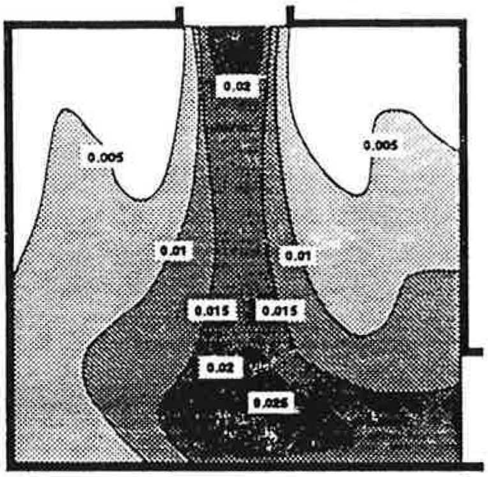


*Figure 5 Distribution of the effective turbulent diffusion coefficient*

the turbulent kinetic energy. The turbulent kinematic viscosity, found by solving the turbulence model, can be used to calculate the normalized effective turbulent diffusion coefficient and its distribution (Figure 5). Note that the actual turbulent diffusion coefficients ($m^2/s$) are 0.2 times the values shown in Figure 5. The highest diffusion takes place at the bottom of the main flow path. Because the effective turbulent diffusion coefficient represents air mixing, a higher contaminant mixing takes place at the region of higher diffusion. The next highest diffusion appears in the vicinities of inflow and outflow and the main flow stream region. In general, the contaminant diffusion diminishes with increasing distance from the main airflow path.

The steady-state contaminant concentration distribution shown in Figure 6 is the case where the source is placed at the left side of the main airflow stream. Note that the contaminant level shown in Figure 6 is a relative value. The contaminant concentration is significantly higher on the left-hand side of the main airflow stream with very few contaminants present on the right-hand side of the main airflow stream. This implies that the main airflow stream behaves like an air curtain despite contaminant diffusion.

When the source is on the right-hand side of the room, the contaminant concentration distributions are as shown in Figure 7. Because the source is located in the main airflow stream, the average concentration is significantly lower (less than one-third), compared to the case for Figure 6. Most of the contaminants are swept away by the main airflow, but some are diffused to the upper-right section of the room.

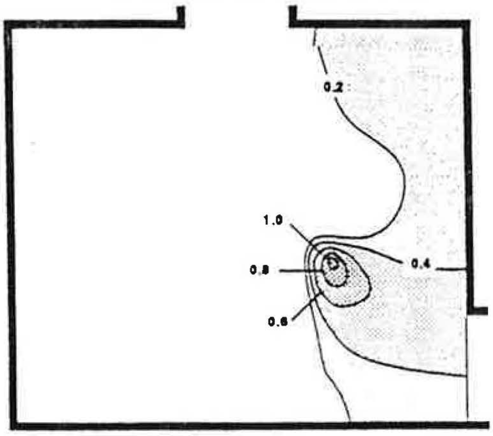


*Figure 7 Steady-state contaminant concentration distribution when the source is placed on the right side*

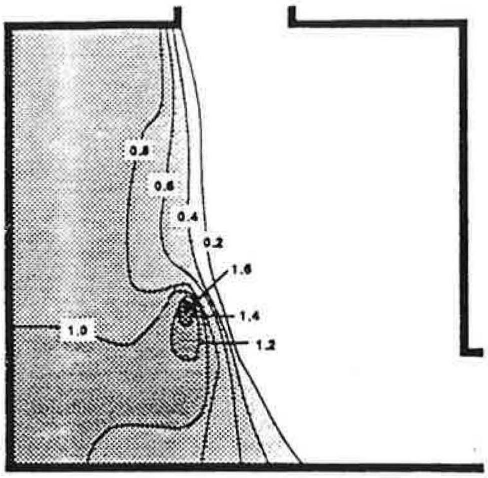


*Figure 6 Steady-state contaminant concentration distribution when the source is placed on the left side*

Airflow streamlines and velocity vectors are shown in Figures 8a and 8b for the case where the supply air duct is shifted to the left. The airflow distribution is completely modified, and only one large recirculation zone is observed at the upper-right corner of the room.

Figure 9 shows the distribution of the effective turbulent diffusion coefficient for this case. Although its distribution is significantly changed, the relative value remains about the same (see Figure 5). In other words, the effective turbulent diffusion coefficient is higher along the main airflow path and becomes lower in the stagnation region.

Figure 10 shows the contaminant concentration profile when the source is at the left side. The average concentration for this case is significantly smaller than in the case where the supply duct is located at the center (see Figure 6) because the source is located in the main flow streamline.

Figure 11 shows the contaminant concentration distribution when the source is moved to the right side. Most of the contaminants remain in the upper-right-hand corner, indicating poor ventilation. The average concentration becomes more than three times higher than in the case of Figure 10. It is clear that the ventilation effectiveness is largely affected by the source locations and the airflow distributions in a room for all cases.

## CONCLUSIONS

A user-friendly numerical simulation was developed to provide an analytical tool for those involved in indoor air quality engineering problems. The model allows the use of a personal computer with appropriate accuracy and resolution. It provides rapid analysis of airflow distribution and contaminant concentration distribution for evaluating indoor air quality problems and for evaluating ventilation systems. Experimental data are needed to verify this model.

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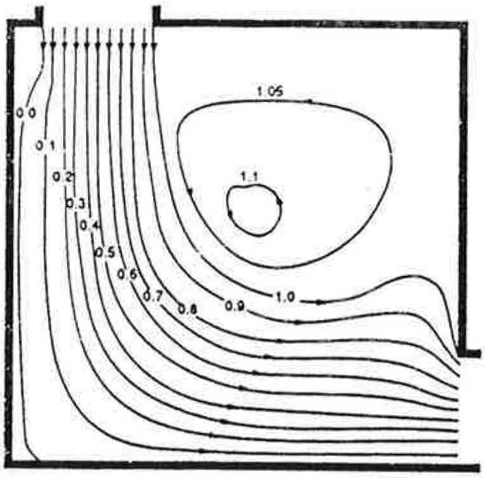

*Figure 8a* *Flow streamlines*

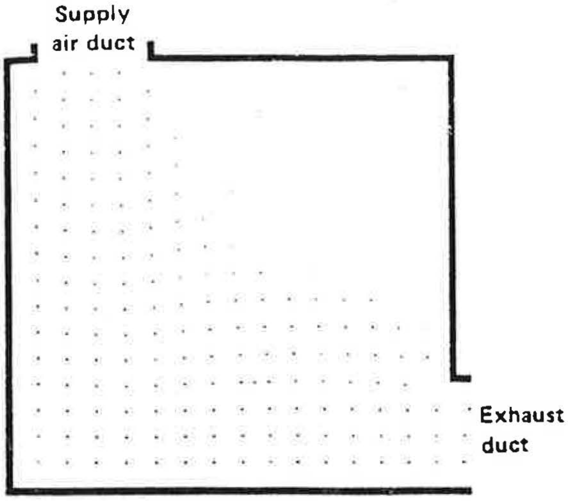

*Figure 8b* *Velocity vectors when the supply air duct is on the left side*

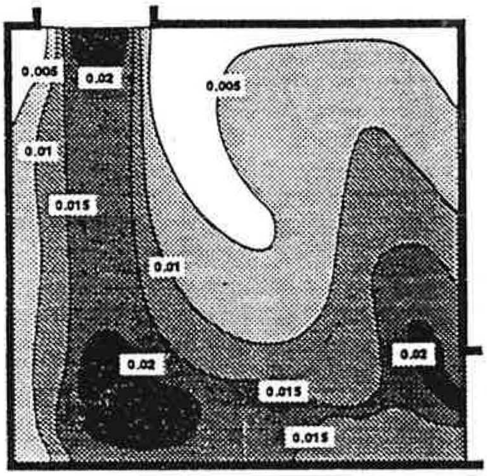

*Figure 9* *Distribution of the effective turbulent diffusion coefficient when the supply air duct is on the left side*

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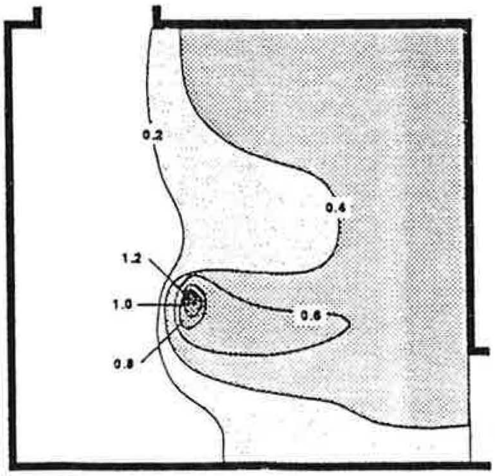

*Figure 10* *Contaminant concentration profile when the source is on the left side*

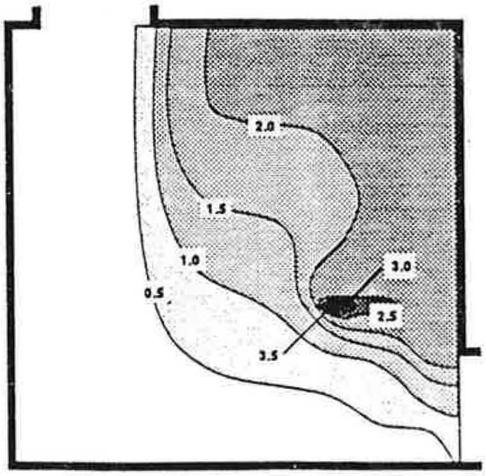

*Figure 11* *Contaminant concentration distribution when the source is on the right side*