The Selection of Turbulence Models for Prediction of Room Airflow

Peter V. Nielsen, Ph.D.
Member ASHRAE

ABSTRACT

The airflow in buildings involves a combination of many different flow elements. It is, therefore, difficult to find an adequate, all-round turbulence model covering all aspects. Consequently, it is appropriate and economical to choose turbulence models according to the situation that is to be predicted.

This paper discusses the use of different turbulence models and their advantages in given situations. As an example, it is shown that a simple zero-equation model can be used for the prediction of special situations as flow with a low level of turbulence. A zero-equation model with compensation for room dimensions and velocity level also is discussed.

A k-ε model expanded by damping functions is used to improve the prediction of the flow in a room ventilated by displacement ventilation. The damping functions especially take into account the turbulence level and the vertical temperature gradient.

Low Reynolds number models (LRN models) are used to improve the prediction of evaporation-controlled emissions from building material, which is shown by an example.

Finally, large eddy simulation (LES) of room airflow is discussed and demonstrated.

INTRODUCTION

The airflow in buildings involves a combination of most of the typical flow elements discussed in the textbooks on fluid dynamics. The flow will always be incompressible and often turbulent due to the velocity levels and dimensions involved.

Figure 1 shows an example of mixing ventilation in industrial surroundings and an example of displacement ventilation. The flow in a room ventilated by mixing ventilation typically is driven by the momentum flow from the supply openings, and it is described by elliptic equations. A closer look at the air movement shows that it is possible to identify an area in the surroundings of the supply opening where the flow can be characterized as a jet flow (plane, radial, or three-dimensional) described by parabolic equations. On the other hand, the flow close to the exhaust opening can be characterized as a potential flow described by the Laplace equation, which is an elliptic equation.

Displacement ventilation also can be expressed as a combination of different flow elements (see Figure 1B). The flow from the wall-mounted diffuser is partly a wall jet flow, in the case of a small heat load in the room, and partly a stratified flow, which can express both a subcritical flow and a supercritical flow (Nielsen 1994). The plume above the heat source is a buoyancy-driven flow. This air movement can be transferred to a stratified flow at a given height due to the vertical temperature gradient, and it may relaminarize because of the damping effect of buoyancy. A temperature difference between surface and room air will generate plumes and cold downdraft with entrainment or detrainment effect.

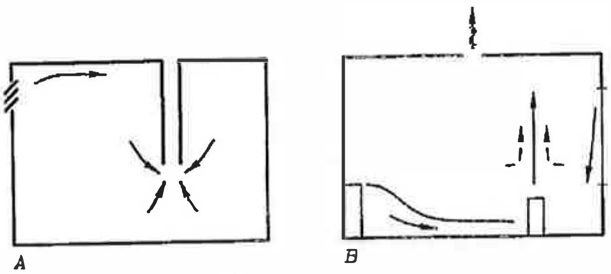

Figure 1 *Two different types of air distribution systems with indication of the main flow elements; A, mixing ventilation; B, displacement ventilation.*

Peter V. Nielsen is a professor in the Department of Building Technology and Structural Engineering, Aalborg University, Aalborg, Denmark.

Different turbulent models are able to cope with different flow elements, but it is difficult to find a single model that can handle all the flow elements in an optimal and economical way. The selection of a turbulence model for the prediction of room airflow will, therefore, represent a compromise. This paper describes a few models that have been selected with the intention of obtaining a quick and provisional solution (zero-equation models), as well as models that are optimal for the given problem (k-ε model with damping function, low Reynolds number model [LRN models], and large eddy simulation [LES]).

TURBULENCE MODELS

The air movement in a ventilated room often is turbulent. Figure 2 shows the instantaneous velocity measured in a radiator-heated room (Olesen 1979). It is impossible to make a direct numerical simulation (DNS) of this flow, although it is described fully by the Navier-Stokes equation, because it requires an extremely high number of cells to describe the turbulence and the dissipation of turbulence expressed by the fluctuations indicated in Figure 2.

It is possible to obtain a practical level of cell numbers if the numerical simulation is based on average variables. The flow is filtered with respect to time, as shown in the following equation for the instantaneous velocity $\hat{u}$ in a given point (x, y, z).

$$\hat{u} = u + u' \tag{1}$$

where the mean velocity u is given by

$$u(x, y, z) = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \hat{u}(x, y, z, t)dt. \tag{2}$$

The fluctuations (e.g., u') will influence the flow in such a way that it will exhibit an apparent increase in resistance to deformation (fluctuations manifest themselves by an apparent increase in the viscosity). This is reflected in the mean motion equations where this apparent increase in viscosity is described as a turbulent viscosity μ_t added to the physical viscosity μ, giving an effective viscosity of

$$\mu_{eff} = \mu_t + \mu \tag{3}$$

to be used in the averaged flow equations. The eddy-viscosity models are models that predict the distribution of μ_t. They can be very simple models, such as the zero-equation model, where μ_t may even be given as a constant value, or they can be based on a number of partial differential equations.

The k-ε model is a two-equation model based on both a transport equation for turbulent kinetic energy k and a transport equation for the dissipation of turbulent kinetic energy ε (Launder and Spalding 1974).

A general formulation is given by Equations 4, 5, and 6.

$$\frac{D\rho k}{Dt} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right) + P + G - \rho\varepsilon - C_5 2\mu\left(\frac{\partial\sqrt{k}}{\partial x_i}\right)^2 \tag{4}$$

$$\frac{D\rho\varepsilon}{Dt} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right) + C_1 f_1 \frac{\varepsilon}{k}(P + C_3 G)$$

$$-C_2 f_2 \rho\frac{\varepsilon^2}{k} + C_4\frac{2\mu\mu_t}{\rho}\left(\frac{\partial^2 u_i}{\partial x_i \partial x_j}\right)^2 \tag{5}$$

where

$$P = \mu_t \frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

and the buoyancy term

$$G = \beta g_i \frac{\mu_t \partial T}{\sigma_t \partial x_i}.$$

The turbulent viscosity μ_t is obtained from

$$\mu_t = \rho C_\mu f_\mu \frac{k^2}{\varepsilon}. \tag{6}$$

C_1, C_2, and C_μ, are equal to 1.44, 1.92, and 0.09 in all the models, and σ_k and σ_ε are equal to 1.0 and 1.3, respectively.

The conventional k-ε model is achieved when f_1, f_2, f_μ and C_3 are equal to one and C_4 and C_5 are equal to zero in Equations 4, 5, and 6.

A low Reynolds number k-ε model describing flow close to a solid surface can be obtained from Equations 4, 5, and 6 by using the following expressions (Launder and Sharma 1978):

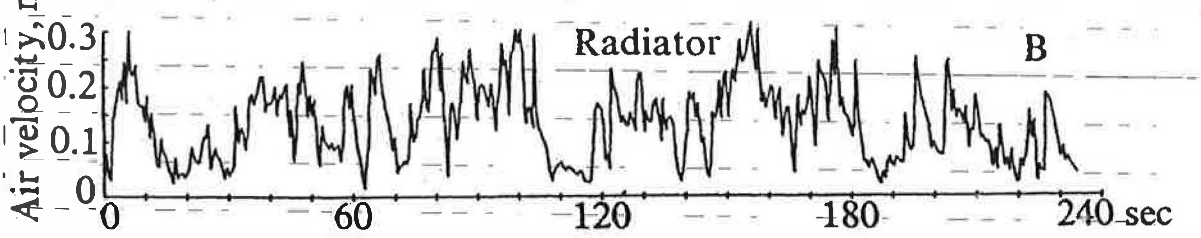

Figure 2 *Recording of velocity in a heated room. The velocity is sampled at a frequency of 1.7 Hz during a period of 240 seconds.*

BACK TO PAGE ONE

$$f_1 = C_3 = C_4 = C_5 = 1.0$$

$$f_2 = 1.0 - 0.3\exp(-R_t^2) \quad (7)$$

$$f_\mu = \exp(-3.4/(1+R_t/50)^2) \quad (8)$$

where the turbulent Reynolds number is

$$R_t = \frac{\rho k^2}{\mu\varepsilon}. \quad (9)$$

Equations 4, 5, and 6 also can express a version of the k-ε model with damping functions. The equations will be used later to predict the stratified flow in a room ventilated by displacement ventilation. The damping functions f_b and f_{R_t} have been described by Chikamoto et al. (1992). The f_b damping function serves to reduce the turbulent viscosity in areas with buoyancy destruction of turbulent kinetic energy. The f_{R_t} damping function reduces the turbulent viscosity in areas with low turbulent Reynolds number corresponding to a flow in stagnant areas with low velocity and relaminarization.

$$f_b = \begin{cases} 0.0 & for \quad b \le -10 \\ 1 + b/10 & for \quad -10 < b < 0 \\ 1.0 & for \quad b \ge 0 \end{cases} \quad (10)$$

$$f_{R_t} = \exp(-3.4/(1+R_t/50)^2) \quad (11)$$

$$f_\mu = f_{R_t} \cdot f_b \quad (12)$$

where

$$b = G/\varepsilon. \quad (13)$$

Some models work with C_3 equals one in all situations, whereas other models assume that C_3 is equal to zero for stratified flow ($G < 0$) and equal to one for unstable flow ($G > 0$); f_1 and f_2 are equal to one and C_4 is equal to zero because the model is used together with wall functions. C_5 is equal to zero.

Furthermore, the effect of stratification can be introduced into the energy transport equation via the turbulent Prandtl number σ_t (Launder 1975). Nielsen et al. (1979) have shown prediction of mixing ventilation where σ_t was given as a function of a buoyancy parameter rather similar to b (Equation 13). An increase of the vertical temperature gradient $\partial T/\partial x_i$ will increase the buoyancy term G and the buoyancy parameter b. This will increase σ_t up to a level of about twice the one for nonbuoyant flow. The net effect is a decrease in the diffusion coefficient μ_t/σ_t, which implies that the heat fluxes are damped in the energy transport equation.

The k-ε model is, strictly speaking, only valid for fully developed turbulence, which will not always be present in room air distribution. It is possible to make a statement on the level of turbulence from the low Reynolds number model; f_2 and f_μ in Equations 7 and 8 express the low Reynolds number effect in the boundary layer close to a surface. The equations show that f_2 and f_μ are equal to 1.0—corresponding to a fully developed turbulent flow—for R_t larger than 350. It is assumed that this condition also is valid for free turbulence far from surfaces. Equations 6 and 9 will thus give the following local condition for fully developed turbulence ($R_t > 350$):

$$\mu_t > 30\mu. \quad (14)$$

Room air distribution, and especially displacement ventilation and ventilation in rooms with large dimensions may, in some situations, show predictions based on a k-ε model where volumes with low velocity fail to fulfill the conditions in Equation 14. The flow domain is described by elliptic equations, which, in principle, means that an insufficient use of the k-ε model in some areas may influence the whole solution domain. In practice, the problem is bypassed when the air movement in a room can be described by separate flow elements of parabolic character, as discussed in the introduction, because those elements will only be slightly influenced by the turbulence in the entrainment flow.

All the models discussed up to now are based on time averaging. It also is possible to obtain a practical level of cell numbers in the numerical simulation by filtering with respect to space. Equations 15 and 16 show this filtering for an instantaneous velocity $\hat{u}$ in a given point (x, y, z).

$$\hat{u} = \bar{u} + u'' \quad (15)$$

where the mean velocity $\bar{u}$ is given by

$$\bar{u}(x, y, z, t) = \frac{1}{\Delta x \Delta y \Delta z}\iiint \hat{u}(x, y, z, t)dxdydz. \quad (16)$$

It should be observed that the mean value $\bar{u}$ is time-dependent in this situation.

This type of filtering with respect to grid space in the Navier-Stokes equations is the basis of large eddy simulation —see, e.g., Murakami (1988). The equation system is closed by an expression for subgrid-scale Reynolds Stresses (SGS). The turbulence is represented as the time-dependent solution of this equation system, and it is important that the grid spacing is fine enough to allow a description of the energy-containing eddies. The mean flow quantities are predicted from transient calculations conducted over a time span sufficient to obtain a steady solution.

ZERO-EQUATION MODELS

A zero-equation model is a turbulence model where the eddy viscosity μ_t is given as a constant number or given from an analytical equation without involvement of transport equations. Results are shown in this chapter.

The first example is the study of smoke movement in a tunnel. Figure 3 shows the setup for some scale model experiments. The upper drawing indicates the situation with a fire in a tunnel with one opening (corresponding to a tunnel with two openings and a fire in the middle of the double circumference). It is difficult to reduce the scale in model experiments with smoke movements and simulated fire. The lower drawing shows a setup used in the experiments where the smoke movement and replacement air are supplied through openings. This design makes it possible to work with small-scale modeling, and the experiments correspond to a 1:20

BACK TO PAGE ONE

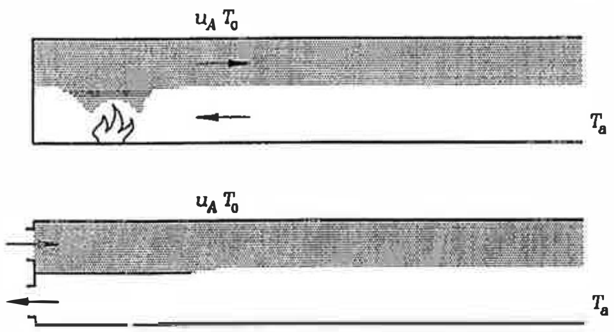

Figure 3 *Scale model experiments with smoke movement in a tunnel. The lowest drawing shows the setup for the experiments and predictions.*

scale of the experiments in the Ofenegg tunnel in Switzerland (Haerter 1994). The experiments are characterized by the Froude number,

$$Fr = \frac{u_A}{\sqrt{\beta g h \Delta T_o}} \tag{17}$$

where u_A is the volume flow of smoke divided by the cross-square area of the tunnel, and ΔT_o is the temperature difference between "smoke" temperature and replacement air temperature.

Measurements and predictions of the velocity profile are given in Figure 4. Two- and three-dimensional predictions based on the k-ε model show a low velocity level, as well as a low value of μ_t in large areas of the flow. Visualization with smoke in the experiments indicates, together with the low level of μ_t, that the flow is a low Reynolds number flow in large areas of the tunnel. The low level of turbulence is especially pronounced in the shear layer between the hot "smoke" and the cold replacement air because the flow is relaminarizing due to the damping effect of buoyancy in stable stratification.

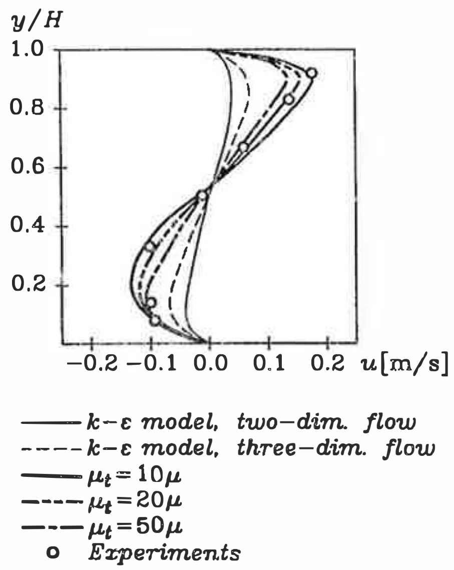

Figure 4 *Measured and predicted vertical velocity profile in the tunnel at the position x/H = 16.00. Length of the tunnel is L/H = 16.67 and Fr = 0.34.*

The importance of the turbulence level can be studied by provisional predictions with a zero-equation model. The predictions show that an eddy viscosity μ_t of 10μ to 20μ seems to be a good estimate (see Figure 4). A more detailed prediction will, of course, require a model that is able to identify the location of the layer with low eddy viscosity.

The iteration procedure in a numerical prediction often will be stabilized by a high level of turbulence. Initial iterations can be performed with a high and constant eddy viscosity (corresponding to a small Peclet number) and the predictions can, at a later stage, be connected to a k-ε model. Some commercial CFD codes make use of this fact, and they have a zero-equation model with $\mu_t = 100\mu$ as a default option. The turbulent level in room airflow may have a larger level, and similarity analysis shows that a zero-equation model can have the following form:

$$\mu_t = \text{const}\rho u_o H \tag{18}$$

where ρ is density, u_o is a characteristic velocity (supply velocity) and H is a characteristic length (room height). Equation 18 can be used for judgment of the eddy viscosity in rooms with different velocity levels and dimensions, and it can be used to obtain a suitable level for the initial iterations.

The principles of similarity imply that the dimensionless eddy viscosity μ_t^* given as $\mu_t/\rho u_o H$ should be independent of the velocity level and the dimensions in rooms of identical geometry. The predictions in Figure 5 are based on a k-ε model, and they show the vertical distribution of turbulent viscosity μ_t^* in a room ventilated by mixing ventilation. It is obvious from the figure that μ_t^* is independent of the supply

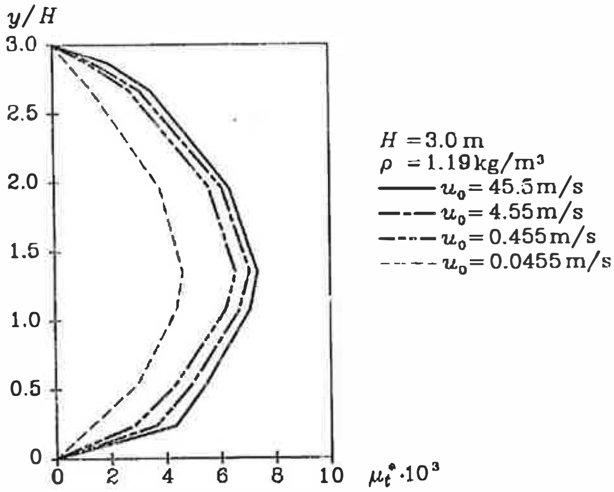

Figure 5 *Distribution of dimensionless eddy viscosity predicted from a k-ε model. The vertical profile is located at x/H = 2.0 in the room described in Figure 8.*

velocity μ_o as long as μ_t has a high level, which also supports the concept of Equation 18.

k-ε MODEL WITH DAMPING FUNCTIONS

This section discusses the use of a k-ε model with damping functions (Equations 4, 5, 6, 10, 11, 12, and 13). The damping functions are developed to improve the predictions of flow with low velocity and relaminarization as in, for example, the case of displacement ventilation. CFD simulations discussed in this section are carried out for the room shown in Figure 6 with an inlet flow rate of 300 m /h (177 cfm), an inlet temperature of 15.3°C (59.5°F), and a heat load of 600 W (2050 Btu/h).

Air movement in a displacement-ventilated room is characterized by being mainly buoyancy driven, which implies that the temperature gradient in the room is decisive. The shape of the resulting temperature gradients is, consequently, a suitable criterion for the comparison and evaluation of the different turbulence models. The vertical temperature profiles for the comparisons are located in a point of the room where no direct influence of the heat sources and the inlet device is present (x = 4.0 m [13.1 ft], z = 3.0 m [9.8 ft]).

The results presented in Figure 7 show the temperature distribution in the following three cases (Jacobsen and Nielsen 1993):

- Buoyancy term G and damping functions excluded from Equations 4, 5, and 6.
- Buoyancy term G included in the k-ε model and damping functions excluded.
- k-ε model with buoyancy term G in Equations 4 and 5 and damping functions f_b and f_R (Equations 10 and 11) in Equation 6.

Radiation between surfaces has been ignored, and all surfaces are considered to be adiabatic.

The effect of the buoyancy term is clearly illustrated in the figure. The mixing between the cool supply air and the surrounding room air is decreased and the resulting temperature profile becomes strongly nonlinear. This low level of entrainment predicted in stratified flow from supply openings

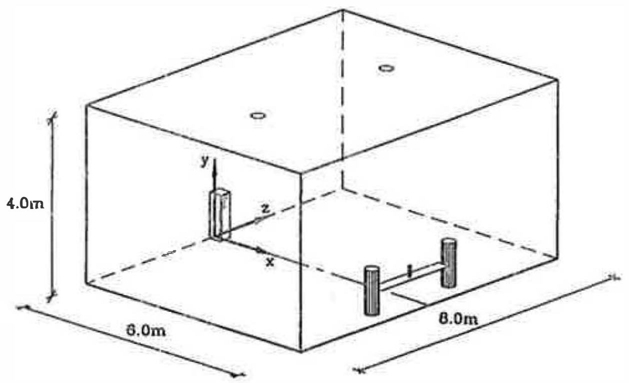

Figure 6 *Geometry for the room ventilated by displacement ventilation.*

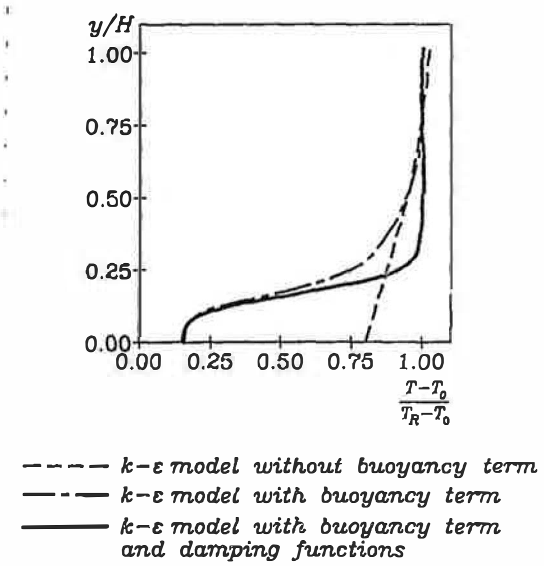

Figure 7 *Predicted vertical temperature profile in the room ventilated by displacement ventilation (Figure 6).*

also has been measured by Nielsen (1994) in another geometry. Figure 7 shows that the damping functions, Equations 10 and 11, have only a minor influence, except where extremely high temperature gradients occur, as in the interfacial mixing in the layer between cool and warm air. The temperature gradient will be reduced if radiation is introduced into the calculations. This also will reduce the effect of the damping functions.

It is a general experience—for a displacement-ventilated room—that the damping functions reduce the turbulence in areas that are mainly located outside the primary flow regime. The air movement in the primary flow regime (as stratified flow from wall-mounted diffusers or plumes above heat sources) is influenced only slightly by the low level of the surrounding eddy viscosity, and the damping functions have, therefore, only a small influence on the final predictions.

Dagestad (1991) has also used a modified k-ε turbulence model in the simulation of a stable, stratified tunnel flow. The geometry and the flow correspond to the situation described in Figure 3, except that the lower (cold) air flows in the same direction as the upper (warm) air. Three models were tested. The first model has a buoyancy term G both in the k equation and the ε equation (C_3 = 1.0), and the second model has only a buoyancy term in the k equation (C_3 = 0). The last model has a buoyancy term in the k equation only (C_3 = 0) and a low Reynolds number damping function f_μ used in connection with Equation 6. This model is, to some extent, similar to the model with damping functions, and it shows the best results for the velocity and temperature profiles in the tunnel flow. The success of the model in the simulation of free flow can be explained by the connection between an increased destruction of turbulent kinetic energy (negative G term) and a corresponding decline of R_t.

Figure 7 shows that the exclusion of the buoyancy term G from the k-ε model has a very large influence on the predicted results in the case of displacement ventilation with stratified flow. The predicted results in the case of mixing ventilation with recirculating flow are also significantly influenced by the exclusion of the buoyancy term (Nielsen et al. 1979).

It is physically correct to include the buoyancy term G in the k-ε model, but many commercial codes offer the possibility of excluding the term because this will—in some situations—stabilize the convergence of the residuals.

LOW REYNOLDS NUMBER k-ε MODEL

The low Reynolds number model is very suitable for the prediction of mass and energy transfer coefficients at surfaces. This model predicts the transport processes in the laminar sublayer and the log-law zone in contrast to the standard k-ε model where this part of the flow is given by analytical wall functions. This section will show the use of an LRN model for prediction of velocity distribution in a room ventilated by mixing ventilation and prediction of mass transfer coefficients in connection with evaporation-controlled emission of volatile organic compounds (VOCs).

In this section, the flow is studied in a simple two-dimensional room geometry that has been used by many authors as a benchmark test case (see Figure 8). The geometry and the experimental data for validation of predictions are described in an internal International Energy Agency (IEA) Annex 20 report by Nielsen (1990). The height H and the length L are equal to 3.0 m (9.8 ft) and 9.0 m (29.5 ft), respectively. The height of the supply opening h is 0.168 m (0.55 ft). This height is rather large compared with practical diffusers, but it simplifies the description of boundary conditions. Skovgaard and Nielsen (1991a) have predicted the isothermal air movement in this geometry at a Reynolds number of Re = 5000. Figure 8 shows the results in two vertical cross sections where the prediction is compared with measured data. The effect from the shear layer outside the potential core of the jet is seen, and it is observed that the recirculating flow recorded in the measurements in both cross sections is well predicted in the simulation, although the magnitude of the counter flow is slightly underestimated. The maximum velocity in the occupied zone is accurate with respect to both location and magnitude.

It is possible to compare the measured RMS value $\sqrt{\overline{u'^2}}$ in Figure 8 with the square root of the turbulent kinetic energy k because the recirculation flow can be considered as a flow with wall jet profiles $\left(\sqrt{k} \approx 1.1\sqrt{\overline{u'^2}}\right)$. It is obvious from the figure that the predicted level of turbulence in the room is in good agreement with the measurements made by a laser-doppler anemometer.

The velocities in ventilated rooms can be small, and the free flow in the main part of the room is not always fully turbulent. Skovgaard and Nielsen (1991b) have studied the possibilities of using the LRN model in that situation, although it was developed for the prediction of low Reynolds number flow near walls. The flow and penetration length of a ceiling jet are studied in a deep room, and satisfactory results are obtained for laminar flow and fully turbulent flow, but it is not possible to get a solution for the transitional flow by the use of an LRN model. Low Reynolds number free flow $(\mu_t/\mu \sim 25)$ has, on the other hand, been predicted with success for a buoyancy-driven flow in a cavity by an LRN model (Davidson 1989; Chen et al. 1990).

It is necessary to use an LRN model for the prediction of evaporation-controlled emission because this quantity is strongly dependent on the flow conditions in the boundary

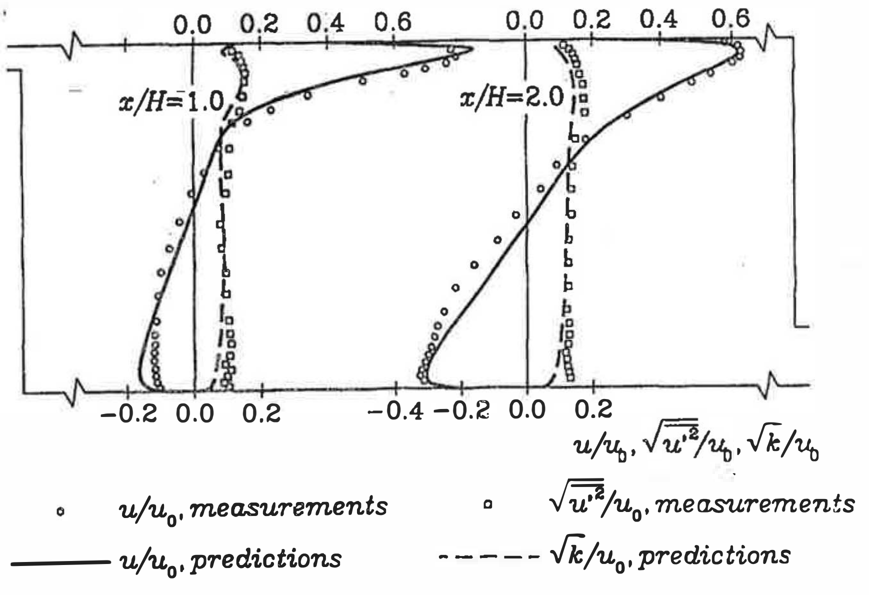

Figure 8 Velocity profiles and profiles of turbulence intensity in a room with mixing ventilation.

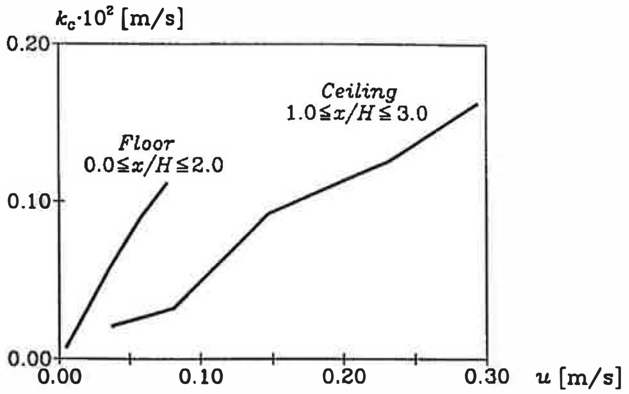

Figure 9 *Predicted mass transfer coefficient k_c vs. local velocity u. The predictions are made by an LRN model in the room described in Figure 8.*

layer and, therefore, also on the air distribution in the room. The emission E is given by

$$E = k_c(c_s - c_\infty) \tag{19}$$

where k_c is the mass transfer coefficient, c_s is the surface concentration, and c_∞ is the fully mixed concentration in the room or the local concentration in the flow surrounding the surface. The mass transfer coefficient for evaporation-controlled emission k_c is a function of parameters such as local velocity u, turbulence intensity $\sqrt{u'^2}/u$, etc.

Figure 9 shows the mass transfer coefficient for the ceiling and the floor as a function of the local velocity level in the surroundings of the surface (Topp et al. 1997). The predictions are made of the room geometry shown in Figure 8, and they are all based on an LRN model. The local velocity at the floor is the maximum velocity at the position $x/H = 1.0$, and the local velocity at the ceiling is the maximum velocity in the wall jet at the position $x/H = 2.0$. Figure 9 shows that k_c is not only a function of a local velocity but it is also influenced by turbulence. Figure 8 shows that the turbulence intensity $\sqrt{u'^2}/u$ is different at the two positions. The value close to the floor ($x/H = 1.0$) is about 80%, whereas it is 20% at the ceiling ($x/H = 2.0$). It is obvious that parameters such as velocity, turbulence, boundary layer thickness, etc., are important when the emissions from different materials—found by experiments in small-scale test chambers at one turbulence level— have to be converted to full scale at another turbulence level.

LARGE EDDY SIMULATION

Large eddy simulation can be used to obtain detailed information on turbulence, which cannot be achieved by the traditional time-averaged turbulence models. The turbulence is predicted in detail, and it is possible to make a direct prediction of $\sqrt{u'^2}$. The time-dependent three-dimensional momentum and continuity equations are filtered in space and solved together with a dynamic subgrid turbulence model (Germano et al. 1991a, 1991b). Figure 10 shows the predictions by Davidson and Nielsen (1996) of velocity and turbulence intensity distribution at $x/H = 1.0$ and 2.0 in a room with the geometry described in Figure 8 in the case of isothermal flow and a Reynolds number of $Re = 5000$. The recirculation flow is predicted well in both cross sections, but the results are not improved compared with the results based on the k-ε model (Figure 8).

The previous section shows that the mass transfer coefficient k_c for evaporation-controlled emission is a function of the turbulence in the boundary layer close to the surface. It is possible to throw light on the subject by the use of LES. Figure 11 shows the probability density function of $\bar{u}$ for the flow close to the emission area at the ceiling and close to the emission area at the floor (Davidson and Nielsen 1996). The flow has a well-defined mean velocity in the ceiling regions, and the velocity fluctuates around the mean velocity, giving a symmetrical probability density function. It is more difficult

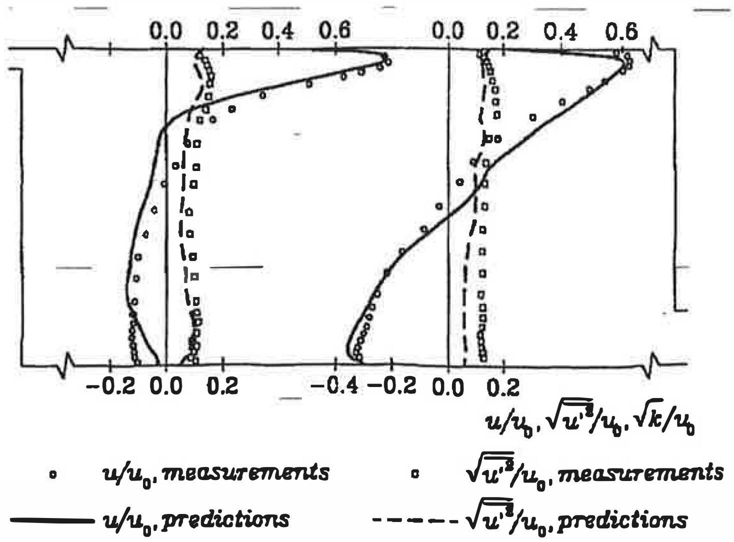

Figure 10 *Time-averaged velocity and turbulence intensity in the symmetry plane predicted by large eddy simulation.*

BACK TO PAGE ONE

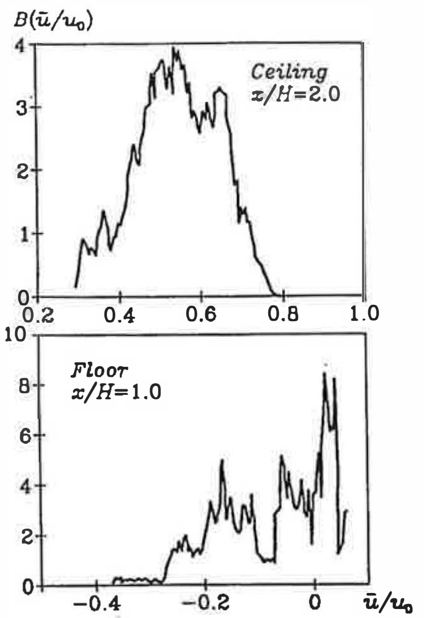

Figure 11 *Probability density function of $\bar{u}/u_0$ close to the two emitting surfaces described in Figure 9. The predictions are made in the room geometry given in Figures 8 and 10.*

to find any preferred value of $\bar{u}$ close to the emission surface at the floor. The flow is irregular and unstable with separation and without a well-defined mean velocity. Figure 11 shows that the probability density function is asymmetrical (has a skewness) with a probability of both negative and positive velocity.

CONCLUSION

This paper discusses a number of turbulent models applied to different problems in connection with air distribution in rooms. A simple zero-equation model can be useful for provisional studies of special situations, such as flow with a low level of turbulence, and the concept can be used to get stable iterations at the beginning of an iterative procedure.

A k-ε model with damping functions can be used for the simulation of flow in the case of stratification due to the damping effect of buoyancy. Predictions of the flow in a displacement-ventilated room show only a small influence from damping functions. Large areas in the room will have a very low velocity and a low level of turbulence, but the main flow elements in the room are not particularly influenced by this low level of turbulence. The predictions show, however, that the buoyancy term G is very important for the k equation.

Comparison with measurements of stratified flow in a tunnel shows that the damping function may be important for the predictions when there is a certain overall velocity level.

It is suitable to use a low Reynolds number k-ε model when transport processes are studied close to surfaces. This is illustrated by an example showing the mass transfer coefficient for evaporation-controlled emission predicted as a function of local velocity. Furthermore, it is demonstrated that the level of turbulence has a great influence on the mass transfer coefficient.

Large eddy simulation will give the highest level of information on turbulence. This is demonstrated by the prediction of velocity, turbulence intensity, and probability density functions for selected areas of a room.

NOMENCLATURE

b	= buoyancy parameter (G/ε)
B	= probability density function
c_s	= surface concentration
c_∞	= background concentration
C	= coefficients in turbulence models
E	= emission
f	= functions to modify the model
Fr	= Froude number
g	= gravitational acceleration
G	= buoyancy production of k
H	= room or tunnel height
k	= turbulent kinetic energy
k_c	= mass transfer coefficient
L	= length of room or tunnel
P	= stress production of k
Re	= Reynolds number based on slot height
R_t	= turbulent Reynolds number
t	= time
T	= temperature
T_a	= ambient temperature
T_o	= supply temperature
T_R	= return temperature
u	= mean velocity
$\bar{u}$	= filtered velocity with respect to space
$\hat{u}$	= instantaneous velocity
u'	= instantaneous deviation from time-averaged velocity
u''	= instantaneous deviation from velocity filtered with respect to space
u_o	= supply velocity
u_A	= mean velocity in tunnel
x,y,z	= coordinates
β	= volume expansion coefficient
ΔT_o	= temperature difference (T_o - T_a)
ε	= dissipation of turbulent kinetic energy
μ	= viscosity
μ_t	= turbulent viscosity
μ_{eff}	= effective viscosity ($\mu_t + \mu$)
ρ	= density
σ_t	= turbulent Prandtl num