Zhai, Z., Zhang, Z., Zhang, W., and Chen, Q. 2007. "Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: Part-1: summary of prevent turbulence models," *HVAC&R Research*, 13(6).

Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part-1: Summary of Prevalent Turbulence Models

Zhiqiang Zhai, Member ASHRAE
Zhao Zhang, Student Member ASHRAE
Wei Zhang, Member ASHRAE
Qingyan Chen*, Fellow ASHRAE

Air distributions in enclosed environments are crucial to thermal comfort and air quality. Computational fluid dynamics (CFD) has been playing an important role in evaluating and designing various air distributions. Many factors can have influence on the applications of CFD for studying air distributions. The most critical factors are the selection of an appropriate CFD approach and a turbulence model. Recent advances in CFD approaches and turbulence models provide a great potential of improving prediction accuracy of air distributions in enclosed environments. This paper summarized recent progress in CFD turbulence modeling and applications to some practical indoor environment studies. This paper also described the turbulence models that either are commonly used or have been proposed and used recently for indoor environment modeling. Finally, this study further identified a few turbulence models that show great potential for modeling airflows in enclosed environments. A companion paper presents the evaluation of the selected models by using experimental data from the literature.

INTRODUCTION

Enclosed environments, such as commercial, institutional, and residential buildings; healthcare facilities; sport facilities; manufacturing plants; animal facilities; transportation vehicles, are confined spaces with certain functionalities. It is essential to control air distributions in the enclosed environments. The parameters of air distribution include, but not limited to, air velocity, temperature, relative humidity, enclosure surface temperature, air turbulence intensity, and concentrations of airborne gaseous, particulate, and liquid droplet contaminants in the enclosed environments. The air distribution control is to create and maintain a comfortable and healthy environment required by occupants and/or thermo-fluid conditions for industrial processes in the enclosed environments.

Air distribution in an enclosed environment can be driven by different forces, for instance, natural wind, mechanical fan, and/or thermal buoyancy. The combination of these flow mechanisms (forced, natural, and mixed convection) creates complex indoor airflow characteristics with impingement, separation, circulation, reattachment, vortices, buoyancy etc. as illustrated in Figure 1. Most indoor environments have a low mean air velocity of less than 0.2 m/s, and the Reynolds number, Re, is generally very low ($\sim 10^5$). The corresponding flow regime may span from laminar, transitional, to turbulent flows or combination of all the flow regimes under transient conditions. The complexity of indoor airflow makes experimental investigation extremely difficult and expensive.

* **Zhiqiang Zhai** is an assistant professor in the Department of Civil, Environmental & Architectural Engineering, University of Colorado, Boulder, CO. **Zhao Zhang** is a PhD candidate, **Wei Zhang** is an affiliate, and **Qingyan Chen** is a professor in the School of Mechanical Engineering, Purdue University, West Lafayette, IN.

With the rapid advance in computer capacity and speed, the Computational Fluid Dynamics (CFD) technique has become a powerful alternative for predicting airflows in enclosed environments. By solving the conservation equations of mass, momentum, energy, and species concentrations, CFD can quantitatively calculate various air distribution parameters in an enclosed environment. It offers richer details, a higher degree of flexibility, and lower cost than experimental study. Nielsen (1974) was the first one who applied CFD for room airflow prediction. Applications of CFD for airflows in enclosed spaces have been increasing since the 1980s. The International Energy Agency Annex 20, for instance, has sponsored a research project on room airflow prediction with participants from 13 countries (Moser 1992).

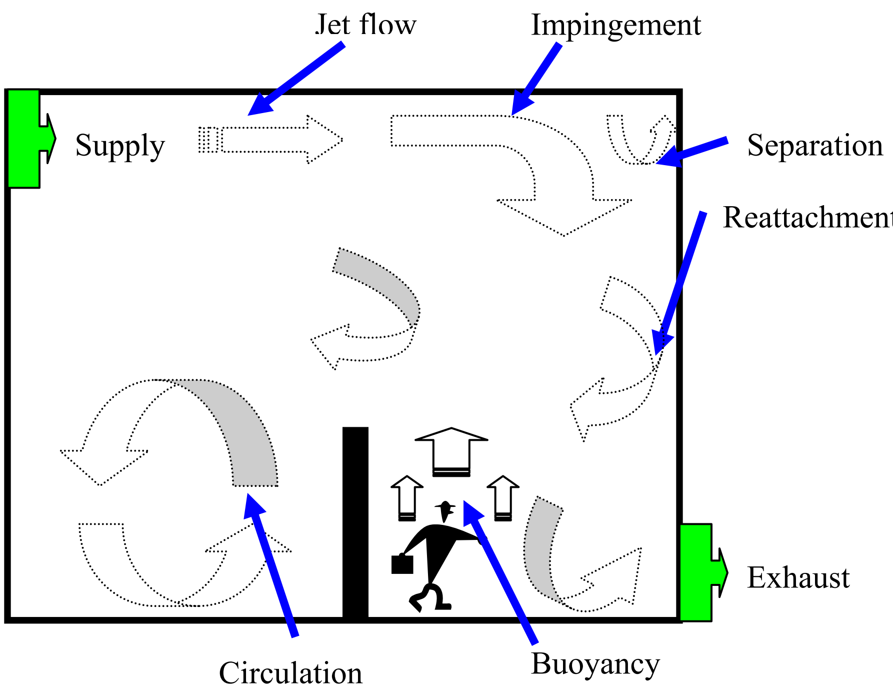

Figure 1. Typical flow characteristics in an enclosed environment with various flow mechanisms.

CFD applications to airflow simulation for enclosed environments have achieved considerable successes, as reviewed by Whittle (1986), Nielsen (1989, 1998), Liddament (1991), Jones and Whittle (1992), Chen and Jiang (1992), Moser (1992), Lemaire et al. (1993), Ladeinde and Nearon (1997), Emmerich (1997), Spengler and Chen (2000), Chen and Zhai (2004), and Zhai (2006). These reviews concluded that CFD is a valuable tool for predicting air distributions in enclosed environments. However, there are many factors influencing the results predicted. Different users may obtain different results for the same problem even with the same computer program. The accuracy of the simulation heavily depends on user's knowledge in fluid dynamics and experience and skills in numerical techniques. Among various CFD influential factors, proper selection of turbulence modeling method is a key issue that will directly affect the simulation accuracy and efficiency.

Recent advance in CFD turbulence modeling methods may bring new potential of improving the accuracy and efficiency of indoor airflow modeling. It is thus of great interest and value to review the progress in CFD turbulence modeling and provide solid suggestions on proper application of the models for indoor airflow simulation. The study consists of two parts. Part 1 (this paper) is to identify the most popular (and/or new) turbulence models that have been (and/or have potential to be) used for modeling air distributions in enclosed environments by searching the most recent literatures. Part 2 (a companion paper from Zhang et al. 2007) will then evaluate systematically the identified models by comparing their prediction performance against a series of benchmark experimental results so as to recommend appropriate turbulence models for indoor environment modeling.

CFD APPROACHES

Generally, CFD predicts turbulent flows through three approaches: Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), and Reynolds-Averaged Navier-Stokes (RANS) equation simulation with turbulence models.

DNS computes a turbulent flow by directly solving the highly reliable Navier-Stokes equation without approximations. DNS resolves the whole range of spatial and temporal scales of the turbulence, from the smallest dissipative scales (Kolmogorov scales) to the integral scale, L (case characteristic length), which is associated with the motions containing most of the kinetic energy. As a result, DNS requires a very fine grid resolution to capture the smallest eddies in the turbulent flow. According to the turbulence theory (Nieuwstadt, 1990), the number of grid points required to describe turbulent motions should be at least $N \sim Re^{9/4}$. The computer systems must become rather large (memory at least 10^{10} words and peak performance at least 10^{12} flops) in order to compute the flow (Nieuwstadt et al., 1994). In other words, since the smallest eddy size is about 0.01 m to 0.001 m in an enclosed environment, at least $1000 \times 1000 \times 1000$ grids are needed to solve airflow in a room. In addition, the DNS method requires very small time steps, which makes the simulation extremely long. Neither existing nor near-future personal computers can meet the needs so that application of DNS for indoor flows is not feasible now or in the near future.

According to the Kolmogorov's theory of self similarity (Kolmogorov, 1941), large eddies of turbulent flows depend on the geometry while the smaller scales are more universal. Smagorinsky (1963) and Deardorff (1970) developed LES with the hypothesis that the turbulent motion could be separated into large-eddies and small-eddies such that the separation between the two does not have a significant impact on the evolution of large-eddies. The large-eddies corresponding to the three-dimensional, time-dependent equations can be directly simulated on existing computers. Turbulent transport approximations are made for small-eddies, which eliminates the need for a very fine spatial grid and small time step. The philosophy behind this approach is that the macroscopic structure is characteristic for a turbulent flow. Moreover, the large scales of motion are primarily responsible for all transport processes, such as the exchange of momentum and heat. The success of the method stems from the fact that the main contribution to turbulent transport comes from the large-eddy motion. Thus the large-eddy simulation is clearly superior to turbulent transport closure wherein the transport terms (e.g. Reynolds stresses, turbulent heat fluxes, etc.) are treated with full empiricism. In the last decade, rapid advance in computer capacity and speed has made it possible to use LES for some airflows related to enclosed environments. LES provides detailed information of instantaneous airflow and turbulence with the compensation of still considerable computing time.

For design and study of air distributions in enclosed environments, the mean air parameters are more useful than instantaneous turbulent flow parameters. Thus the interest is stronger in solving the RANS equations with turbulence models that can quickly predict air distributions. The RANS approach calculates statistically averaged (Reynolds-averaged) variables for both steady-state and dynamic flows and simulates turbulence fluctuation effect on the mean airflow by using different turbulence models. Many turbulence models have been developed since the 1970s but very few of them are for enclosed environment. A few turbulence models developed for other engineering applications, such as the standard k-ε model (Launder and Spalding, 1974), have been adopted for indoor air modeling. Despite the challenges associated with turbulence modeling, the RANS approach has become very popular in modeling airflows in enclosed environments due to its significantly small requirements on computer resources and user skills.

TURBULENCE MODEL DEVELOPMENTS AND APPLICATIONS FOR ENCLOSED ENVIRONMENTS

As stated previously, the laminar to turbulent flow characteristics in enclosed environments are very complicated (Ferrey and Aupoix 2006) and impose significant challenges on turbulence models. This paper reviews the recent development and application of the major turbulence models for predicting air distribution in enclosed environments. Instead of developing an inclusive review article, this study focuses on identifying popular and/or most recently proposed turbulence models for indoor environments. The review focused on recent applications with model validation and comparison. Brief introduction of key model evolutions is also included to make the paper complete.

The following part of this paper gives an overall review of various popular turbulence models for indoor airflow simulations, including both RANS and LES models. RANS turbulence models are divided into two primary categories: eddy-viscosity models and Reynolds-stress models. Among the turbulence models studied, some are well-known and in widespread use while others may be undergoing development. For those popular models, this study emphasizes their applicability to various indoor flows without detailing the fundamentals. For more recent models, this investigation discusses their development and potential in predicting indoor airflows. The paper is not intended to judge or criticize the conclusions from the references without knowing the simulation details. In fact, opposite results and conclusions were observed even for similar cases, which may be attributed to factors beyond turbulence models. This paper is solely to sense the application popularity of the models for indoor environment and to identify the prevailing models in practice. The popular models identified will then be evaluated against a series of benchmark experiments and be analyzed for their prediction performance in different indoor airflows as detailed in part 2 of this study (Zhang et al. 2007).

RANS Eddy-Viscosity Models

Eddy-viscosity models are normally classified according to the number of transport equations used. This section will review various eddy-viscosity models from the simplest to the most complex ones.

- **Zero-equation eddy-viscosity models**

The zero-equation turbulence models are the simplest eddy viscosity models. The models have one algebra equation for turbulent viscosity, and no (zero) additional partial differential transport equations (PDE) beyond the Reynolds-averaged equations for mass, momentum, energy, and species conservation. The earliest zero-equation model was developed by Prandtl (1925) with the mixing-length hypothesis. Although the mixing-length model is not theoretically sound and the mixing-length need calibrations for each specific type of flow, the model has yielded good results in predicting simple turbulent flows. Some simple zero-equation models, once calibrated, may even provide surprisingly good results for mean-flow quantities of some complex flows. For instance, Nielsen's study (1998) revealed that the constant eddy-viscosity model provides results closer to the measured data than the standard k-ε model for the prediction of smoke movement in a tunnel. Nilsson (2007) also used the constant eddy-viscosity model to study the comfort conditions around a thermal manikin, which provided acceptable accuracy with significantly less computing efforts.

One important development in zero-equation models for modeling airflows in enclosed environments is the zero-equation model developed by Chen and Xu (1998). By using the assumption of uniform turbulence intensity, they derived an algebraic formula to express turbulent viscosity ν_t as a function of local mean velocity, U, and the distance to the nearest wall, L:

$$\nu_t = 0.03874\, U L \tag{1}$$

The equation has an empirical constant of 0.03874 for different flows. The validations conducted by Chen and Xu (1998), Srebric et al. (1999), and Morrison (2000) have demonstrated the feasibility of this model in predicting general room airflows. The model has been widely used for simulating airflows in different indoor environments with acceptable accuracy and significant reduction in computing time (e.g., Kameel and Khalil 2003, Chen et al. 2005). Li et al. (2005) further applied this zero-equation model for outdoor thermal environment simulations, which also provided reasonable predictions when compared with the measured data. Airpak, a commercial CFD software for HVAC applications, has adopted this model as its default. This model is the most popular zero-equation model for enclosed environments.

- **One-equation eddy-viscosity models**

The turbulent viscosity correlations of zero-equation models may sometimes fail due to the inherent physical deficiencies such as not considering non-local and flow-history effects on turbulent eddy-viscosity. One-equation turbulence models use additional turbulence variables (such as the turbulent kinetic energy $k = \frac{1}{2}\overline{u'_i u'_i}$) to calculate eddy viscosity ν_t such as:

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

where k is obtained by solving a transport equation, l is a turbulence length scale, and C is a constant coefficient. The one-equation models need to prescribe the length scale l in a similar manner as that for the zero-equation models.

Most one-equation models solve the transport equation for turbulent kinetic energy k. Some one-equation models derive transport equations for other turbulent variables, such as the turbulent Reynolds number (Baldwin and Barth, 1990). Spallart and Allmaras (1992) proposed to directly solve a transport equation for eddy viscosity (the S-A model). Unlike most other one-equation models, the S-A model is local so that the solution at one point is independent of the solutions at neighboring cells and thus compatible with grids of any structure. This model is most accurate for free shear and boundary layer flows. The literature review shows that the S-A model, among very few one-equation models used for indoor environment simulation, is a relatively popular and reliable one-equation model at present. Toraño et al. (2006) simulated ventilation in tunnels and galleries with the constant turbulent eddy viscosity, the k-ε, and the S-A models. The comparison of simulation results with detailed experimental data shows great performance of the k-ε and the S-A models. In addition, the S-A model has been incorporated by one of the newest turbulence modeling methods – detached eddy simulation (DES), which will be discussed below.

- **Two-equation eddy-viscosity models**

In addition to the *k*-equation, two-equation eddy-viscosity models solve a second partial differential transport equation for z ($z = k^{\alpha} l^{\beta}$) to represent more turbulence physics. Different α and β values form various kinds of two-equation models. Two-equation models are generally superior to zero- and one-equation models because they do not need prior knowledge of turbulence structure. The eddy viscosity can be calculated from the *k* and the length scale, *l*. Table 1 lists some typical two-equation models.

Table 1. Typical Forms of z Variable in Two-Equation Eddy-Viscosity Models

z	$k^{1/2}/l$	$k^{3/2}/l$	k/l^2	k/l
Symbol	ω	ε	W	kl
Reference	Kolmogorov (1942)	Chou (1945)	Spalding (1972)	Rodi and Spalding (1984)

(1) k-ε two-equation eddy-viscosity model

The k-ε model family is the most popular turbulence model and has the largest number of variants. The "standard" k-ε model developed by Launder and Spalding (1974) is one of the most prevalent models for indoor airflow simulation due to its simple format, robust performance, and wide validations. The turbulent eddy viscosity ν_t is calculated in the k-ε model as:

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \quad (3)$$

where k is the turbulence kinetic energy, ε is the dissipation rate of turbulence energy, and C_μ = 0.09 is an empirical constant. The standard k-ε model was developed for high Reynolds number flows. To apply the model for low Reynolds number flows, such as near wall flows, wall functions (Launder and Spalding, 1974) are usually used to connect the outer-wall free stream and the near-wall flow. The use of wall functions avoids modeling the rapid changes of flow and turbulence near the walls with a fine grid and thus saves the computing time.

The standard k-ε model with wall functions can predict reasonably well the airflow and turbulence in enclosed environments. For example, Holmes et al. (2000) simulated two ideal rooms with several one- and two-equation models and found the standard k-ε model provides a reasonably good prediction. Gadgil et al. (2003) also verified that the k-ε model predicted fairly well the indoor pollutant mixing time in an isothermal closed room. Nahor et al. (2005)

simulated a complex airflow case in an empty and a loaded cool store with agricultural product by using the standard k-ε model. They concluded that the model was capable of predicting both the air and product temperature with reasonable accuracy. Zhang and Chen (2006) successfully applied the standard k-ε model to predict the airflow and particle distribution in a room with an under-floor air distribution system.

Meanwhile, the Re-Normalization Group (RNG) k-ε model (Yakhot and Orszag, 1986) has also been widely used for predicting indoor airflows with many successes. For instance, Yuan et al. (1999a and 1999b) simulated airflow, temperature and gas concentration distribution in a room with displacement ventilation and obtained good agreement with the experimental data. Sekhar and Willem (2004) successfully used the RNG k-ε model to study flow in a large office area. Craven and Settles (2006) modeled the thermal plume from a highly simplified human model with the RNG k-ε model and the results agreed quite well with the PIV data. Zhang et al. (2005) conducted a comprehensive validation of the RNG k-ε model for air distributions in an individual office, a cubicle office, and a quarter of a classroom with displacement ventilation. The study found that the computed air temperature and velocity agreed reasonably well with the measured data.

Another high Reynolds number k-ε model family is realizable k-ε models. Realizable k-ε models usually provide much improved results for swirling flows and flows involving separation when compared to the standard k-ε model. For example, Van Maele and Merci (2006) indicated that the realizable k-ε model (Shih et al., 1995) performs better than the standard k-ε model for predicting various buoyancy plumes. It was observed that the model developed by Shih et al. (1995) is the mostly used realizable model for indoor environment.

The high Reynolds number models may usually fail when the near-wall region is of great concern (Chen, 1995) due to the equilibrium assumption of turbulence production and dissipation in wall functions. One method to remedy the near-wall problem is to use two-layer or even three-layer turbulence models. The two-layer models divide the wall vicinity into a viscosity-affected near-wall region resolved with a one-equation model and an outer region simulated with the standard k-ε model. Another approach for handling near-wall flows is to use a low-Reynolds-number (LRN) turbulence model to solve the governing equations all the way down to the solid surfaces. LRN models request very fine grid near the walls so that the computing time is much longer. Tens of LRN models have been proposed since the 1970s while most of them have the similar form. The observation of the applications of LRN models for indoor simulation reveals that the LRN model may only improve model accuracy for specific cases and lack wide applicability. For instance, Bosbach et al. (2006) simulated airflows in a generic airplane cabin with a group of high and low Reynolds k-ε turbulence models and two-layer k-ε models. Comparison with PIV measurements showed that for reliable prediction of isothermal cabin flow, LRN turbulence models had to be used. However, Costa et al. (1999) tested eight LRN k–ε models to simulate the mixed convection airflow generated by two non-isothermal plane wall jets and found that some LRN models may be able to provide good overall performance but suffer from singular defects occurring near separation/reattachment points of the flow. Hsieh and Lien (2004) also indicated that most LRN models tend to relaminarize the core-region low turbulence flow and, as a consequence, significantly under-predict the near-wall turbulence intensities and boundary-layer thickness, when modeling buoyancy-driven turbulent flows in enclosures. By popularity, it was observed that the LRN models developed by Jones and Launder (1973) and Launder and Sharma (1974) are the most commonly used models, upon which a few variation models were developed (e.g., Radmehr and Patankar, 2001) but less used.

Comparison studies of these models can be found in literature. Chen (1995) compared five k-ε based turbulence models in predicting various convective airflows and an impinging flow. The results showed that the RNG k-ε model had the best overall performance in terms of accuracy, numerical stability, and computing time, while the standard k-ε model had competitive performance. Rouaud and Havet (2002) confirmed that both the standard k-ε and the RNG k-ε model predict well the main features of the flow in clean rooms. Kameel and Khalil (2003) used the standard k-ε model, the RNG k-ε model and the zero-equation model (Chen and Xu, 1998) to calculate airflows in a surgical operating room and found both the k-ε models are superior in predicting flow characteristics in near wall and steep gradient zones. Gebremedhin and Wu (2003) used five RANS models to model a ventilated animal facility, and concluded that the RNG k–ε model is most appropriate for characterizing the flow field and is computationally stable. Posner et al. (2003) evaluated several k–ε models by simulating the airflow in a model room. They found that the simulation results with the laminar flow and the RNG k–ε models agreed better with the experimental data than those with the standard k–ε model. Yang (2004) investigated the mean ventilation flow rates through a naturally-ventilated building with the standard k-ε model and the RNG k-ε model and found that the predicted mean ventilation rates by both models agreed well with the measurements. Walsh and Leong (2004) assessed the performance of several commonly used turbulence models including the standard k-ε, the RNG k-ε and a Reynolds stress model (RSM), in predicting heat transfer due to natural convection inside an air-filled cubic cavity. The study found that the standard k-ε model was the most effective model and the RSM did not improve on any results. It is clearly observed from the literature search that both the standard and the RNG k-ε models have been widely used for indoor environment simulation, and the majority of comparison studies indicated that the RNG k–ε model is slightly better than the standard k–ε model in terms of the overall simulation performance.

(2) k-ω two-equation eddy-viscosity model

The k-ω two-equation eddy-viscosity models (e.g., Wilcox, 1988 and Menter, 1994) have also received increasing attentions in many industrial applications in the last decade. In the k-ω models, ω is the ratio of ε over k. Compared to the k-ε models, the k-ω models are superior in predicting equilibrium adverse pressure flows (Wilcox, 1988; Huang et al., 1992) while less robust in wake region and free shear flows (Menter, 1992). This led to the development of an integrated model that takes advantages of both models, a fairly successful model named shear stress transport (SST) k-ω model developed by Menter (1994). The SST k-ω model is essentially a k-ω model near wall boundaries and is equivalent to a transformed k-ε model in regions far from walls. The switch between the k-ω and k-ε formulations is controlled by blending functions.

The k-ω models have been recently used for a few indoor airflow simulations. Liu and Moser (2003) indicated that the SST k-ω model can predict the transient turbulent flow and heat transfer of forced ventilated fire in enclosures if the transient conjugate heat transfer and thermal radiation are properly modeled. Sharif and Liu (2003) used the LRN k–ω model from Wilcox (1994) and the LRN k-ε model from Lam and Bermhorst (1981) to simulate the buoyancy-driven flow in a two-dimensional square cavity. The performance of the k–ω model was found to be better in capturing the flow physics such as the strong streamline curvature in the corner regions. However, both models failed to predict the boundary-layer transition from laminar to turbulent. Arun and Tulapurkara (2005) computed the turbulent flow inside an enclosure with central partition with three advanced turbulence models: the RNG k–ε model, a Reynolds stress model and the SST k–ω model. They found that the SST k–ω model can capture complex flow features like the movement of vortices downstream of the partition, flow in reverse direction in the top portion of the enclosure, and exit of flow with swirl. Hu et al. (2005) simulated cross-ventilation by using the standard k-ε, RNG k-ε, standard k-ω and SST k-ω models as well as LES and also concluded that the SST k-ω model can depict the flow features satisfactorily. Stamou and Katsiris (2006) used the SST k–ω model, the standard k-ε model, the RNG k-ε model and the laminar flow model to predict air velocity and temperature distributions in a model office room with a task ventilation system. By comparing with the experimental data, the study concluded all the three turbulent models predict satisfactorily the main qualitative features of the flow with slightly best performance from the SST k–ω model. Kuznik et al. (2007) also evaluated the realizable k-ε model (Shih et al., 1995), the k-ε RNG model, the standard k-ω model (Wilcox, 1988), and the SST k-ω model with experimental measurements of air temperature and velocity for a mechanically ventilated room with a strong jet inflow. The research found that all the models can accurately predict the global occupied zone temperature and velocity for the isothermal and hot cases, but none of the models is good and reliable for the cold cases. The k-ω model appears most reliable and can simulate the expansion rates in the highly anisotropic cold case at the same magnitude order as the measurements but not a match.

The k-ω models undoubtedly present a new potential to model indoor environment with good accuracy and numerical stability. Many existing studies indicate that the SST k-ω model has a better overall performance than the standard k-ε model and the RNG k-ε model. Recently, one of the commercial CFD software, CFX, has placed its emphasis on ω-equation based turbulence models due to its multiple advantages, such as simple and robust formulation, accurate and robust wall treatment (low-Re formulation), high quality for heat transfer predictions, and easy combination with other models. However, a systematic model evaluation must be performed in order to reach a solid conclusion, especially for modeling indoor environment airflows.

- **Multiple-equation eddy-viscosity models**

Another noticed development in eddy-viscosity models is multiple-equation eddy-viscosity models. A multiple-equation eddy-viscosity model is often developed and used for near-wall flows. Durbin (1991) suggested that the wall blocking effect, i.e., zero normal velocity at walls, is much more crucial than the viscous effect on near-wall flows. Instead of using the turbulent kinetic energy to calculate near-wall turbulence eddy viscosity, he suggested the use of a more proper quantity, the fluctuation of normal velocity $\overline{v'^2}$, as the velocity scale in the near-wall eddy viscosity calculation. Durbin introduced a transport equation of $\overline{v'^2}$ and a corresponding damping function f for the $\overline{v'^2}$ equation, which thus created a three-equation eddy-viscosity model (named v2f model) including k, ε and $\overline{v'^2}$ transport equations. The model received continuous improvement and modification afterwards (e.g., Durbin, 1995; Lien and Durbin, 1996; Davidson et al., 2003; and Laurence et al., 2004).

The v2f model, as one of the most recently developed eddy viscosity models, has a more solid theoretical ground than LRN models but is less stable for segregated solvers. Choi et al.

(2004) tested the accuracy and numerical stability of the original v2f model (Durbin, 1995) and a modified v2f model (Lien and Kalitzin, 2001) along with a two-layer model (Chen and Patel 1988) for natural convection in a rectangular cavity. The study found the original v2f model with the algebraic heat flux model best predicted the mean velocity, velocity fluctuation, Reynolds shear stress, turbulent heat flux, local Nusselt number, and wall shear stress. The predicted results agreed fairly well with the measurements. However, this model exhibits the numerical stiffness problem in a segregate solution procedure such as the SIMPLE algorithm, which requires remedy. Davidson et al. (2003) discovered that the v2f model could over-predict $\overline{v'^2}$ in regions far away from walls. They, therefore, analyzed the f equation in isotropic condition and postulated a simple but effective way to limit $\overline{v'^2}$ in nearly isotropic flow regions. With this restriction function, the v2f model can improve the accuracy in regions far away from walls. The v2f model brings more turbulence physics especially for low speed near-wall flows, which are critical in enclosed environments. However, the model has not been well tested and evaluated for indoor environment modeling under different flow conditions. A comprehensive and quantitative evaluation is inevitable before the model can be recommended.

Other than the v2f models, some other multiple-equation eddy-viscosity models can be found in literature. For instance, Hanjalic (1996) proposed a new three-equation eddy-viscosity model by introducing a transport equation for RMS temperature fluctuation $\overline{\theta'^2}$ for high Raleigh number flows. However, all these models become more complicated and have not been well accepted and applied for predicting air distributions in enclosed environments.

RANS Reynolds Stress Models

Most eddy viscosity models assume isotropic turbulence structures, which could fail for flows with strong anisotropic behaviors, such as swirling flows and flows with strong curvatures. Reynolds stress models (RSM), instead of calculating turbulence eddy viscosity, explicitly solve the transport equations of Reynolds stresses and fluxes. However, the derivation of the Reynolds stresses transport equations leads to higher order unsolved turbulence correlations, such as $\overline{u_i'u_j'u_k'}$, which need be modeled to close the equations.

The development and application of Reynolds stress models can be traced back to the 1970s. Studies directed towards three-dimensional flows, however, began to appear in the 1990s. Early applications of RSM in room airflow computation include those by Murakami et al. (1990) and Renz and Terhaag (1990). They computed airflow patterns in a room with jets. The results showed that the Reynolds stress model is superior to the standard k-ε model, because anisotropic effects of turbulence are taken into account. The same conclusions were reached recently by Moureh and Flick (2003) who investigated the characteristic of airflow generated by a wall jet within a long and empty slot-ventilated enclosure. Dol and Hanjalic (2001) predicted the turbulent natural convection in a side-heated near-cubic enclosure. They found that the second-moment closure is better in capturing thermal three-dimensionality effects and strong streamline curvature in the corners while the k-ε model still provides reasonable predictions of the first moments away from the corners.

Chen (1996) compared three Reynolds-stress models with the standard k-ε model for natural convection, forced convection, mixed convection, and impinging jet in a room. He concluded that the Reynolds-stress models are only slightly better than the k-ε model but have a severe penalty in computing time. Based on a large number of applications for engineering flows, Leschziner (1990) concluded that Reynolds stress models is appropriate and beneficial when the flow is dominated by a recirculation zone driven by a shear layer. Among various RSMs, the model developed by Gibson and Launder (1978) and the one by Gatski and Speziale (1993) are often used in practice. The models, however, still have some weaknesses that need to be addressed. Tornstrom and Moshfegh (2006), for instance, found that the RSM with linear pressure-strain approximation over-predicted the lateral spreading rate and the turbulent quantities of 3-D cold wall jets. The RSM models are still receiving continuous study and improvement, mostly related to the fundamental research of turbulence mechanism. The models will need significant justification of application advantages before they can be soundly accepted and used for room airflow prediction. Most existing room airflow studies indicated that the marginal improvement on prediction quality of RSM is not well justified by the high computational costs.

To reduce the computing time of the RSMs, algebraic Reynolds stress models (ASM) were developed (e.g., Rodi, 1976) accordingly. The ASM derives algebraic equations for all Reynolds stress and fluxes from the differential stress models, in which each Reynolds stress correlates with others and the derivatives of velocity and temperature. Jouvray et al. (2007) tested several ASMs against the standard k-ε and k- l models (Wolfshtein, 1969) for two rooms with displacement and mixing ventilation. The results showed that the nonlinear ASMs give marginally better agreement with the measured data than did others. The application of the nonlinear models may not be well justified due to the strong case-dependent stability performance and the high additional computational costs.

Large Eddy Simulation Models

LES models have been receiving increased attention recently for modeling engineering flows due to the rapid development of computer speed and power. LES is an intermediate modeling technique between DNS and RANS. LES solves filtered (transformed) Navier-Stokes equations for large-scale eddies while models small-scale (also known as subgrid scale) eddies. Filtering of various variables in the Navier-Stokes equations is similar to the process of Reynolds averaging and the resulting equations for incompressible flow can be written in a similar form as the RANS equations. Smagorinsky (1963) proposed the first subgrid model correlating eddy viscosity to the strain rate, which can be written in the form of eddy viscosity as follows,

$$\tau_{ij} = \frac{1}{3}\tau_{kk}\delta_{ij} - 2\upsilon_t \overline{S}_{ij} \tag{4}$$

where, $\overline{S}_{ij}$ is the strain rate tensor based on the filtered velocity field, the isotropic part τ_{kk} is a unknown scalar and is usually combined with $\overline{p}$. The eddy viscosity is expressed as

$$\upsilon_t = (c_s \Delta)^2 \,|\,\overline{S}\,| \tag{5}$$

where, $|\,\overline{S}\,| = \sqrt{2\overline{S}_{ij}\overline{S}_{ij}}$, Δ is the filter width and C_s is the Smagorinsky constant. Different Smagorinsky constants C_s were proposed by various researchers. Lilly (1966) suggested a value of 0.17 for C_s in homogeneous isotropic turbulent flow. Many variants of Smagorinsky model were proposed thereafter. In physics, the C_s may not be a constant. Thus, the dynamic

Smagorinsky-Lilly model based on the Germano identity (Germano et al., 1991; Lilly, 1992) calculates the C_s with the information from resolved scales of motion

$$(C_s)^2 = \frac{\langle L_{ij} M_{ij} \rangle}{\langle M_{ij} M_{ij} \rangle} \tag{6}$$

where, the L_{ij} and M_{ij} are the resolved stress tensor, and < > is an average operation on homogeneous region. Without the average, the dynamic model has been found to yield a highly variable eddy viscosity field with negative values, which caused the numerical instability. However, the average operation is difficult to implement when the flow field does not have statistical homogeneity direction. Meneveau et al. (1996) proposed the Lagrangian dynamic model, in which a Lagrangian time average was applied to Equation (6). Zhang and Chen (2000) proposed to apply an additional filter for Equation (6), which improved the simulation of indoor airflows. Other more complex models have been proposed to improve accuracy such as the dynamic models as reviewed by Meneveau and Katz (2000).

In the last decade, LES has been growingly applied to model airflows in enclosed environments due to its rich dynamic details compared with RANS models. Some representative applications include: forced convection flow in a room (Davidson and Nielsen, 1996; Emmerich and McGrattan, 1998) or an airliner cabin (Lin et al. 2005), fire-driven air and smoke flows (McGrattan et al., 2000), natural ventilation flow in buildings (Jiang and Chen, 2001), particle dispersion in buildings (Jiang and Chen, 2002; Béghein et al., 2005; Chang et al., 2006; Zhang and Chen, 2006).

Chow and Yin (2004) indicated that the k-ε turbulence model is still a practical approach (the first choice) for simulating fire-induced airflows due to the short computing time and less knowledge demand of users, although the LES approach would give more detailed information that are important for understanding dynamic fire and smoke behaviors. Tian et al. (2006) compared the predictions of indoor particle dispersion and contaminant concentration distribution in a model room with LES and the standard k-ε model and the RNG k-ε model. Their study showed that all the three turbulence model predictions were in good agreement with the experimental data while the LES model yielded the best agreement. Their paper thus concluded that the LES prediction can be effectively employed to validate various k–ε models that are widely applied in building simulations. Musser and McGrattan (2002) evaluated LES for indoor air quality modeling and smoldering fires, and indicated that LES can in general predict the experimental data reasonably well; however, care must be taken in defining convection from heated surfaces and grid resolution. As indicated by most studies, the LES model provides more detailed and accurate prediction of air distributions in enclosed environments, which could be important for understanding the flow mechanism; however, the high demand on computing time and user knowledge makes LES still mainly for research and RANS model development purposes.

Detached Eddy Simulation Models

Detached eddy simulation (DES) method presents the most recent development in turbulence modeling, which couples the RANS and LES models to solve problems when RANS is not sufficiently accurate while LES is not affordable. The earliest DES work includes Spalart et al. (1997) and Shur et al. (1999), in which the one-equation eddy-viscosity model (Spalart and

Allmaras, 1992) was used for the attached boundary layer flow while LES for free shear flows away from the walls. Since the formation of eddy viscosity in RANS and LES models is similar, the S-A model and the LES model can be coupled by using this similarity. In the near wall region, the wall distance *d* of a cell is normally much smaller than the stream-wise and span-wise grid size. In the regions far away from the wall, the wall distance is usually much larger than the cubic root of the cell volume, Δ. Hence, the switch between the S-A model and the LES model can be determined by comparing d and Δ. When d is much larger than Δ, large eddy simulation is performed; Otherwise, the RANS (S-A) model is executed.

In practice, the switch between the RANS and LES models requires more programming and computing efforts rather than simply changing the calculation of the length scale. In fact, many implementations of the DES approach allow for regions to be explicitly designated as RANS or LES regions, overruling the distance function calculation. Squires (2004) reviewed and summarized the current status and perspectives of DES for aerospace applications. Keating and Piomelli (2006) combined a RANS near-wall layer with a LES outer flow with a dynamic stochastic forcing method, which can provide more accurate predictions of the mean velocity and velocity fluctuations.

Some comparison studies of DES, LES and RANS can be found in the recent literature (Roy et al., 2003, Jouvray et al., 2005 and 2007). These recent studies indicated that DES appears a promising model, giving the best velocity agreement and overall good agreement with measured Reynolds stresses. However, they also mentioned that the encouraging DES results could be fortuitous because the method has the potential for LES zones to occur downstream of RANS zones, and thus results in poor LES boundary conditions. In addition, the eddy resolving approaches (LES and DES) demanded extremely high computational costs and computer powers. As an emerging technology, DES still needs more studies before it can be applied for predictions of air distributions in enclosed environments.

SUMMARY REMARKS

This paper reviews the primary turbulence models that have been used for CFD prediction of air distributions in enclosed environments. The selective literature review shows that a large collection of turbulence models can be (and have been) applied for diverse indoor air simulations. Each turbulence model has its own pros and cons. There are no universal turbulence models for indoor airflow simulation. The selection of a suitable model depends mainly on accuracy needed and computing time afforded.

Table 2 presents the selected prevalent turbulence models for predicting airflows in enclosed environments, ranging from RANS to LES. The models are organized into eight sub-categories. Based on the perceived model popularity, we have identified one prevailing turbulence model from each of the eight sub-categories. The prediction performance of these models for indoor airflows has been further evaluated and analyzed by modeling a series of benchmark test cases. This evaluation is presented in the companion paper (Zhang et al. 2007).

Note that Table 2 is necessarily not a comprehensive representation of all previously developed turbulence models. Rather, this paper only reviews the turbulence models that consider the turbulence at single time and length scale at a point for simplicity needed in practice. Increasing knowledge of turbulence modeling has made it challenging to conduct a systematical classification and review of existing turbulence models.

As observed from the literature, the conclusions from past studies are not always consistent. Opposite observations can be attributed to the differences in cases simulated, numerical factors (e.g., scheme, grid and program), judging criteria, and user skills. Without knowledge of all details of the simulations and cases studied, it is difficult to pass judgment on the merits of each turbulence model based solely on the presentation in the literature. This study has instead identified turbulence models that are either popularly used or which have been proposed recently and which have some potential for indoor air flow applications. Part 2 of this study will then evaluate the selected models by comparing them to published experimental data. Despites the disparities among the studies in the literature, some general remarks for turbulence modeling of air distributions in enclosed environments can be stated as follows:

(1) The standard k-ε model with wall functions (Launder and Spalding, 1974) is still widely used and provides acceptable results (especially for global flow and temperature patterns) with good computational economy. The model may have difficulty dealing with special room situations (e.g., high buoyancy effect and/or large temperature gradient).

(2) The RNG k-ε model (Yakhot and Orszag, 1986) provides similar (or slightly better) results as the standard k-ε model and is also widely used for airflow simulations in enclosed environments.

(3) The zero- and one-equation models with specially tuned coefficients are appropriate (sometimes even better than significantly more detailed models) for the cases with similar flow characteristics as those used to develop the models.

(4) Most LRN k-ε models and nonlinear RANS models provide no or marginal improvements on prediction accuracy but suffer from strong case-dependent stability problems and has long computing time.

(5) The Reynolds-stress models can capture some flow details that cannot be modeled by the eddy viscosity models. The marginal improvements on the mean variables, however, are not well justified by the severe penalty on computing time.

(6) The k-ω model (Wilcox, 1988) presents a new potential to model airflows in enclosed environments with good accuracy and numerical stability. Most existing studies indicate that the SST k-ω model (Menter, 1994) has a better overall performance than the standard k-ε and the RNG k-ε models, but a systematic evaluation (especially for modeling indoor airflows) is needed before a solid conclusion can be reached.

(7) The v2f model (Durbin, 1995) looks very promising for indoor environment simulations, but needs to resolve some inherent numerical problems and undergo a comprehensive evaluation.

(8) The LES model provides more detailed and maybe more accurate predictions for indoor airflows, which could be important for understanding the flow mechanism. However, the high demand on computing time and user knowledge still makes LES a tool mainly for research and RANS model developments.

(9) The DES model can be a valuable intermediate modeling approach but needs significant further study, improvement, and validation before it can be used for room airflow predictions.

Table 2. List of Popular and Prevalent Turbulence Models for Predicting Airflows in Enclosed Environments

Model classification			Primary turbulence models used in indoor air simulations	Prevalent models identified
RANS	EVM	Zero-eqn	0-eq. (Chen and Xu, 1998)	Indoor zero eq.
		Two-eqn	Standard k-ε (Launder and Spalding, 1974) RNG k- ε (Yakhot and Orszag, 1986) Realizable k- ε (Shih et al., 1995)	RNG k- ε
			LRN-LS (Launder and Sharma,1974) LRN-JL (Jones and Launder, 1973) LRN-LB (Lam and Bremhorst, 1981)	LRN-LS
			LRN k-ω (Wilcox, 1994) SST k-ω (Menter, 1994)	SST k-ω
		Multi-eqn	v2f-dav (Davidson et al., 2003) v2f-lau (Laurence et al., 2004)	v2f-dav
	RSM		RSM-IP (Gibson and Launder, 1978) RSM-EASM (Gatski and Speziale, 1993)	RSM-IP
LES			LES-Sm (Smagorinsky, 1963) LES-Dyn (Germano et al., 1991; Lilly, 1992) LES-Filter (Zhang and Chen, 2000, 2005)	LES-Dyn
DES			DES (S-A) (Shur et al., 1999) DES (ASM) (Batten et al., 2002)	DES-SA

ACKNOWLEDGEMENT

Z. Zhang and Q. Chen would like to acknowledge the financial support to the study presented in this paper by the U.S. Federal Aviation Administration (FAA) Office of Aerospace Medicine through the Air Transportation Center of Excellence for Airliner Cabin Environment Research under Cooperative Agreement 04-C-ACE-PU. Although the FAA has sponsored this study, it neither endorses nor rejects the findings of this research. The presentation of this information is in the interest of invoking technical community comment on the results and conclusions of the research.

REFERENCES

Arun, M., and E.G. Tulapurkara. 2005. Computation of turbulent flow inside an enclosure with central partition. *Progress in Computational Fluid Dynamics* 5:455-465.

Batten, P., U. Goldberg, and S. Chakravarthy. 2002. LNS – An approach towards embedded LES. *AIAA paper*: AIAA-2002-0427.

Baldwin, B.S., and T.J. Barth. 1990. A one-equation turbulence transport model for high Reynolds number wall-bounded flows. *NASA TM-102947.*

Béghein, C., Y. Jiang, and Q. Chen. 2005. Using large eddy simulation to study particle motions in a room. *Indoor Air* 15 (4):281–290.

Bosbacha, J., J. Pennecota, C. Wagnera, M. Raffela, T. Lercheb, and S. Reppb. 2006. Experimental and numerical simulations of turbulent ventilation in aircraft cabins. *The Second ASME-ZSIS International Thermal Science Seminar (ITSS II)* 31(5):694-705.

Chang, T., Y. Hsieh, and H. Kao. 2006. Numerical investigation of airflow pattern and particulate matter transport in naturally ventilated multi-room buildings. *Indoor Air* 16 (2):136–152.

Chen, C., and V.C. Patel. 1988. Near-wall turbulence models for complex flows including separation. *AIAA J.* 26: 641–648.

Chen, F.Z., S.C.M. Yu, and A.C.K. Lai. 2006. Modeling particle distribution and deposition in indoor environments with a new drift-flux model. *Atmospheric Environment* 40: 357-367.

Chen, Q., and Z. Jiang. 1992. Significant questions in predicting room air motion. *ASHRAE Trans.* 98(l):929-939.

Chen, Q. 1995. Comparison of different k-ε models for indoor air flow computations. *Numerical Heat Transfer, Part B* 28: 353-369.

Chen, Q. 1996. Prediction of room air motion by Reynolds-stress models. *Building and Environment* 31(3): 233-244.

Chen, Q., and W. Xu. 1998. A zero-equation turbulence model for indoor airflow simulation. *Energy and Buildings* 28(2):137-144.

Chen, Q., and Z. Zhai. 2004. The Use of CFD Tools for Indoor Environmental Design. *Advanced Building Simulation*, edited by A. Malkawi and G. Augenbroe, pp.119-140, Spon Press, New York.

Chen, X., B. Zhao, and X. Li. 2005. Numerical investigation on the influence of contaminant source location, occupant distribution and air distribution on emergency ventilation strategy. *Indoor and Built Environment* 14(6): 455-467.

Chen, Y.S., and S.W. Kim. 1987. Computation of turbulent flows using an extended k–e turbulence closure model. NASA CR-179204.

Choi, S., E. Kim, and S. Kim. 2004. Computation of turbulent natural convection in a rectangular cavity with the k–e–v2–f model. *Numerical Heat Transfer, Part B* 45: 159–179.

Chow, W.K., and J. Li. 2007. Numerical simulations on thermal plumes with k–ε types of turbulence models. *Building and Environment* 42: 2819 – 2828.

Chow, W.K., and R. Yin. 2004. A new model on simulating smoke transport with computational fluid dynamics. *Building and Environment* 39: 611 – 620.

Costa, J.J., L.A. Oliveira, and D. Blay. 1999. Test of several versions for the k–ε type turbulence modeling of internal mixed convection flows. International *Journal of Heat and Mass Transfer*, 42 (23): 4391–4409.

Craven, B.A., and G.S. Settles. 2006. A computational and experimental investigation of the human thermal plume. *Journal of Fluids Engineering* 128(6): 1251-1258.

Davidson, L., and P.V. Nielsen. 1996. Large eddy simulations of the flow in a three-dimensional ventilated room. *Proc. Roomvent '96* 2: 161-168.

Davidson, L., P.V. Nielsen, and A. Sveningsson. 2003. Modification of the v2f model for computing the flow in a 3D wall jet. *Turbulence, Heat and Mass Transfer* 4: 577-584.

Deardorff, J.W. 1970. A numerical study of three-dimensional turbulent channel flow at large Reynolds numbers. *J. Fluid Mech.* 42: 453-480.

Dhinsa, K., C. Bailey, K. Pericleous. 2005. Turbulence modelling for electronic cooling: a review. *Electronics Materials and Packaging* 2005: 275 - 281
Dol, H.S., and K. Hanjalic. 2001. Computational study of turbulent natural convection in a side-heated near-cubic enclosure at a high Rayleigh number. *International Journal of Heat and Mass Transfer* 44(12): 2323-44.
Durbin, P.A. 1991. Near-wall turbulence closure modeling without "damping functions". *Theoretical and Computational Fluid Dynamics* 3(1):1-13.
Durbin, P.A. 1995. Separated Flow Computations with the k–e–v2 Model, *AIAA J.* 33: 659-664.
Emmerich, S. 1997. Use of computational fluid dynamics to analyze indoor air quality issues. National Institute of Standards and Technology, Report NISTIR 5997, USA.
Emmerich, S., and K. McGrattan. 1998. Application of a large eddy simulation model to study room airflow. *ASHRAE Trans.* 104(1).
Ferrey, P., and B. Aupoix. 2006. Behaviour of turbulence models near a turbulent/non-turbulent interface revisited. *International Journal of Heat and Fluid Flow* 27: 831–837.
Gadgil, A.J., C. Lobscheid, M/O. Abadie, and E.U. Finlayson. 2003. Indoor pollutant mixing time in an isothermal closed room: an investigation using CFD. *Atmospheric Environment* 37 (39-40): 5577-5586.
Gatski, T.B., and C.G. Speziale. 1993. On explicit algebraic stress model for complex turbulent flows. *J. Fluid Mech.* 254: 59–78.
Gebremedhin, K.G., and B.X. Wu. 2003. Characterization of flow field in a ventilated space and simulation of heat exchange between cows and their environment. *Journal of Thermal Biology*, 28(4): 301–319.
Germano, M., U. Piomelli, P. Moin, P., and W.H. Cabot. 1991. A dynamic subgrid-scale eddy viscosity model. *Phys Fluids* A 3:1760-1765.
Gibson, M.M., and B.E. Launder. 1978. Ground Effects on Pressure Fluctuations in the Atmospheric Boundary Layer. *J. Fluid Mech.* 86: 491-511.
Hanjalic, K., S. Kenjereš, and F. Durst. 1996. Natural convection in partitioned twodimensional enclosures at higher Rayleigh numbers. *Int. J. Heat Mass Transfer* 39: 1407-1427.
Holmes, S.A., Jouvray, A., and Tucker, P.G. 2000. An assessment of a range of turbulence models when predicting room ventilation. *Proceedings of Healthy Buildings 2000* 2: 401.
Hsieh, K.J., and F.S. Lien. 2004. Numerical modeling of buoyancy-driven turbulent flows in enclosures. *International Journal of Heat and Fluid Flow* 25: 659–670.
Hu, C., T. Kurabuchi, and M. Ohba. 2005.Numerical study of cross-ventilation using two-equation rans turbulence models. *International Journal of Ventilation* 4: 123-132.
Huang, P.G., P. Bradshaw, and T.J. Coakley. 1992. Assessment of closure coefficients for compressible-flow turbulence models. *NASA TM-103882*.
Jayaraman, B., E.U. Finlayson, M.D. Sohna, et al. 2006. Tracer gas transport under mixed convection conditions in an experimental atrium: Comparison between experiments and CFD predictions. *Atmospheric Environment*, 40(27):5236-5250.
Jiang, Y., and Q. Chen. 2001. Study of natural ventilation in buildings by large eddy simulation. *Journal of Wind Engineering and Industrial Aerodynamics* 89(13): 1155-1178.
Jiang, Y., and Q. Chen. 2002. Study of particle dispersion in buildings with large eddy simulation. *Proceedings of Indoor Air 2002*, Monterey, California.
Jones, W.P., and B.E. Launder. 1973. The calculation of low-Reynolds-number phenomena with a two-equation model of turbulence. *International Journal of Heat and Mass Transfer* 16: 1119-1130.
Jones, P.J., and G.E. Whittle. 1992. Computational fluid dynamics for building air flow prediction—current status and capabilities. *Building and Environment* 27(3): 321-338.
Jouvray, A., and P.G. Tucker. 2005. Computation of the flow in a ventilated room using non-linear RANS, LES and hybrid RANS/LES. *International Journal for Numerical Methods in Fluids* 48(1): 99 – 106.

Jouvray, A., P.G. Tucker, and Y. Liu. 2007. On nonlinear RANS models when predicting more complex geometry room airflows. *International Journal of Heat and Fluid Flow* 28: 275–288.

Kameel, R., and E. Khalil. 2003. The Prediction of Airflow Regimes in Surgical Operating Theatres: A Comparison of Different Turbulence Models. *AIAA-2003-859*.

Keating, A., and U. Piomelli. 2006. A dynamic stochastic forcing method as a wall-layer model for large-eddy simulation. *Journal of Turbulence* 7(12).

Kolmogorov, A.N. 1941. The local structure of turbulence in incompressible viscous fluid for very large Reynolds number. *Dokl. Akad. Nauk SSSR* 30: 299–303.

Kolmogorov, A.N. 1942. Equations of turbulent motion of an incompressible fluid. *Izvestia Academy of Science, USSR, Physics* 6(1-2): 56-58.

Kuznik, F., G. Rusaouen, and J. Brau. 2007. Experimental and numerical study of a full scale ventilated enclosure: Comparison of four two equations closure turbulence models. *Building and Environment* 42: 1043-1053.

Ladeinde, F., and M. Nearon. 1997. CFD applications in the HVAC&R industry. *ASHRAE Journal* 39(1): 44-4.

Lam, C.K.G., and K. Bremhorst. 1981. A Modified Form of the k–e Model for Predicting Wall, *Turbulence, J. Fluids Eng.* 103: 456-460.

Launder, B.E., and B.I. Sharma. 1974. Application of the energy dissipation model of turbulence to the calculation of flow near a spinning disk. *Letters in Heat Mass Transfer* 1: 131-138.

Launder, B.E., and D.B. Spalding. 1974. The Numerical Computation of Turbulent Flows. *Computer Methods in Applied Mechanics and Energy* 3: 269-289.

Laurence, D.R., J.C. Uribe, and S.V. Utyuzhnikov. 2004. A robost formulation of the v2-f model. *Flow, Turbulence and Combustion* 73: 169-185.

Lemaire, A.D., Q. Chen, M. Ewert, et al. 1993. Room air and contaminant flow, evaluation of computational methods. *IEA Energy Conservation in Buildings and Community Systems Programme Annex 20 Subtask 1 Summary Report*.

Leschziner, M.A. 1990. Modelling engineering flows with Reynolds stress turbulence closure. *J. Wind Eng. and Industrial Aerodynamics* 35: 21-47.

Li, X., Z. Yu, B. Zhao, and Y. Li. 2005. Numerical analysis of outdoor thermal environment around buildings. *Building and Environment* 40: 853–866.

Lien, F.S., W.L. Chen, M.A. Leschziner. 1996. Low-Reynolds-number-eddy-viscosity modeling based on non-linear stress–strain/vorticity relations. *Proceedings of the Third Symposium On Engineering Turbulence Modeling and Measurements*, Crete, Greece.

Lien, F.S., and P.A. Durbin. 1996. Non-linear k−e−v2 modeling with application to high-lift. *Summer Program Proceedings*. Center for Turbulence Research, NASA/Stanford Univ., 5-22.

Lien, F.S., and G. Kalitzin. 2001. Computations of Transonic Flow with the v2–f Turbulence Model. *Int. J. Heat Fluid Flow* 22: 53–61.

Liddament M.W. 1991. A review of building air flow simulation. AIVC Technical Note 33, Air Infiltration and Ventilation Centre, UK.

Lilly, D.K. 1992. A Proposed Modification of the Germano Subgrid-Scale Closure Model. *Physics of Fluids* 4: 633-635.

Lilly, D.K. 1966. On the application of the eddy viscosity concept in the inertial sub range of turbulence. *NCAR Manuscr*. 123.

Lin, C.H., Horstman, R.H., Ahlers, M.F., Sedgwick, L.M., Dunn, K.H., Topmiller, J.L., Bennett, J.S., and Wirogo, S. 2005. Numerical simulation of airflow and airborne pathogen transport in aircraft cabins - Part 1: Numerical simulation of the flow field. *ASHRAE Transactions* 111(1):755-63.

Liu, Y., and A. Moser. 2003. Numerical study of forced ventilated fire in enclosure. *Proceedings of the 2003 4th International Symposium on Heating, Ventilating and Air Conditioning*, 243-250, Oct 9-11 2003, Beijing, China.

McGrattan, K.B., et al. 2000. Fire Dynamics Simulator - Technical Reference Guide. NISTIR 6467.

Meneveau, C., T.S. Lund, and W.H. Cabot. 1996. A Lagrangian dynamic sub-grid scale model of turbulence. *J. Fluid Mech.* 319: 353-85.

Meneveau, C., and J. Katz. 2000. Scale-invariance and turbulence models for large-eddy simulation. *Annu. Rev. Fluid Mach.* 32: 1-32.

Menter, F.R. 1992. Improved two-equation k-w turbulence model for aerodynamic flows. *ASA TM-103975*.

Menter, F.R. 1994. Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA J.* 32: 1598-1605.

Morrison, B.I. 2000. The adaptive coupling of heat and air flow modeling within dynamic whole-building simulation. Ph.D. Thesis, University of Strathclyde, Glasgow, UK.

Moser, A. 1992. Numerical simulation of room thermal convection - review of IEA Annex-20 results. *Proceeding of International Symposium on Room Air Convection and Ventilation Effectiveness*.

Moureh, J., and D. Flick. 2003. Wall air–jet characteristics and airflow patterns within a slot ventilated enclosure. *International Journal of Thermal Sciences* 42(7): 703-711.

Murakami, S., S. Kato, and Y. Kondo. 1990. Examining k-e EVM by means of ASM for a 3-D horizontal buoyant jet in enclosed space. *Int. Symp. on Eng. Turbulence Modelling and Measurements*, Dubrovnik: ICHMT.

Musser, A., and K, McGrattan. 2002. Evaluation of a Fast Large-Eddy-Simulation Model for Indoor Airflows. *J. Arch. Engrg.* 8(1): 10-18.

Nahor, H.B., M.L. Hoang, P. Verboven, M. Baelmans, and B.M. Nicolaï. 2005. CFD model of the airflow, heat and mass transfer in cool stores. *International Journal of Refrigeration* 28(3): 368-380.

Nielsen P.V. 1974. Flow in air-conditioned rooms. Ph.D. Thesis, Technical University of Denmark, Copenhagen, Denmark.

Nielsen P.V. 1989. Progress and trends in air infiltration and ventilation research. *Proc. 10th AIVC Conf.*, Convetry.

Nielsen P.V. 1998. The selection of turbulence models for prediction of room airflow. *ASHRAE Transactions*, SF-98-10-1.

Nieuwstadt F.T.M. 1990. Direct and large-eddy simulation of free convection. *Proc. 9th Int. Heat Transfer Conf.* 1: 37-47, Jerusalem.

Nieuwstadt F.T.M., J.G.M. Eggles, R.J.A. Janssen, and M.B.J.M. Pourquie. 1994. Direct and large-eddy simulations of turbulence in fluids. *Future Generation Computer Systems* 10: 189-205.

Nilsson, H.O. 2007. Thermal comfort evaluation with virtual manikin methods. *Building and Environment* (in press).

Posner, J.D., C.R. Buchanan, and D. Dunn-Rankin. 2003. Measurement and prediction of indoor air flow in a model room. *Energy and Building*, 35(5): 515–526.

Prandtl, L. 1925. Uber die ausgebildete turbulenz. *ZAMM* 5: 136-139.

Predicala, B.Z., and R.G. Maghirang. 2003. Numerical simulation of particulate matter emissions from mechanically ventilated swine barns. *Transactions of the American Society of Agricultural and Biological Engineers (ASAE)* 46(6): 1685-1694.

Radmehr, A., and S.V. Patankar. 2001. A new low-reynolds-number turbulence model for prediction of transition on gas turbine blades. *Numerical Heat Transfer* Part B, 39:545-562.

Renz, U., and U. Terhaag. 1990. Predictions of air flow pattern in a room ventilated by an air jet, the effect of turbulence model and wall function formulation. *Proc. Roomvent '90*: 18.1-18.15, Oslo.

Rodi, W. 1976. A new algebraic relation for calculating the Reynolds stresses. *ZAMM* 56: 219–221.

Rodi, W., and D.B. Spalding. 1984. A two-parameter model of turbulence and its application to separated and reattached flows. *Numerical Heat Transfer* 7: 59-75.

Roy, C., F. Blottner, and J. Payne. 2003. Bluff-body flow simulations using hybrid RANS/LES. AIAA-2003-3889. *33rd AIAA Fluid Dynamics Conference and Exhibit*, Orlando, Florida, June 23-26.

Rouaud, O., and M. Havet. 2002. Computation of the airflow in a pilot scale clean room using k–ε turbulence models. *International Journal of Refrigeration,* 25(3): 351–361.

Sekhar, S.C., and H.C. Willem. 2004. Impact of airflow profile on indoor air quality- a tropical study. *Building and Environment* 39: 255-266.
Sharif, M.A.R., and W. Liu. 2003. Numerical Study of Turbulent Natural Convection in a Side-heated Square Cavity at Various Angles of Inclination. *Numerical Heat Transfer* 43: 693-716.
Shih, T., W. Liou, A. Shabbir, Z. Yang, and J. Zhu. 1995. A new k–e eddy viscosity model for high reynolds number turbulent flows. *Journal Computer Fluids* 24: 227-238.
Shur, M., P.R. Spalart, M. Strelets, and A. Travin. 1999. Detached-Eddy Simulation of an Airfoil at High Angle of Attack. *In 4th Int. Symposium on Eng. Turb. Modeling and Experiments*, Corsica, France, May.
Smagorinsky, J. 1963. General circulation experiments with the primitive equations I: the basic experiment. *Month. Wea. Rev.* 91: 99-164.
Spalart, P., and S. Allmaras. 1992. A one-equation turbulence model for aerodynamic flows. *Technical Report AIAA-92-0439*, AIAA.
Spalart, P.R., W.H. Jou, M. Stretlets, and S.R. Allmaras. 1997. Comments on the feasibility of LES for wings and on the hybrid RANS/LES approach. *Proceedings of the First AFOSR International Conference on DNS/LES*.
Spalding, D.B. 1972. A two-equation model of turbulence. *VDI-Forshungsheft* 549: 5-16.
Spengler, J.D., and Q. Chen. 2000. Indoor air quality factors in designing a healthy building. *Annual Review of Energy and the Environment* 25: 567-600.
Squires, K. D. 2004. Detached-Eddy Simulation: Current Status and Perspectives. *Proceedings of Direct and Large-Eddy Simulation-5*.
Srebric J., Q. Chen, and L.R. Glicksman. 1999. Validation of a zero-equation turbulence model for complex indoor airflows. *ASHRAE Transactions*, 105(2): 414-427.
Stamou, A., and I. Katsiris. 2006. Verification of a CFD model for indoor airflow and heat transfer. *Building and Environment* 41(9): 2171-1181.
Tian, Z.F., J.Y. Tu, G.H. Yeoh, and R.K.K. Yuen. 2006. On the numerical study of contaminant particle concentration in indoor airflow. *Building and Environment* 41(11): 1504-1514.
Toraño, J., R. Rodríguez, and I. Diego. 2006. Computational Fluid Dynamics (CFD) use in the simulation of the death end ventilation in tunnels and galleries. *WIT Transactions on Engineering Sciences* 52.
Tornstrom, T., and B. Moshfegh. 2006. RSM predictions of 3-D turbulent cold wall jets. *Progress in Computational Fluid Dynamics* 6: 110-121.
Van Maele, K., and B. Merci. 2006. Application of two buoyancy-modified k–ε turbulence models to different types of buoyant plumes. *Fire Safety Journal* 41: 122–138.
Walsh, P.C., and W.H. Leong. 2004. Effectiveness of Several Turbulence Models in Natural Convection. *International Journal of Numerical Methods for Heat and Fluid Flow* 14: 633-648.
Whittle G.E. 1986. Computation of air movement and convective heat transfer within buildings. *Int. J. Ambient Energy* 3: 151-164.
Wilcox, D.C. 1988. Reassessment of the Scale-Determining Equation for Advanced Turbulence Models. *AIAA Journal* 26: 1299-1310.
Wilcox, D.C. 1994. Simulation of Transition with a Two-Equation Turbulence Model, *AIAA J.* 32: 247-254.
Wolfshtein, M. 1969. The Velocity and Temperature Distribution in One Dimensional Fow with Turbulence Augmentation and Pressure Gradient. Int. J. Heat Mass Transfer 12, 301–318.
Yakhot, V., and S.A. Orszag,. 1986. Renormalization group analysis of turbulence. *Journal of Scientific Computing* 1: 3-51.
Yang, T. 2004. CFD and Field Testing of a Naturally Ventilated Full-scale Building. PhD dissertation. May 2004. BE MSc - 2004 - etheses.nottingham.ac.uk.
Yuan, X., Q. Chen, L.R. Glicksman, Y. Hu, and X. Yang. 1999a. Measurements and computations of room airflow with displacement ventilation. *ASHRAE Transactions* 105(1): 340–352.
Yuan, X., Q. Chen, and L.R. Glicksman. 1999b. Models for prediction of temperature difference and ventilation effectiveness with displacement ventilation. *ASHRAE Transactions* 105(1): 353-367.

Zhai Z. 2006. Applications of CFD in Building Design: Aspects and Trends. *Indoor and Built Environment*, 15(4): 305-313.
Zhang, L., T.T. Chow, Q. Wang, K.F. Fong, L.S. Chan. 2005. Validation of CFD model for research into displacement ventilation. *Architectural Science Review*, 48(4):305-316.
Zhang, W., and Q. Chen. 2000. Large eddy simulation of indoor airflow with a filtered dynamic subgrid scale model. *International Journal of Heat and Mass Transfer* 43(17): 3219-3231.
Zhang, Z., and Q. Chen. 2006. Experimental measurements and numerical simulations of particle transport and distribution in ventilated rooms. *Atmospheric Environment* 40(18): 3396-3408.
Zhang, Z., W. Zhang, Z. Zhai, and Q. Chen. 2007. Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: Part-2: comparison with experimental data from literature. *ASHRAE HVAC&R* (accepted).