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Verification of a CFD model for indoor airflow and heat transfer

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Abstract

The SST k–ω based model is applied to calculate air-flow velocities and temperatures in a model office room. Calculations are compared with experiments and with the results of the standard k–ε, the RNG k–ε model and the laminar model. It is concluded that (a) all the three tested turbulent models predict satisfactorily the main qualitative features of the flow and the layered type of temperature fields and (b) computations with the SST k–ω based model show the best agreement with measurements. The use of this model is proposed combined with a suitable grid.

Keywords: Computational fluid dynamics (CFD); Mathematical models; Indoor environment; Office spaces; Thermal comfort; CFX

1. Introduction

In ventilated interior environments of buildings, the determination of air-flow velocities, temperatures and concentrations of pollutants is required to evaluate comfort conditions (thermal and draught) and indoor air quality. This determination can be performed with computational fluid dynamics (CFD) methods. In the last 15 years, a significant number of papers has been published on the application of CFD methods in pilot, experimental or real scale interior environments with considerable success.

In general, the main types of CFD methods are the following: direct numerical simulation (DNS), large eddy simulation (LES) and Reynolds averaged Navier–Stokes (RANS).

1.1. Direct numerical simulation

Most flows encountered indoors are turbulent, characterized by eddies with a wide range of length and time scales. The largest eddies are typically comparable in size to the characteristic length of the mean flow (such as the dimensions of the interior spaces) and the smallest scales (which are responsible for the dissipation of turbulence kinetic energy) are of the order of the Kolmogorov microscale. It is theoretically possible to directly (without any approximations) resolve the whole spectrum of turbulent scales by solving the exact Navier–Stokes equations, using the approach of DNS. However, DNS is not feasible for indoor environment spaces, because it requires a very fine grid resolution, which is prohibitive for the current computers.

Two alternative methods can be employed to transform the exact Navier–Stokes equations in such a way that the small-scale turbulent fluctuations do not have to be directly simulated: Filtering and Reynolds averaging.

1.2. Filtering—large eddy simulation

Filtering is a manipulation of the exact Navier–Stokes equations to remove the eddies, which are smaller than the size of the filter (usually taken equal to the grid size). The "filtered" equations are used to compute the large eddies (large eddy simulation, LES) and the small eddies are modeled independently of the flow geometry. This results in grid sizes that are at least one order of magnitude smaller than with DNS, but extremely fine grids are still required. The application of LES to indoor environments is in its infancy. Only a few applications exist to date, which are restricted to very simple geometries (due to the large

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computer resources required to resolve the energy-containing turbulent eddies) and use high-order spatial discretisation schemes (with great care being taken to resolve all scales larger than the inertial sub-range). Furthermore, the use of wall functions with LES is an approximation that requires further validation. Zhang and Chen [1] used a LES model with a filtered dynamic sub-grid scale model and a second-order explicit differencing scheme to calculate natural, forced and mixed convection flows in rooms having the simple geometry of a cavity. It was concluded that "LES has a good potential to simulate indoor airflow in the near future", due to the explosive increases in computer hardware performance coupled with the availability of parallel processing.

1.3. Reynolds averaged Navier–Stokes

RANS equations represent transport equations only for the mean flow quantities with all the scales of the turbulence being modeled. The RANS approach has been applied in the majority of the existing indoor airflow CFD calculations using turbulence models, such as the standard k–ε model and its variants, the standard k–ω and its variants, and the Reynolds-stress model (RSM).

The standard k–ε model is a semi-empirical model, which is valid only for fully turbulent flows. The model is based on model transport equations for the turbulent kinetic energy, k, and its dissipation rate, ε. The turbulent viscosity is computed from these scalars. The k–ε formulation is derived using a high Reynolds number hypothesis; also near wall treatment is based on the application of wall functions, rather than solving the governing equations inside the boundary layer. This model has been extensively used in the first CFD applications in indoor environments performed in the period 1978–1998; see [2] for a brief literature review.

The standard k–ε model has proven very successful for numerous engineering applications. However, certain characteristics of indoor airflow, such as the creation of regions with very low velocities and thus low Reynolds numbers, especially near the wall boundaries, require the use of more effective models. This requirement led to the formulation of modified k–ε turbulence models, which are expected to be more effective for such regions. These models are the low-Reynolds number k–ε model (LR k–ε) and the RNG k–ε model.

The LR k–ε model differs from the standard k–ε model in the values of the empirical coefficients. A disadvantage of the model is that one of the damping functions requires the calculation of the local distance to the nearest wall. Costa et al. [3] have tested eight LR k–ε models to simulate the mixed convection airflow generated by two non-isothermal plane wall jets. It was concluded that the model of Nagano and Hishida [4] provided the best overall performance, although suffering from singular defects occurring near separation/reattachment points of the flow.

The RNG k–ε model is derived using a rigorous statistical method called renormalization group (RNG). It involves a theory for the large scales, in which the effects of the small scales are represented by modified transport coefficients. A basic characteristic of the RNG k–ε model is that it involves an analytically derived differential formula for effective viscosity that accounts for low-Reynolds-number effects. This feature combined with an appropriate treatment of the near-wall region makes the RNG k–ε model more accurate and reliable for a wider class of indoor airflows than the standard k–ε model. Chen [5] compared five different k–ε models, including the standard k–ε, the LR k–ε and the RNG k–ε model. He recommended only the RNG k–ε model for simulations of indoor air-flow and noted that the performance of the other models was not stable. Rouaud and Havet [6] showed that both the standard k–ε and the RNG k–ε model predict well the main features of the flow in clean rooms. They also claimed that the RNG k–ε seems to be more suitable, while the standard k–ε model overestimates turbulent diffusion. Gebremedhin and Wu [2] have evaluated five RANS models (the k–ε, the RNG k–ε, the LR k–ε, the k–ω and the RSM) with the code PHOENICS [7]. Based on convergence and computational stability criteria, they concluded that the RNG k–ε model is the most appropriate model that characterizes the flow field in a ventilated space. Cheong et al. [8] evaluated the current thermal comfort conditions of an air-conditioned lecture theatre, using the code Fluent [9] and the RNG k–ε model. Calculations of airflow characteristics and temperature gradients were in fair agreement with empirical measurements. Posner et al. [10] have evaluated the laminar, the standard k–ε and the RNG k–ε models with respect to their performance in simulating the flow in a model room. Their simulations using the code Fluent [9] with the laminar and the RNG k–ε models agreed better with experimental data than calculations with the standard k–ε model.

The standard k–ω model [11] is based on model transport equations for k and the turbulence frequency, ω. The turbulent viscosity is computed from these scalars. The model is numerically stable, especially the low-Reynolds number version, as it tends to produce converged solutions more rapidly than the k–ε model; and the low-Reynolds number version is more efficient than the LR k–ε model in that it does not require calculations of wall distances, additional source term and/or damping functions based on the friction velocity. The main weakness of the k–ω model is its strong sensitivity to free-stream conditions. The application of the k–ω model in indoor environments was not successful [2].

The SST model [12] combines the k–ε and the k–ω models using a blending function. The SST model activates the k–ω model in the near-wall region and the k–ε model for the rest of the flow. By this approach, the attractive near-wall performance of the k–ω model is utilized without the potential errors resulting from the free stream sensitivity of that model. No work was found in