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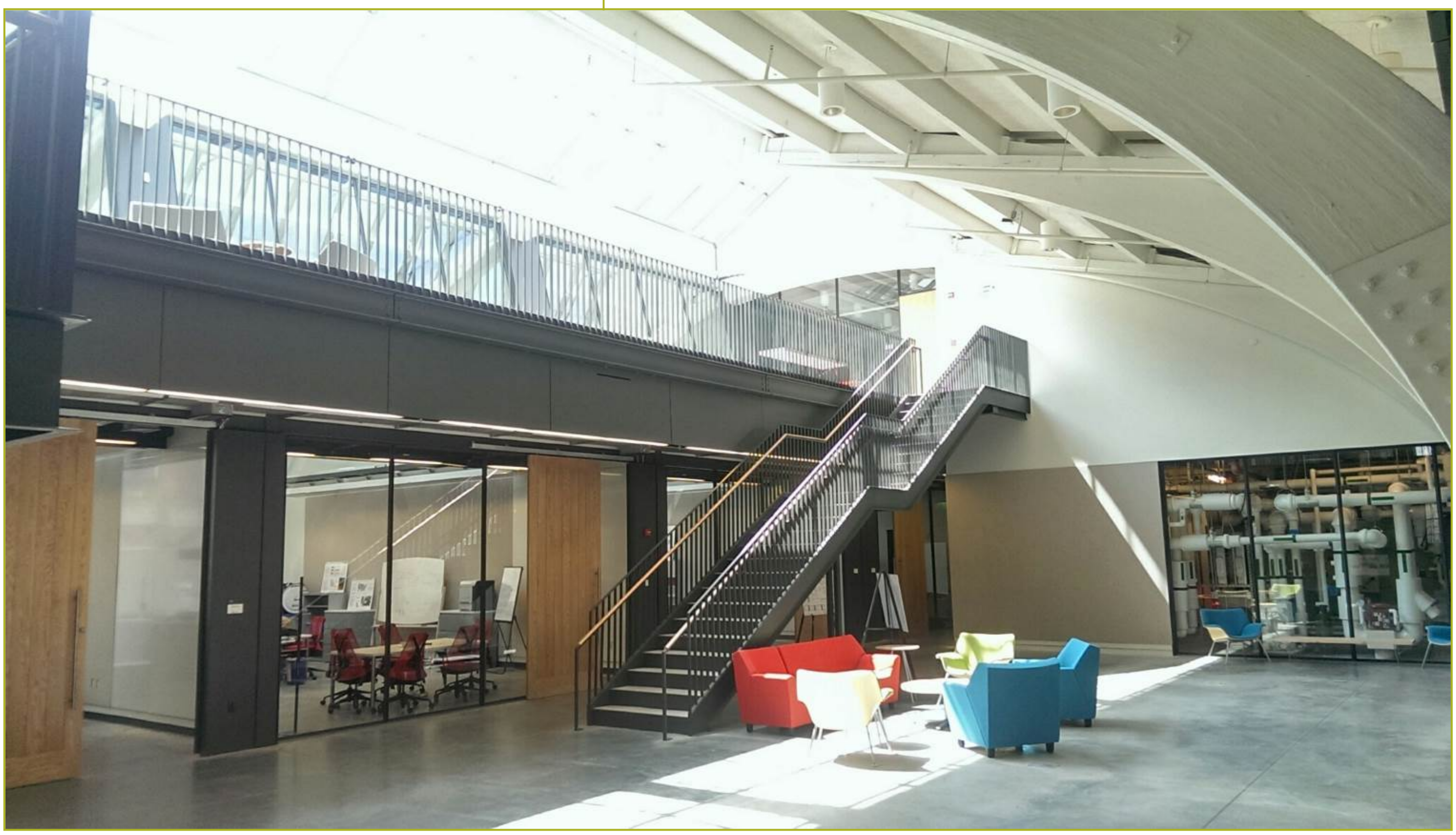

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Report Abstract

The airflow in enclosed environments is a wall bounded flow, consisting of circulation, flow separation, and thermal plumes in transitional to fully developed turbulence. This study developed a new Detached Eddy Simulation model for indoor airflow using a semi-v2f model, and this model correctly predicted near-wall flows. This study applied the new DES model to a mixed-ventilation and a strong buoyancy-driven flow in rooms.

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A NEW DES MODEL FOR INDOOR AIRFLOW MODELING

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Abstract

The airflow in enclosed environments is a wall bounded flow, consisting of circulation, flow separation, and thermal plumes in transitional to fully developed turbulence. This type of flow is difficult to simulate using Reynolds Averaged Navier-Stokes (RANS) models due to the complex flow features. The more advanced Large Eddy Simulation (LES) may solve such flow features, but requires very fine grids near solid surfaces, which makes it very computationally demanding. The hybrid RANS/LES simulation, or Detached Eddy Simulation (DES), which uses a RANS model for the near-wall boundary layers to avoid excessively fine grids, as well as a LES for the far-wall flow region, looks promising. However, the available DES models did not perform well for indoor airflows due to the RANS model they used. This study has developed a new DES model for indoor airflow using a semi-v2f model, and this model correctly predicted near-wall flows by taking into account the wall normal stress. This study applied the new DES model to a mixed-ventilation and a strong buoyancy-driven flow in rooms. The new model can accurately predict the flows, and it is robust.

Keywords: turbulence model, indoor airflow, DES, hybrid RANS/LES, near wall treatment

1 Introduction

Airflow in enclosed spaces, such as buildings and aircraft cabins, can be complicated due to complex flow features such as flow transition and lack of stability. Many indoor airflows are transitional when the Reynolds number based on the supply air grille is in the region of 2000< Re <3500. Turbulence is generated at the grille where the fluctuating component of velocity is a fraction of the mean velocity. As the air travels further into the room, the fluctuating component may decay gradually due to the decrease in the mean flow gradient and the damping effect of the solid surfaces. Therefore, relaminization may occur within the occupied space, and the flow is transitional. In addition to flow transition, in many indoor environments, airflow with relatively high air change rates (between 5 to 20 ACH) can be unstable under the transitional Reynolds number. One reason for this is that the transitional phenomenon makes the flow unstable. In the transitional region, the inertial force is approximately balanced by the viscous force. A random small impact from the main stream can break down this balance and lead to a transitional flow. This mechanism results in the instability of the main flow. Another reason attributed to the unstable flow is the interactions among different flow features. Many enclosed environments are mechanically ventilated. However, the air can also be driven by buoyancy in the occupied zone, where the thermal plume can be as strong as the flow from the mechanical ventilation system. The two flows interact, which results in instability. Besides, the complex geometry of the indoor environment can also lead to an unstable flow. The furniture inside an indoor environment can generate flow separation, which is usually unstable. As discussed above, the flow transition and unstable behaviors cause complicated indoor airflow phenomena, making indoor airflow difficult to model.

To model indoor airflow, one approach is to apply Computational Fluid Dynamics (CFD) to solve the flow equations. The airflow in a room is governed by the Navier-Stokes (N-S) equation. The most straightforward way to solve this equation is called Direct Numerical Simulation (DNS), which directly solves the N-S equation, together with initial and boundary conditions, and produces a realization of the flow. The DNS does not need any model and can provide the most accurate and detailed flow motion. However, the DNS resolves a wide range of spatial and temporal scales, which requires very fine meshes and time steps (Wilcox 2006). Even for steady-state flow, DNS needs to perform unsteady calculation and calculate a long period of time to obtain the mean flow. As a result, the cost of DNS can be extremely high. Therefore, it is not feasible to perform the simulation on a personal computer or a moderate computer cluster in the near future.

A more realistic and widely used approach for indoor airflow simulations is through Reynolds-Averaged Navier-Stokes (RANS) equation modeling. The RANS simulation solves the time-averaged N-S equation and models the Reynolds stresses. The modeling approach can significantly reduce the grid resolution required and can be performed as steady-state. However, due to the time-averaging approach, the RANS models could not correctly predict many flow features, such as separated flow, impinge flow, and unsteady plumes.

With the advance in computing power, Large Eddy Simulation (LES) is becoming more and more popular for engineering applications due to its ability to solve unstable flows. LES solves the filtered N-S equation for the energy-containing eddies (large eddies) and models the subgrid-scale flow motions (small eddies). The LES relies more on fundamental flow physics than on modeling assumptions. As a result, LES is more accurate and informative than RANS models for airflow modeling, especially for a separated and unstable flow. Since LES solves only the large scale eddies, the computing cost is much lower than that of DNS. However, it is difficult to apply LES to the near wall region of indoor airflow modeling, where very fine grids are needed, so the computing cost could be the same as that of the DNS. For airflow in enclosed spaces, the flow is bounded by walls, furniture, and occupants. All of these solid surfaces could significantly increase the computing cost by LES.

To overcome the disadvantages of the LES and RANS, the concept of the DES model has emerged in the past decade. The hybrid model is to apply LES in the fully-developed turbulence flow region to capture the three-dimensional, time-dependent flow and to apply a RANS model in the attached boundary layers so as to avoid the excessively fine meshes required by LES. This approach was first introduced by Spalart et al. (1997), who adopted the one equation Spalart model. Some studies used the Smagoringsky zero-equation LES model with the zero-equation RANS model, such as the Cebeci-Smith and Baldwin-Lomax models (Georgiadis et al., 2003; Kawai and Fujii, 2005). Many other studies adopted multi-equation RANS models with LES, such as the k-ω model (Strelet 2001; Davidson and Peng 2003), k-ε model (Hamba 2001, 2003), and k-l model (Tucker and Davidson 2004). After reviewing the DES models, our goal was to develop a new DES model, the Semi-v2f/LES model, for modeling airflows in an enclosed environment. The new model uses transport equations for k and ε, as well as an algebraic equation for the normal stress near a wall, to model the turbulence viscosity in the RANS region and the subgrid turbulence viscosity for the LES region. The new model was tested by applying it to a mixed convection flow in a model room and to a strong buoyancy-driven flow with a high temperature gradient in a room.

2 Model development

2.1 Hybrid RANS/LES simulation for indoor airflow

Indoor airflow is governed by the N-S and energy equations. Since it is not feasible to use DNS for solving such a flow, the N-S equation should be approximated in order to make it solvable with the present capacity of computers. By using the Reynolds averaged approach, the flow variables can be written as:

$$\phi = \Phi + \phi' \tag{1}$$

where, Φ is the mean value of the flow variables, and ϕ' is the fluctuating part of the flow variables. Also, LES uses a filter to obtain large-scale flow variables:

$$\overline{\phi}(\bar{x},t)=\iiint_V \phi(\bar{x},t)G(\bar{x},\bar{x}',t)d\bar{x}' \tag{2}$$

where the over bar denotes the filtered variables, and G is a filter function.

The two methods can transform the N-S equation into a single form:

$$\frac{\partial \overline{u_i}}{\partial t}+\overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\left(\nu+\nu_t\right)\frac{\partial \overline{u_i}}{\partial x_j}\right] \tag{3}$$

where ν_t is the turbulence viscosity for the RANS model and the subgrid-scale turbulence viscosity for LES.

The DES models are usually classified based on the RANS model they use. Their performance also depends on the RANS model. For indoor airflow simulation, a few preliminary studies in the literature showed that the available RANS/LES hybrid models did not perform as well as LES or even as well as some RANS models. This is because the RANS models used did not work well (Zhang et al. 2007; Wang and Chen, 2009). Therefore, our goal was to identify an appropriate RANS model for developing a new DES model.

2.2 The Semi-v2f/LES model

As discussed above, the accuracy of the RANS model is essential to the performance of a hybrid model. Some studies have evaluated different RANS turbulence models for indoor airflow and concluded that the v2f model is one of the best (Zhai et al. 2007; Zhang et al. 2007; Wang and Chen 2009). The v2f model can be used for the hybrid model since it can resolve the near wall viscous region at a reasonable computational cost, and it accounts for anisotropic behavior near the wall. However, studies from the literature (Durbin, 1991, Davidson, 2003) and our preliminary research show that the transport equation for the wall normal stress $\overline{v'^2}$ and the elliptic equation for the relaxation function f make the model numerically unstable. Therefore, it is essential to simplify the v2f model before implementing it into DES.

Our effort to develop the v2f model further was to introduce an algebraic equation for the normal stress $\overline{v'^2}$:

$$\overline{v'^2}=f\left(k,\varepsilon,\upsilon,y...\right) \tag{4}$$

to replace the transport equation for $\overline{v'^2}$ and the elliptic equation for f, which have been problematic. The procedure is first to derive new equations for $\overline{v'^2}$ and turbulence viscosity. The constant in the equations is then determined through curve fitting of the flow data obtained for indoor airflow. The detailed procedure is as follows.

Starting from the Buossinesq approximation for incompressible flow:

$$-\tau_{ij}=-2\nu_t S_{ij}+\frac{2}{3}k\cdot\delta_{ij} \tag{5}$$

considering the diagonal entries at wall normal direction (i=j=2), and substituting the ν_t formulation of v2f model, it is easy to obtain a correlation:

$$\frac{\overline{v'^2}}{k} = C_1\left(1 - C_2 \frac{\overline{v'^2}}{\varepsilon}\frac{\partial V}{\partial y}\right) \tag{6}$$

where C_1 and C_2 are constants. Through dimensional analysis of equation (6), there are three non-dimensional variables: $\frac{\overline{v'^2}}{k}$, $y^* = \frac{yC_\mu^{1/4}k^{1/2}}{\nu}$, and $l^* = \frac{k^{\frac{3}{2}}}{\varepsilon y}$. Therefore, equation (6) can be written as a dimensionless form:

$$\frac{\overline{v'^2}}{k} = C_1\left[1 - g\left(y^*, l^*\right)\right] \tag{7}$$

where $g\left(y^*, l^*\right)$ g is the function to be determined. If the y* value becomes large (far from the wall), the turbulence should be homogeneous:

$$\frac{\overline{v'^2}}{k} = C_1\left[1 - g\left(y^*, l^*\right)\right] \xrightarrow{y^* \to \infty} C_1 \tag{8}$$

Near a wall, the normal kinetic energy goes to zero:

$$\frac{\overline{v'^2}}{k} = C_1\left[1 - g\left(y^*, l^*\right)\right] \xrightarrow{y^* \to 0} 0 \tag{9}$$

Assuming the wall damping effect only related to the geometry, the influence of l^*, which was the turbulence eddy scale, could be neglected. Thus, equations (8) and (0) could be a good approximation of equation (6). Namely:

$$\frac{\overline{v'^2}}{k} = C_1\left[1 - \exp\left(-\frac{y^*}{y^*_0}\right)\right] \tag{10}$$

where C_1 and y^*_0 are constant.

In the v2f model, the turbulence viscosity is modeled as:

$$\nu_t = C_\mu \overline{v'^2}\frac{k}{\varepsilon} \tag{11}$$

where, $C_\mu = 0.22$ is a constant. By substituting equation (10) into equation (11), the turbulence viscosity can be determined by:

$$\nu_t = \mathrm{A}\cdot\left[1 - \exp\left(-\frac{y^*}{\mathrm{y}^*_0}\right)\right]\cdot\frac{k^2}{\varepsilon} \tag{12}$$

where $A = 0.07$ and $y^*_0 = 50.836$ are empirical constants.

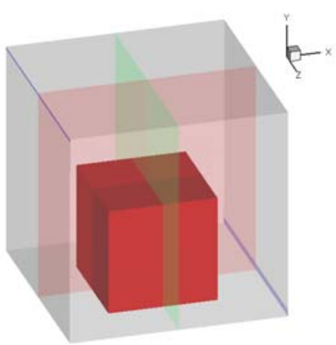
The new Semi-v2f/LES model uses the same k and ε equations as those in the DES realizable k-ε model, but has a new algebraic equation for $\overline{v'^2}$ and a new eddy-viscosity correlation. The new model does not modify the formulation of the turbulence heat flux, and thus uses the same energy equation as that used by the DES realizable k-ε model.

3 Evaluation of the new DES model

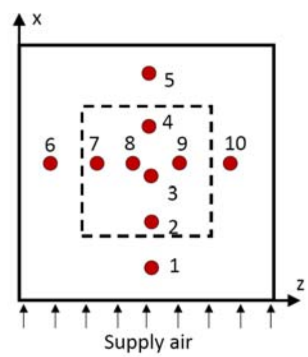
This study evaluated the performance of the new DES model by applying it to calculating a mixed-ventilation flow in a room and a strong buoyancy-driven flow in another room. This section shows the results.

3.1 Mixed convection flow

Figure 1 (a) shows the case schematic. The distributions of air velocity, temperature, and turbulence were measured at ten positions at the stream-wise and the cross sections in the cubic room. The air was supplied from a slot diffuser located at the upper-left corner of the room and exhausted from a slot at the lower-right corner. A heated box was placed in the center on the floor with 700 W of power, which produced a thermal plume and flow separation. Please find more information about this case from Wang and Chen (2009). The new model was tested with two grid resolutions (110x77x101 and 44x44x44) and compared with the LES Dynamic Smagorinsky (LES-DSL) model, the DES Realizable k-ε model, and the v2f model modified by Davidson (v2f-Dav).



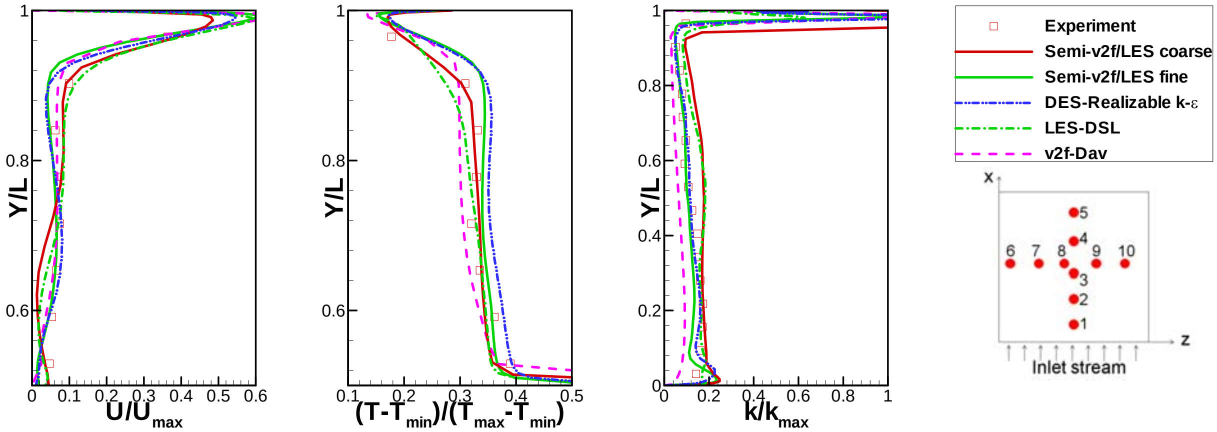
(a)



(b)

Figure 1 A mixed convection flow in a room (Wang and Chen 2009): (a) the case schematic and the measuring section locations and (b) ten positions selected for comparison between the new model results and the experimental data.

Due to the limited space available, the simulated results are only shown at the most representative positions. Figure 2 (a) depicts the air velocity prediction by the four models at position 3. In general, all the models predicted very similar, acceptable results, though small discrepancies could be found for all the models. This is true at other positions. Figure 2 (b) shows the temperature prediction by the models. At position (8), the new model with the coarse grids surprisingly predicted better results compared with the other models. The new model with the fine grids also predicted slightly better results than the Realizable k-ε model and the v2f-Dav model. The results of the LES-DSL model were comparable with those of the new model with the fine grids. Though not shown in this paper, the temperature prediction by the new model was slightly better than that of the other three models in most positions. Figure 2 (c) shows the prediction of the turbulence kinetic energy profiles predicted by the four models. The new model with the fine grids predicted the best result at position (1). The DES Realizable k-ε model performed similarly. The new model with coarse grid had a similar performance to that of the LES-DSL model, which significantly over-predicted the turbulence level. The v2f-Dav model under-predicted the turbulence level.

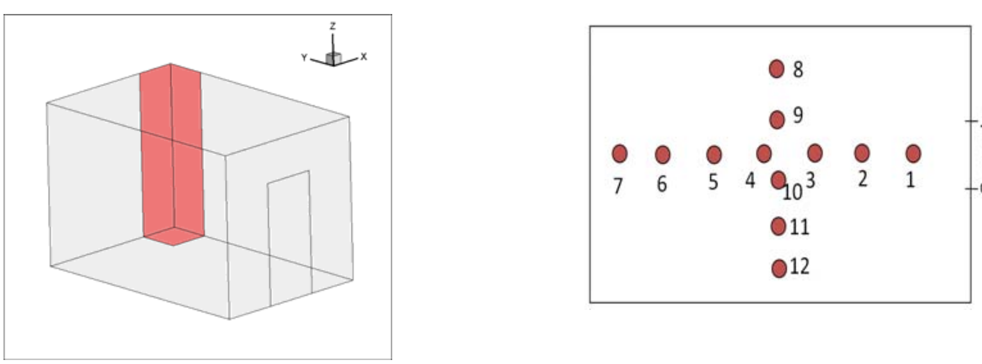


(a) Velocity (position 3) (b) Temperature (position 8) (c) Turbulence Kinetic Energy (position 1)

Figure 2 The performance of different turbulence models for: (a) air velocity, (b) air temperature, and (c) turbulence kinetic energy.

3.2 Strong buoyancy-driven flow

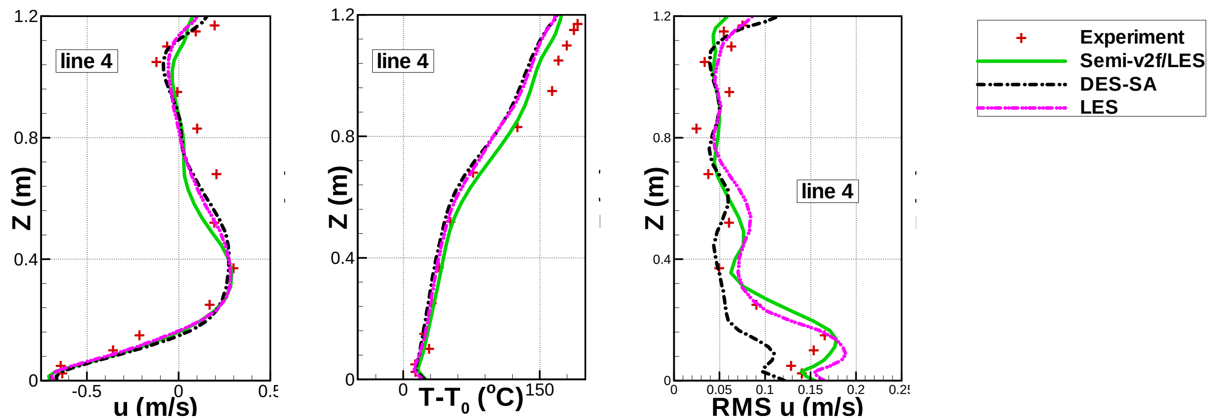
The second case tested was a strong buoyancy-driven flow in a fire room, as shown in Figure 3 (a). This case was chosen for studying the robustness of the new model. The case was designed by Murakami et al. (1995), who measured detailed fluctuating velocity using two-component Laser Doppler Velocimetry (LDV), and the temperature using thermal couples. A total of 9.1 kW of heat source was placed in the corner of the room. The surface temperature at the heat source reached more than 500ºC. An opening connected the air between the test room and the outside chamber. The fluctuating velocity and temperature were measured at 12 lines at two sections, as shown in Figure 3 (b).



(a) (b)

Figure 3 Schematic of the case with strong buoyancy-driven flow (Murakami et al., 1995): (a) the case schematic and the measuring section locations and (b) 12 positions selected for comparison between the new model results and the experimental data.

Although this case was primarily used to test the robustness of the new model, the results from the DES Spalart-Allmaras (DES-SA) model and the LES-DSL model are included for comparison. The test was based on the comparison of the air velocity, the air temperature, and the root-mean-square (RMS) velocity predicted. The RMS reflects the turbulence predicted by the models. The results at all 12 measurement positions were compared, but only those at position 4 are shown here, due to the limited space available in this paper.



(a) (b) (c)

Figure 4 *The performance of different turbulence models for: (a) air velocity, (b) air temperature, and (c) RMS velocity.*

Figure 4 (a) depicts the calculated and measured velocity profiles in x-direction. All the models were stable in this extreme case. The Semi-v2f/LES model predicted comparable results to those of the other models. Figure 4 (b) compares the predicted and measured air temperature profiles. It is not surprising that all the models predicted reasonable results due to their correct velocity predictions. However, all the models under-predicted the temperature near the ceiling. The Semi-v2f/LES model performed relatively better than the other models due to its better turbulence viscosity formulation in the near wall region, which could be important for near-wall heat transfer. Figure 4 (c) shows the root-mean-square velocity profiles at the x-direction. This flow quantity was obtained statistically using the solution at each time step. The three models were able to predict the correct trend of the profile. The DES-SA model predicted poorer results than the other two models because the model solved only one turbulence transport quantity, the modified turbulence viscosity, and could not calculate the turbulence length scale related to the local shear layer thickness. Therefore, the model may not be accurate for a complicated shear flow. The new Semi-v2f/LES model and LES-DSL model had comparable performances.

The computational time needed by the new model is very similar to the time needed by the DES Realizable model since they both solved two additional equations for turbulence. The DES-SA model used slightly less computing time since it only solved one additional equation for turbulence. The LES-DSL model had a simpler formulation than the new model, but required a much finer grid near the wall for full LES simulation. Thus, it could use more computing time.

4 Conclusions

This investigation developed a new RANS/LES hybrid model, the Semi-v2f/LES model, for indoor airflow simulations. The development simplified the v2f model by replacing the transport equations for $\overline{v'^2}$ and f with an algebraic equation for $\overline{v'^2}$.

The study tested the performance of the Semi-v2f/LES model by applying it to predicting mean and turbulence quantities in two indoor airflows. The first case was a mixed convection flow in a model room with typical indoor airflow features. The new model predicted the best turbulence kinetic energy results and comparable velocity and temperature results among several models tested. The second case was a strong buoyancy-driven flow in a room. The new model performed well in this case. It gave the best temperature prediction and is one of the best models for turbulence predictions.

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