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Numerical simulation of turbulent airflow in a room using the OpenFOAM package

Abstract. The results of numerical modeling of turbulent airflow in a room using the computational fluid dynamics approach to solve the Reynolds-averaged Navier-Stokes equation for a fluid are presented. First, a two-dimensional model was studied; the focus is on mesh refinement, the effect of mesh topology, and the influence of the turbulence model. The structured grid results were found to be in better agreement with available experimental measurements. Dimensionless velocities for various turbulence models are presented and compared: standard k- ϵ , standard k- ω , RNG k- ϵ , k- ω SST. The results explain that all turbulence models produce almost identical results.

Keywords: plain jet, turbulence models, RNG k- ϵ , k- ω SST, ventilation.

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Introduction

Air movement and the phenomenon of its transfer are very important characteristics of human thermal comfort. Speed is related to temperature distribution as well as turbulence levels. Thus, air velocity distribution plays a vital role in designing the interior condition of a room. This work is devoted to the study of the airflow model from the point of view of the distribution of speeds at different locations to compare the results of different turbulence models. Numerical simulations were carried out for the 2D model.

In recent years, when designing ventilation systems, computational fluid dynamics methods have increasingly been used, allowing for three-dimensional modeling of turbulent jet flows. In engineering practice, approaches that estimate flow parameters based on the numerical solution of Reynolds-averaged stationary or nonstationary Navier–Stokes equations have become widely used. Numerical simulations were carried out by solving Reynolds-averaged Navier-Stokes equations using OpenFOAM. In this research the results of a numerical simulation of turbulent air flow in a closed room using OpenFOAM.

Problem statement

The air flow in a room with dimensions of 3 m and 1 m, respectively, is considered. The geometry and computational mesh were created using the blockMesh utility in OpenFOAM. The pisoFoam solver was used for the simulations and post-processing was performed in Paraview.

The following turbulence models were used: Standard k- ϵ , Standard k- ω , RNG k- ϵ , k- ω SST. For this simulation, a 2D model of the room was used. On the front wall near the ceiling there is a natural ventilation slot with a slot height of $h = 0.056H$, and on the rear wall near the ground there is an open exit with a height of $h = 0.16H$. The Re number =5000 and depends on the inlet height, inlet velocity and ambient air conditions, so the flow is expected to have turbulent characteristics. Time-averaged results are confirmed by experimental results (Horikiri K et al., 2011; Akhmetov et al., 2021). The relationship between pressure and velocity was solved using the PISO algorithm (OpenFOAM 7.0 User’s Guide, 2022). The time and turbulent terms were discretized using Eulerian and constrained linear schemes, respectively (OpenFOAM 7.0 User’s Guide, 2022). Fig. 1 shows the number areas.

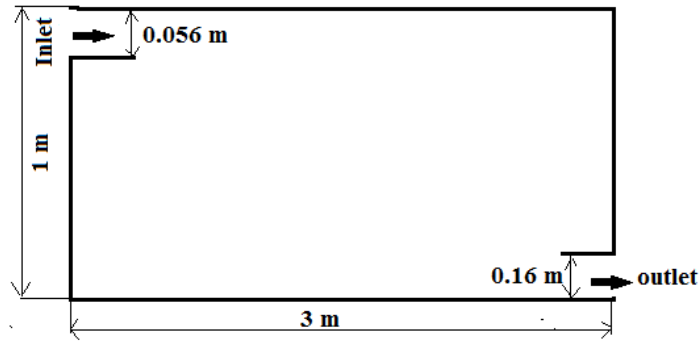


Figure 1. The geometry of the problem and boundaries of the domain

Initial and boundary conditions

We consider the isothermal movement of air described by a model of an incompressible fluid with constant physical properties: density $\rho=1.23 \text{ kg/m}^3$, dynamic viscosity $\mu= 1.79 \cdot 10^{-5} \text{ Pa}\cdot\text{s}$. Air is supplied to the entrance to the room at a speed of 1.3 m/s and air circulation is created inside the room. Soft boundary conditions were specified at the output boundary. The remaining boundaries of the computational domain are solid walls on which no-slip conditions were specified. For our problem, the boundary conditions are determined by a zero pressure gradient normal to the wall - zeroGradient. At all boundaries of the computational domain, it is necessary to set boundary conditions for the main variables.

The computational domain is discretized using the control volume method. This data must be specified in the fvSchemes and fvSolution files located in the system folder. In the fvSchemes file, it is necessary to indicate the selected discretization schemes for all terms of equation (1), as well as describe interpolation schemes for calculating fluxes through the faces of control volumes. In this case, to solve the SLAE, the PISO algorithm is used, in which it is necessary to indicate the number of internal corrections for the velocity and pressure fields. Information about the boundary conditions used in this work, the methods of discretization of the systems of equations (1-19), and the solution of the systems of linear algebraic equations are given in Table 1, Table 2, and Table 3, respectively.

Table1. The boundary conditions used

Variable Boundary	Velocity, m/s	Pressure, Pa	$k, \text{ m}^2/\text{s}^2$	$\omega, \text{ 1/s}$	$\epsilon, \text{ m}^2/\text{s}^3$
Inlet	fixedValue; uniform (1.3 0 0);	zeroGradient	fixedValue; uniform 0.006308284;	fixedValue; \$internalField;	fixedValue; uniform 0.020031953;
outlet	zeroGradient;	fixedValue; uniform 0;	zeroGradient	zeroGradient;	zeroGradient;
wall	noSlip;	zeroGradient	kqRWallFunction; uniform 0.006308284;	omegaWallFunction; \$internalField;	epsilonWallFunction; uniform 0.020031953;
Front and rear	empty	empty	empty	empty	empty

Table 2. Discretization schemes used

The term	Approximation scheme in the OpenFOAM package	The order of accuracy of the scheme
Gradient	cellLimitedGausslinear 1	Second
Divergence	bounded Gauss limitedLinear 1;	Second

Laplacian	Gauss linear corrected;	Second
Interpolation	linear	First

Table3. Solvers of equations for basic variables

Variable	Scheme	Accuracy
Pressure	GAMG resolver using a smoothing agent GaussSeidel	1e-6
U, k, ε, omega	smoothSolver resolver using a smoothing agent symGaussSeidel	1e-5

Mathematical model

The numerical method used here is based on the solution of the averaged Reynolds Navier-Stokes equations. In tensor notation, the equation for incompressible fluid flows can be written as follows (Ferziger J H and Peric M):

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\rho \frac{\partial u_i}{\partial t} + \frac{\partial(u_i u_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \frac{\partial}{\partial x_j} \left(-\rho \overline{u_i' u_j'} \right) \quad (2)$$

Turbulence model

1. k – ε model. The most popular model with two differential equations is the k-ε model proposed by (Chow, 1945) and further developed in the studies of (Launder-Jones,1972).

The equation for the kinetic energy of turbulence is:

$$\rho \frac{\partial k}{\partial t} + \rho \overline{u_j} \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial \overline{u_i}}{\partial x_j} - \rho \varepsilon + \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \quad (1)$$

Equation for specific dissipation rate:

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho \overline{u_j} \frac{\partial \varepsilon}{\partial x_j} = c_{\varepsilon 1} \frac{\varepsilon}{k} \tau_{ij} \frac{\partial \overline{u_i}}{\partial x_j} - c_{\varepsilon 2} \frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] \quad (2)$$

The kinematic eddy viscosity is calculated by the formula: $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$ (3)

Turbulent Reynolds stresses (4)

$$\tau_{ij} = -\rho \overline{u_i' u_j'} = \rho \mu_t \left(\frac{\partial \overline{u_i}}{\partial x_j} - \frac{\partial \overline{u_j}}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij}$$

Model constants:

$$c_{\varepsilon 1} = 1.44; \quad c_{\varepsilon 2} = 1.92; \quad C_\mu = 0.09; \quad \sigma_k = 1.0; \quad \sigma_\varepsilon = 1.3.$$

2. k – ω model. Below is the basic two-layer model of (Menter, 1993):

The equation for the kinetic energy of turbulence is:

$$\rho \frac{\partial k}{\partial t} + \rho \overline{u_j} \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial \overline{u_i}}{\partial x_j} - \beta^* \rho k \omega + \frac{\partial}{\partial x_j} \left[\left(\mu + \sigma_k \mu_t \right) \frac{\partial k}{\partial x_j} \right] \quad (5)$$

Equation for specific dissipation rate:

$$\rho \frac{\partial \omega}{\partial t} + \rho \bar{u}_j \frac{\partial \omega}{\partial x_j} = \gamma \frac{\omega}{k} \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (6)$$

The dynamic eddy viscosity is calculated by the formula:

$$\mu_t = \rho \frac{k}{\omega} \quad (7)$$

Turbulent Reynolds stresses

$$\tau_{ij} = -\rho \overline{u_i' u_j'} = \rho \mu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} - \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \quad (8)$$

$$\beta^* = 0.09; \quad \beta_1 = 0.075; \quad \sigma_{k1} = 0.5; \quad \sigma_{\omega 1} = 0.5;$$

3. k – ω SST model. To summarize the model equations of the k-ω SST model are:

The equation for the kinetic energy of turbulence is:

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_k \nu_T) \frac{\partial k}{\partial x_j} \right] \quad (9)$$

Equation for specific dissipation rate:

$$\frac{\partial \omega}{\partial t} + u_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_\omega \nu_T) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (10)$$

Kinematic eddy viscosity:

$$\nu_T = \frac{\alpha_1 k}{\max(\alpha_1 \omega, S F_2)} \quad (11)$$

The coefficients and additional ratios of the model are equal:

$$F_2 = \tanh \left[\left[\max \left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right) \right]^2 \right] \quad (12)$$

$$P_k = \min \left(\tau_{ij} \frac{\partial U_i}{\partial x_j}, 10 \beta^* k \omega \right) \quad (13)$$

$$F_1 = \tanh \left\{ \left\{ \min \left[\max \left(\frac{\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega} \right), \frac{4\sigma_{\omega 2} k}{C D_{k\omega} y^2} \right] \right\}^4 \right\} \quad (14)$$

$$C D_{k\omega} = \max \left(2\rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}, 10^{-10} \right) \quad (15)$$

$$\phi = \phi_1 F_1 + \phi_2 (1 - F_1) \quad (16)$$

$$\alpha_1 = \frac{5}{9}, \quad \alpha_2 = 0.44 \quad \beta_1 = \frac{3}{40}, \quad \beta_2 = 0.0828 \quad (17)$$

$$\beta^* = \frac{9}{100}, \quad \sigma_{k1} = 0.85 \quad \sigma_{k2} = 1 \quad \sigma_{\omega 1} = 0.5 \quad \sigma_{\omega 2} = 0.856$$

4. RNG k – ε model. A more modern version of the k-ε model turbulence was proposed in works (Launder-Jones,1972; Menter, 1993). This model uses the same equations (1–2) as the standard k-ε turbulence model, but with different coefficients:

$$C_\mu = 0.085; \quad C_{\varepsilon 1} = 1.42; \quad \widetilde{C}_{\varepsilon 2} = 1.68; \quad \sigma_k = 0.72; \quad \sigma_\varepsilon = 0.72. \quad (18)$$

$$C_{\varepsilon 2} = \widetilde{C}_{\varepsilon 2} + \frac{C_{\mu} \lambda^3 (1 - \frac{\lambda}{\lambda_0})}{1 + \beta \lambda^3}; \quad \lambda = \frac{k}{\varepsilon} \sqrt{2 S_{ij} S_{ji}}; \quad \beta = 0.012; \quad \lambda_0 = 4.38 \quad (19)$$

Results and discussion

The structure of the flow in the room is shown in Fig. 2, which shows the velocity modulus fields in several sections of the room. As shown, the inlet flow is sucked into the chamber and curved toward the ground. The calculations determined the longitudinal velocity profile (u) along the vertical axis at two points 1H and 2H, and a previous computational study was also performed by (Zuo and Chen, 2009).

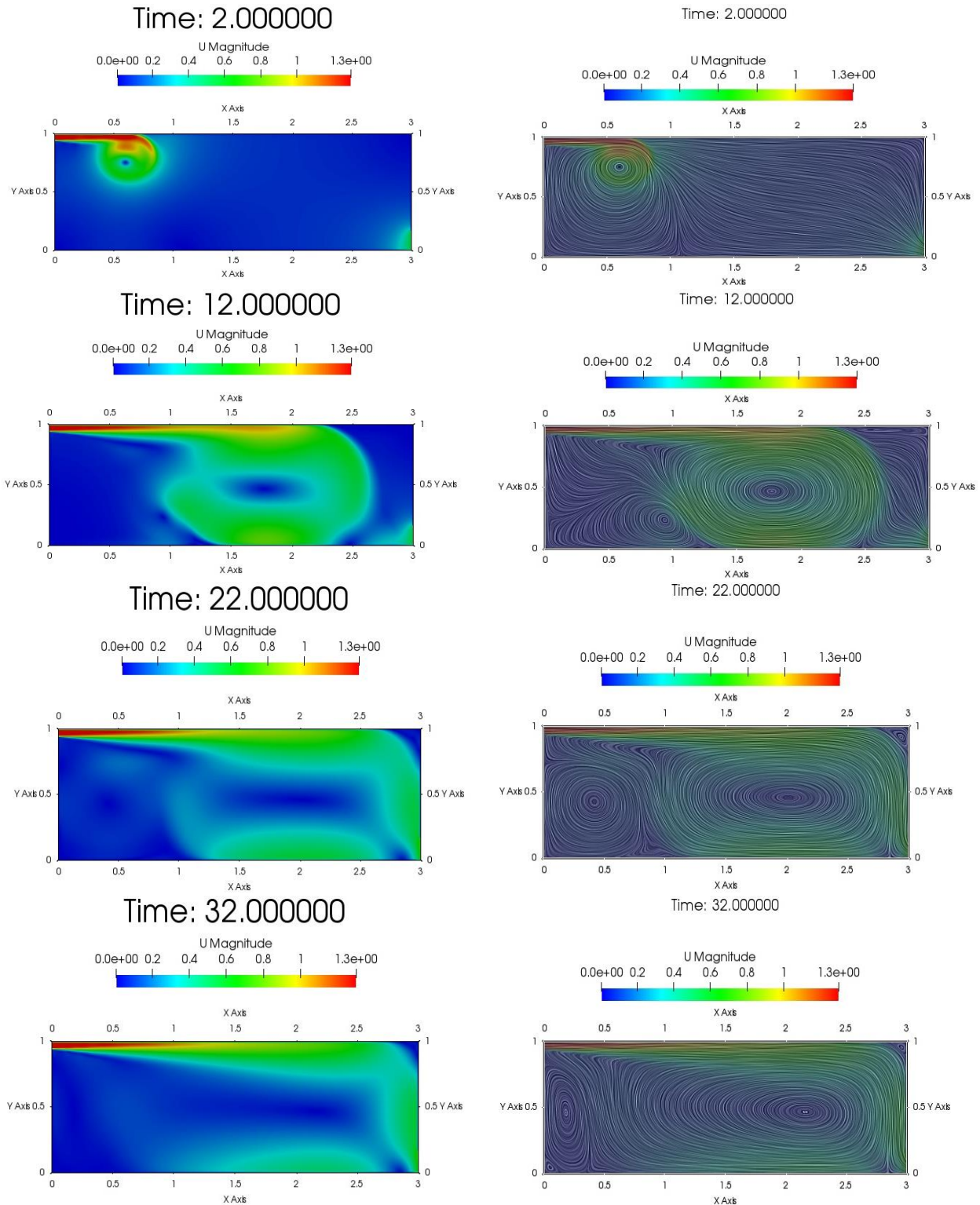


Figure 2. Longitudinal velocity profile (u) along the vertical axis

Near the ceiling, a wall-mounted turbulent air stream develops, which is almost symmetrical relative to the middle section of the room. As the jet propagates from the inlet to the opposite wall, the velocity value decreases by approximately half. After colliding with the opposite wall, the jet turns around and a secondary flow is formed in the lower part of the room with a speed of less than 0.1 m/s.

In ventilation, the entrance and exit are located in opposite side walls. The entrance is located in the upper left corner on the side wall at $z = 6$ m. The exit hole is in the lower right corner. Contaminated air is pumped out of the outlet at a uniform speed of 1 m/s.

As shown in Fig.3, all turbulence models give very close results to experimental data in a 2D model. Within these outputs, the standard k- ω and SST results differ slightly from the other results.

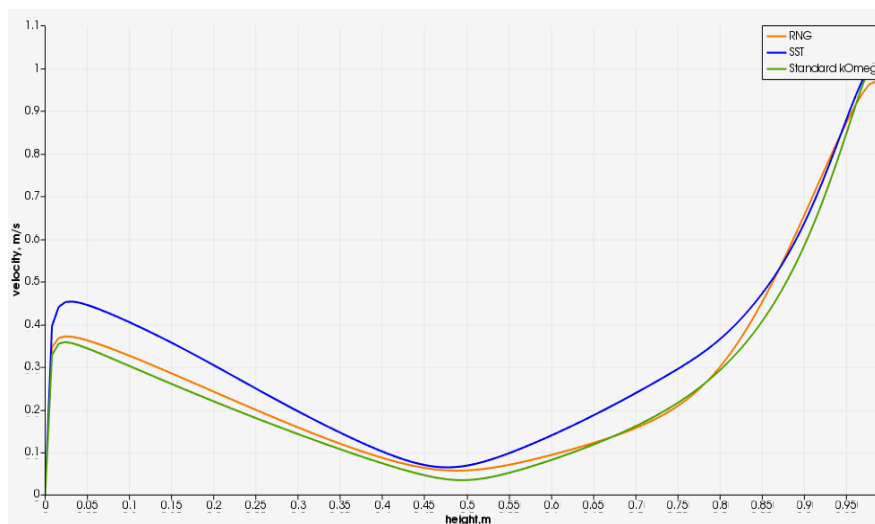


Figure 3. Dimensionless velocity distribution

Conclusions

Numerical modeling of turbulent air flow in a room was carried out using the OpenFOAM package and the presented results are in good agreement with available experimental measurements. Dimensionless velocities for different turbulence models are compared: Standard k- ϵ , standard k- ω , RNG k- ϵ , k- ω SST. The results explain that all turbulence models produce almost identical results.

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