Air Flow Analysis in an Empty Room using OpenFOAM

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Abstract

Forced convective flow of air inside an empty room was numerically studied. The non-dimensional velocities are presented and compared for different turbulence models; Standard k- ϵ, Standard k-ω, RNG k- ϵ, k-ω SST and v^2f. The results explain that all the turbulence models provide nearly similar results.

Keywords: k- ϵ, k-ω, RNG, SST, v^2f

Nomenclature

k	Turbulent kinetic energy
RNG	ReNormalization Group
SST	Shear Stress Transport
v^2	Velocity fluctuation normal to the streamlines
f	Elliptic relaxation function
PISO	Pressure-Implicit with Splitting of Operators
2D	2-Dimensional
3D	3-Dimensional
u	Fluid velocity
G	Generation of k
Y_M	Compressibility effect on the turbulence
S	Source term
i, j, k	Indices
L_t	Turbulent length scale
$\overline{u'_i\, u'_j}$	Reynolds stresses

Greek Symbols

ϵ	Energy dissipation rate
ω	Specific dissipation
ρ	Density
μ	Dynamic viscosity
ν	Kinematic viscosity
μ_T	Turbulence viscosity or, Eddy viscosity
μ_{eff}	Effective viscosity

Notations

∂/∂t	Partial time derivative
∂/∂x	Partial positional derivative

Non-dimensional Numbers

Re_{in}	Reynolds number based on air inlet

1. Introduction

Air movement and its transport phenomenon are very important characteristics concerning human thermal comfort. Velocity is related to temperature distributions as well as turbulence levels. Hence, air velocity distribution plays a vital role to design indoor condition of a room.

The current work covers the study of forced convective air flow pattern in terms of velocity distributions at different locations to compare the various turbulence models outcomes. The numerical studies were carried out for both 2D and 3D models.

2. Problem Statement and Computational Technique

The geometries and uniform mesh were created using *blockMesh* utility in OpenFOAM. *pisoFoam* solver was used for the simulation and, post-processing was completed in *Paraview* along with *Sigma Plot*. The turbulence models applied were *Standard k- ϵ, Standard k-ω, RNG k- ϵ, k-ω SST* and *v^2f*. Primarily, a 2D model of empty room was used for this investigation. The length and height of 2D room were 3m and 1m respectively. Air inlet = 0.056m and outlet = 0.16m were taken for the computation. Re_{in} was considered as 5000. The time averaged results are validated with the experimental results [1]. Later, the simulation was carried out for a 3D room model with length = width = height = 2.44 m. The air inlet = 0.03 m and outlet = 0.08 m. The pressure and velocity coupling were solved by *PISO* algorithm [2]. The time and turbulent terms were discretized by using *Eulerian* and *limitedLinear* schemes respectively [2]. Fig.1. and Fig.2. show the numerical domains.

Number of cells in 2D model = *46,875*

Number of cells in 3D model = *3,05,122*

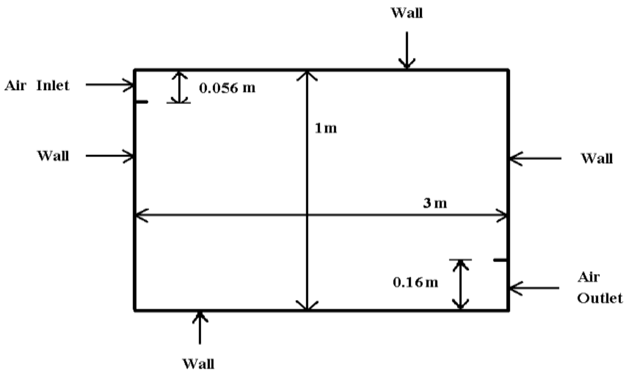

Fig. 1. 2D numerical domain

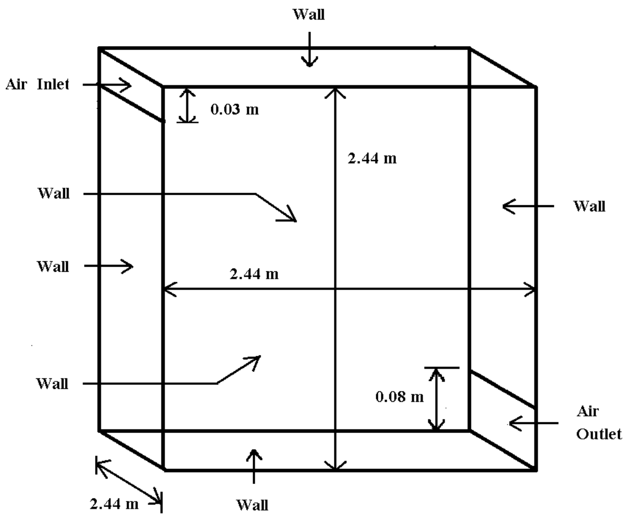

Fig. 2. 3D numerical domain

Table 1. Parameters for the Simulation

Parameter	***Value***
Density	1.225 kg/m^3
nu	1e-05
mu	1.78e-05
Re$_{in}$	5000
Outlet Pressure	0 pa
2D Inlet Velocity	1.30 m/sec
3D Inlet Velocity	1.20 m/sec
Time Step	0.005 sec
Total Time	50 sec

3. Turbulence Equations

3.1. Standard $k-\epsilon$

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial xi}(\rho k u_i)=\frac{\partial}{\partial xj}\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\frac{\partial k}{\partial xj}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \quad (1)$$

Eq (1) is the k transport equation of Standard $k-\epsilon$ model

And,

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial xi}(\rho\varepsilon u_i)=\frac{\partial}{\partial xj}\left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial xj}\right] +C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \quad (2)$$

Eq (2) is the ϵ transport equation of Standard $k-\epsilon$ model

Where,

$$G_k=-\rho\overline{u_i'u_j'}\frac{\partial uj}{\partial xi},\ \mu_T=\rho C_\mu\frac{k^2}{\varepsilon}$$

$$Y_M=2\rho\varepsilon {M_t}^2 \quad \text{and} \quad M_t=\sqrt{\frac{V}{\gamma RT}}$$

The coefficients C_μ, $C_{1\epsilon}$, $C_{2\epsilon}$, σ_k and σ_ϵ are

$$C_\mu=0.09, C_{1\epsilon}=1.44, C_{2\epsilon}=1.92, \sigma_k=1.0, \sigma_\epsilon=1.3$$

3.2. RNG $k-\epsilon$

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial xi}(\rho k u_i)=\frac{\partial}{\partial xj}\left(\alpha_k\mu_{eff}\frac{\partial k}{\partial xj}\right) +G_k+G_b-\rho\varepsilon-Y_M+S_k \quad (3)$$

Eq (3) is the k transport equation of RNG $k-\epsilon$ model

And,

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial xi}(\rho\varepsilon u_i)=\frac{\partial}{\partial xj}(\alpha_k\mu_{eff}\frac{\partial\varepsilon}{\partial xj}+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b) -C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon \quad (4)$$

Eq (4) is the ϵ transport equation of RNG $k-\epsilon$ model

Where,

$$C_{2\varepsilon}^*=C_{2\varepsilon}+\frac{C_\mu\eta^3\left(1-\frac{\eta}{\eta_0}\right)}{1+\beta\eta^3}$$

$$\eta=\frac{Sk}{\varepsilon}, S=\sqrt{2S_{ij}S_{ij}}$$

The default values of the model constants are

$C_\mu = 0.09, C_{1\epsilon} = 1.42, C_{2\epsilon} = 1.68,$

$\sigma_k = 0.7194,\ \sigma_\epsilon = 0.7194, \eta_0 = 4.38, \beta = 0.012$

3.3. Standard $k-\omega$

$$\frac{\partial}{\partial x_i}(ku_i) = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\left(\mu + \sigma^* \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \frac{1}{\rho}G_k - \beta^* k\omega \quad (5)$$

Eq (5) is the k transport equation of Standard $k-\omega$ model

$$\frac{\partial}{\partial x_i}(\omega u_i) = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\left(\mu + \sigma^* \frac{\mu_t}{\sigma_k}\right)\frac{\partial \omega}{\partial x_j}\right] + \gamma\frac{\omega}{k}\frac{1}{\rho}G_k - \beta^*\omega^2 \quad (6)$$

Eq (6) is the ω transport equation of Standard $k-\omega$ model

Turbulent viscosity is defined as,

$$\mu_t = \rho\frac{k}{\omega}$$

The values of coefficients are $\beta^* = 0.09$, $\beta = 3/40$, $\gamma = 5/9$, $\sigma^* = 1/2$, $\sigma = 1/2$

3.4. SST $k-\omega$

$$\rho\frac{\partial k}{\partial t} + \rho u_i\frac{\partial k}{\partial x_i} = \tilde{\tilde{P}}_k - \beta^*\rho k\omega + \frac{\partial}{\partial x_i}\left[(\mu + \sigma_k\mu_T)\frac{\partial k}{\partial x_i}\right] \quad (7)$$

Eq (7) is the k transport equation of SST $k-\omega$ model

$$\rho\frac{\partial \omega}{\partial t} + \rho u_i\frac{\partial \omega}{\partial x_i} = \alpha\rho S^2 - \beta\rho\omega^2 + \frac{\partial}{\partial x_i}\left[(\mu + \sigma_\omega\mu_T)\frac{\partial \omega}{\partial x_i}\right]$$
$$+2(1-F_1)\rho\sigma\omega_2\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \quad (8)$$

Eq (8) is the ω transport equation of SST $k-\omega$ model

The blending function F_1 is,

$$F_1 = \tanh\left\{\left\{\min\left[\max\left(\frac{\sqrt{k}}{\beta^*\omega y}, \frac{500\mu}{y^2\omega}\right), \frac{4\rho\sigma_{\omega 2}k}{CD_{k\omega}y^2}\right]\right\}^4\right\}$$

Where,

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

Another blending function F_2 is,

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

The turbulence viscosity will be,

$$\mu_t = \frac{a_1 k}{\max(a_1\omega, SF_2)}$$

The production limiter used to prevent the build-up of turbulence in the stagnation region which is,

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

And,

$$\tilde{\tilde{P}}_k = \min(P_k, 10\beta^*\rho k\omega)$$

The SST model constants are,

$\alpha_1 = \frac{5}{9}, \beta^* = 0.09, \beta_1 = \frac{3}{40}, \alpha_{k1} = 0.85, \alpha_2 = 0.44,$

$\beta_2 = 0.0828, \alpha_{k2} = 1, \alpha_{w2} = 0.856$

3.5. $\mathbf{v^2}\boldsymbol{f}$

$$\frac{\partial k}{\partial t} + u_j\frac{\partial k}{\partial x_j} = P_k - \varepsilon + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \quad (9)$$

Eq (9) is the k transport equation of v^2f model

$$\frac{\partial \varepsilon}{\partial t} + u_j\frac{\partial \varepsilon}{\partial x_j} = \frac{C_{\varepsilon 1}P_k - C_{\varepsilon 2}\varepsilon}{T_t} + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] \quad (10)$$

Eq (10) is the ϵ transport equation of v^2f model

$$\frac{\partial \overline{v'^2}}{\partial t} + u_j\frac{\partial \overline{v'^2}}{\partial x_j} = kf - \overline{v'^2}\frac{\varepsilon}{k} + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial \overline{v'^2}}{\partial x_j}\right] \quad (11)$$

Eq (11) is the v^2 transport equation of v^2f model

$$L_t^{\,2}\frac{\partial^2 f}{\partial x_j^{\,2}} - f = \frac{1}{T_t}(C_1 - 1)\left[\frac{\overline{v'^2}}{k} - \frac{2}{3}\right] - C_2\frac{P_k}{k} \quad (12)$$

Eq (12) is the f transport equation of v^2f model

Where, $\mu_T = C_\mu\overline{v'^2}T_t$

To prevent $1/T_t$ becoming infinite at the wall;

$$T_t = \min\left[\max\left[\frac{k}{\varepsilon}, 6\sqrt{\frac{\nu}{\varepsilon}}\right], \frac{0.6k}{\sqrt{6}C_\mu\overline{v^2}s}\right]$$

Where, $s = \sqrt{s_{ij}s_{ij}}$ for $s_{ij} = 0.5\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$

$P_k = -\overline{u_i'u_j'}\frac{\partial u_i}{\partial x_j}$ and

$$L_t = C_L \max\left[\min\left[\frac{k^{3/2}}{\varepsilon}, \frac{k^{3/2}}{\sqrt{6}C_\mu \overline{v^2} S}\right], C_\eta \frac{\nu^{3/4}}{\varepsilon^{1/4}}\right]$$

The coefficients used in the original v2f model are,

$C_1 = 1.4, C_2 = 0.3, C_L = 0.3, C_\eta = 70,$

$C_\mu = 0.19, \sigma_k = 1, \sigma_\varepsilon = 1.3, C_{\varepsilon 2} = 1.9,$

$C_{\varepsilon 1} = 1.3 + 0.25/[1 + (C_L d/2L)^2]^4$

Where d = distance to the wall.

4. Results

4.1. 2-Dimensional

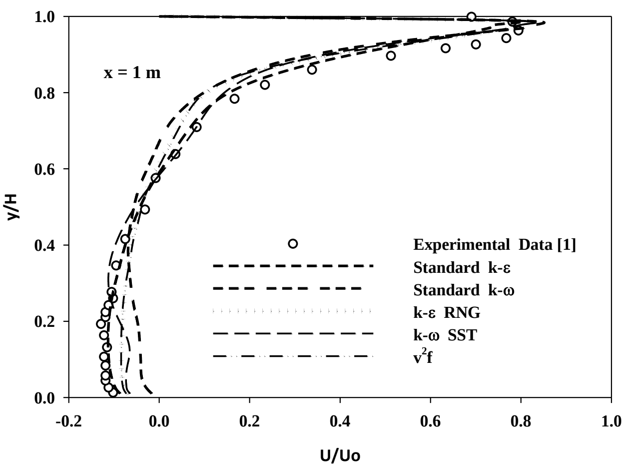

Fig. 3. Non-dimensional velocity distribution at x = 1m

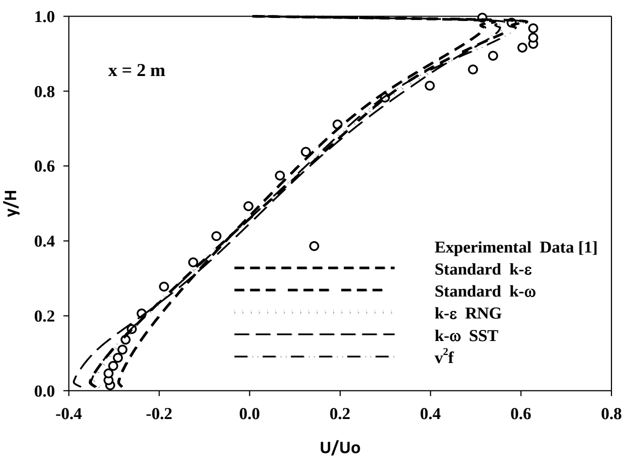

Fig. 4. Non-dimensional velocity distribution at x = 2m

All the turbulence models provide very close results to the experimental data in 2D model. Within those outputs, Standard *k-ω* and *SST* results marginally vary from the other results.

4.1. 3-Dimensional

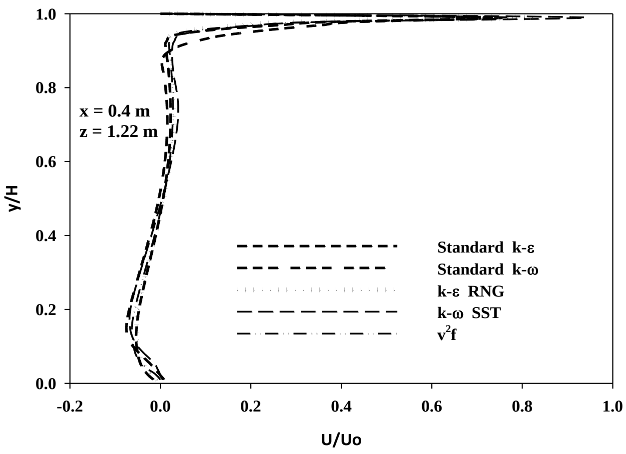

Fig. 5. Non-dimensional velocity distribution at x = 0.4m, z = 1.22m

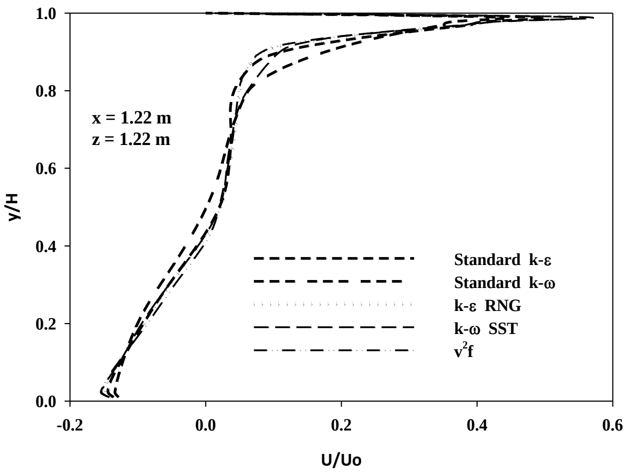

Fig. 6. Non-dimensional velocity distribution at x = 1.22m, z = 1.22m

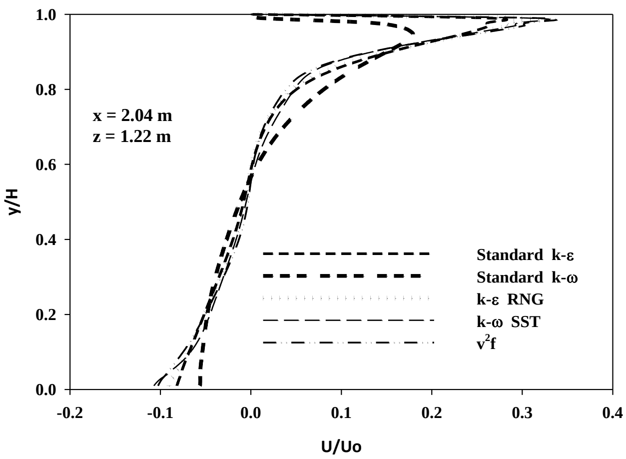

Fig. 7. Non-dimensional velocity distribution at x = 2.04m, z = 1.22m

Again, in 3D model the Standard *k-ω* results deviate from the other turbulence models.

5. Contours

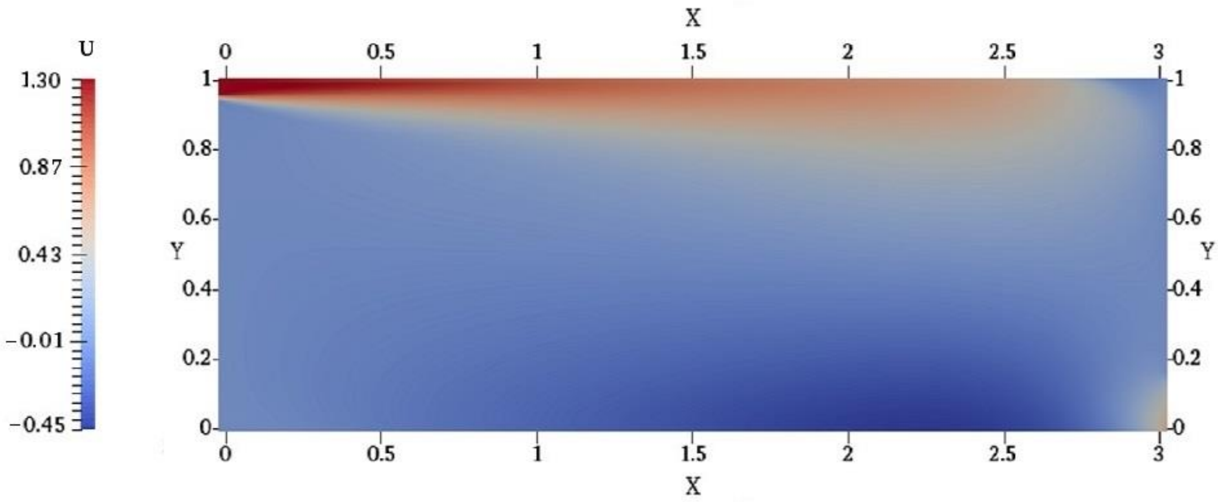

Fig. 8. Velocity contour in 2D model

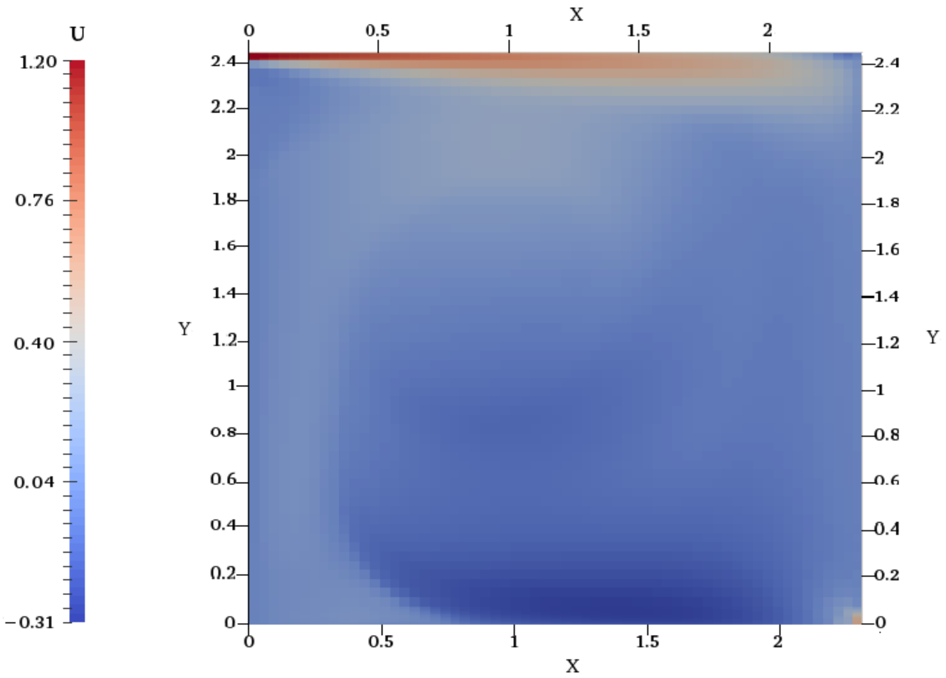

Fig. 9. Velocity contour in 3D model

References

[1] Horikiri K., Yao Y., Yao J., Numerical Simulation of Convective Airflow in an Empty Room, International Journal of Energy and Environment, vol. 5, issue 4, 2011

[2] OpenFOAM User Guide version 6.0 (2018)