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TURBULENCE MODEL AND VALIDATION OF AIR FLOW IN WIND TUNNEL

Gun Gun Ramdlan G.[1,2*], Ahmad Indra Siswantara[1], Budiarso[1], Asyari Daryus[1,3], Hariyotejo Pujowidodo[1]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia*
[2]*Department of Mechanical Engineering, Politeknik Negeri Jakarta, Depok 16424, Indonesia*
[3]*Department of Mechanical Engineering, Universitas Darma Persada, Jl. Radin Inten, Pondok Kelapa, Jakarta 13450, Indonesia*

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ABSTRACT

As an initial analysis, numerical simulation has more advantages in saving time and costs regarding experiments. For example, variations in flow conditions and geometry can be adjusted easily to obtain results. Computational fluid dynamics (CFD) methods, such as the k-ε model, renormalization group (RNG) k-ε model and reynolds stress model (RSM), are widely used to conduct research on different objects and conditions. Choosing the appropriate model helps produce and develop constant values. Modeling studies as appropriate, i.e., in the turbulent flow simulation in the wind tunnel, is done to get a more accurate result. This study was conducted by comparing the results of the simulation k-ε model, RNG k-ε model and RSM, which is validated by the test results. The air had a density of 1,205 kg/m^3, a viscosity of 4×10^{-5} m^2/s and a normal speed of 6 m/s. By comparing the simulation results of the k-ε model, RNG k-ε model and RSM, which is validated by the test results, the third turbulence model provided good results to predict the distribution of speed and pressure of the fluid flow in the wind tunnel. As for predicting the turbulent kinetic energy, turbulent dissipation rate and turbulent effective viscosity, the k-ε model was effectively used with comparable results to the RSM models.

Keywords: k-ε model; Reynolds Stress Model (RSM); RNG k-ε model; Turbulent flow; Turbulence Model

1. INTRODUCTION

Turbulence model simulation eliminates facilities' need for experimental equipment that is expensive and time consuming, as flow phenomena can be quickly obtained to save time and money. Many turbulence models have been developed, including those models in the group RANS (Reynolds averaged Navier-Stokes equation). The most popular and widely used turbulence models are the standard (STD) k-ε, renormalization group (RNG) k-ε and reynolds stress model (RSM). The STD k-ε turbulence model, also called the k-ε turbulence model, is a simple model which only requires the input of boundary conditions, is mostly used for engineering analysis in industry and is stable and widely validated (Versteeg & Malalasekera, 1995). However, despite its advantages, the STD k-ε model also has drawbacks, such as a lack of good results when used for a flow simulation that is not walled, flow with large strain, rotational flow and flow-developed in a non-circular channel (Versteeg & Malalasekera, 1995).

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*Corresponding author's email: gungun.rg@mesin.pnj.ac.id, Tel. +6281-21464153, Fax. +62-21-7270034
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The RNG k-ε turbulence model, which is the improved STD k-ε turbulence model, is also used in modeling (Mohammadi & Pironneau, 1994). Based on the renormalization group (RNG) statistical theory developed by Yakhot and Orszag, this model enters some additional equations into the STD k-ε model, such as additional terms in the equation ε, the effect of swirl in the turbulence, formula analytics for Prandtl turbulent numbers and the formula differential for effective viscosity, thereby increasing the predicted values for some types of flow, such as a stream with streamline curvature and high strain rate, a transition flow, a flow separation, a wall of heat and mass transfer and a time-dependent flow with a large eddy motion. The weakness of this model is that it is still not able to estimate the round jet bursts exactly.

The RSM turbulence model is the most complete model in the group of RANS, which has the advantage that it only needs to input the initial conditions and/or boundary conditions and is very accurate for all Reynolds strains from simple to complex flows (Versteeg & Malalasekera, 1995). However, this model's weaknesses are: (1) it has a very large cost calculation for modeling more complex calculations that take longer; (2) it is not validated widely; and (3) in some types of flows, such as jet asymmetric flow and recirculation flow without limits, it gives poor results (Versteeg & Malalasekera, 1995).

This paper will discuss the comparison of different turbulence models in analyzing the nature or characteristics of flow in a wind tunnel with the help of CFD simulations. The models used are the STD k-ε, RNG k-ε and RSM turbulence models.

2. METHODS

2.1. Turbulence Models

This paper used three turbulence models: the standard (STD) k-ε, the renormalization group (RNG) k-ε and the Renoldys Stress Model (RSM). The RSM model is the model with the most complex equation, which indicates that its simulation results are the most thorough, followed by the RNG k-ε and STD k-ε models.

The STD k-ε turbulence model has two additional transport equations for turbulent flow; the kinetic energy transport equation (*k*), and the dissipation transport equation (ε). Transport equation *k* is given by the Equation 1 and transport equation *ε* is given by the Equation 2 (Versteeg & Malalasekera, 1995).

$$\frac{\partial(\rho k)}{\partial t} + div\,(\rho\, k\mathbf{U}) = div\left[\frac{\mu_t}{\sigma_k}\, grad\; k\right] + 2\mu_t E_{ij}.E_{ij} - \rho\varepsilon \tag{1}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + div\,(\rho\varepsilon\,\mathbf{U}) = div\left[\frac{\mu_t}{\sigma_\varepsilon}\, grad\;\;\varepsilon\right] + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t\, E_{ij}.E_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{2}$$

where:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{3}$$

ρ is density, **U** is the velocity vector, μ_t is the viscosity eddy and E_{ij} Eij is the average speed of deformation. If *i* or *j* = 1, it relates to the x-direction; if *i* or *j* = 2, it relates to the y-direction; and if *i* or *j* = 3, it relates to the z-direction. C_μ, σ_k, σ_ε, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants.

The RNG *k-ε* turbulence model also has two additional transport equations; the kinetic energy transport equation, *k*, and the transport equation dissipation, ε. Transport equation *k* is given by the Equation 4 and transport equation ε is given by the Equation 5 (Yakhot et al., 1992).

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k-\rho\varepsilon \tag{4}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}P_k-C_{2\varepsilon}^{*}\rho\frac{\varepsilon^2}{k} \tag{5}$$

where;

$$P_k=-\rho\overline{u'_i\,u'_j}\,\frac{\partial u_j}{\partial x_i} \tag{6}$$

$$C_{2\varepsilon}^{*}=C_{2\varepsilon}+\frac{C_\mu\eta^3(1-\eta/\eta_0)}{1+\beta\eta^3} \tag{7}$$

$\eta=Sk/\varepsilon$ and $S=(2S_{ij}S_{ij})^{1/2}$

S is the average rate of strain, and C_μ, σ_k, σ_ε, $C_{1\varepsilon}$, $C_{2\varepsilon}$, η_0 and β are constants.

The RSM turbulence model uses the transport equation, R_{ij}, by the equation $R_{ij}=-\tau_{ij}/\rho=\overline{u'_i\,u'_j}$ (also called Kinematic Reynolds Stress), which calculates the individual Reynolds Stress. The exact equation for transport R_{ij} by the Equation 8 (Versteeg & Malalasekera, 1995).

$$\frac{DR_{ij}}{Dt}=P_{ij}+D_{ij}-\varepsilon_{ij}+\Pi_{ij}+\Omega_{ij} \tag{8}$$

where P_{ij} is the rate of production, D_{ij} is the diffusion transport, ε_{ij} is the rate of dissipation, Π_{ij} is the transport turbulent interaction of the stress-strain and Ω_{ij} is the transport rotation.

2.2. Geometry

Figure 1 shows a sketch and construction of the wind tunnel, which has a length of 1.025 m, a height of 0.306 m and a width of 0.306 m. The wind tunnel inlets ambient air at a speed of 6 m/s.

Figure 1 Wind tunnel

2.3. Meshing

A 3-dimensional model was used for the simulation. The grid was created with the same software that was used for the calculation of the simulation, which is CFDSOF(r).

The grid used was a type of structured cell with dimensions 100×30×15 (The boundary conditions were taken from data on wind tunnel experiments located in the Fluid Mechanics Laboratory, Department of Mechanical Engineering, Faculty of Engineering, University of Indonesia. Incoming air speed in the wind tunnel was 6 m/s, assuming a 10% turbulence intensity.). In the wall and middle areas of the x-axis, the grid's aim was refined to obtain more accurate simulation results.

Dependence on the grid was tested on various dimensions of the grid, namely the cells with sizes 100×30×15, 100×40×20 and 100×60×30, where the test results have been consistent not influenced by the size of the grid.

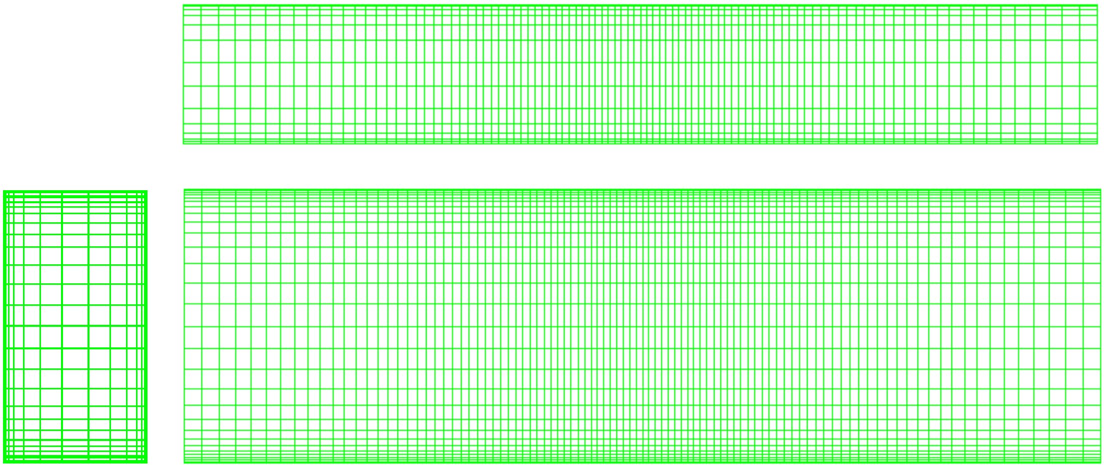

Figure 2 Wind tunnel geometry with a 3-dimensional grid

2.4. Boundary Conditions

The boundary conditions were taken from data on wind tunnel experiments located in the Fluid Mechanics Laboratory, Department of Mechanical Engineering, Faculty of Engineering, University of Indonesia. Incoming air speed in the wind tunnel was 6 m/s, assuming a 10% turbulence intensity.

3. RESULTS AND DISCUSSION

Figure 3 and Figure 4 show the average pressure simulation results for STD k-ε, RNG k-ε and RSM turbulence models on the entrance and exit sides, the pressure drop simulation results for STD k-ε, RNG k-ε and RSM turbulence models and the test results.

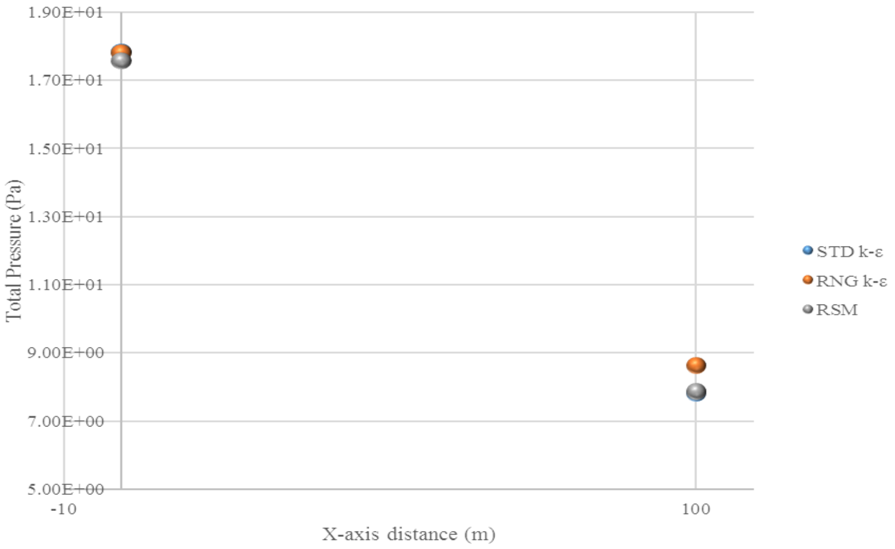

Figure 3 Pressure in and out of wind tunnel

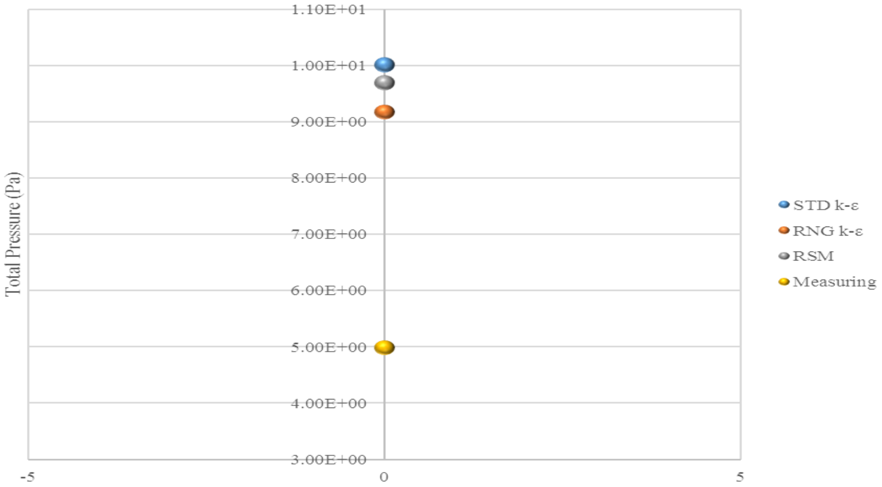

Figure 4 Pressure drop

Figure 5 shows the curve of the magnitude velocity versus the distance along position-I = 50 and position-K = 7 wind tunnel for the three types of turbulence models. All three models provided identical results where you see the three curves coincide, indicating that the type of turbulence model does not have a significant influence on the simulation results.

The same result was obtained for the total pressure curve, as can be seen in Figure 6, where the three turbulence models gave identical results. Again, this indicates that the type of turbulence model does not have a significant influence on the total pressure curve.

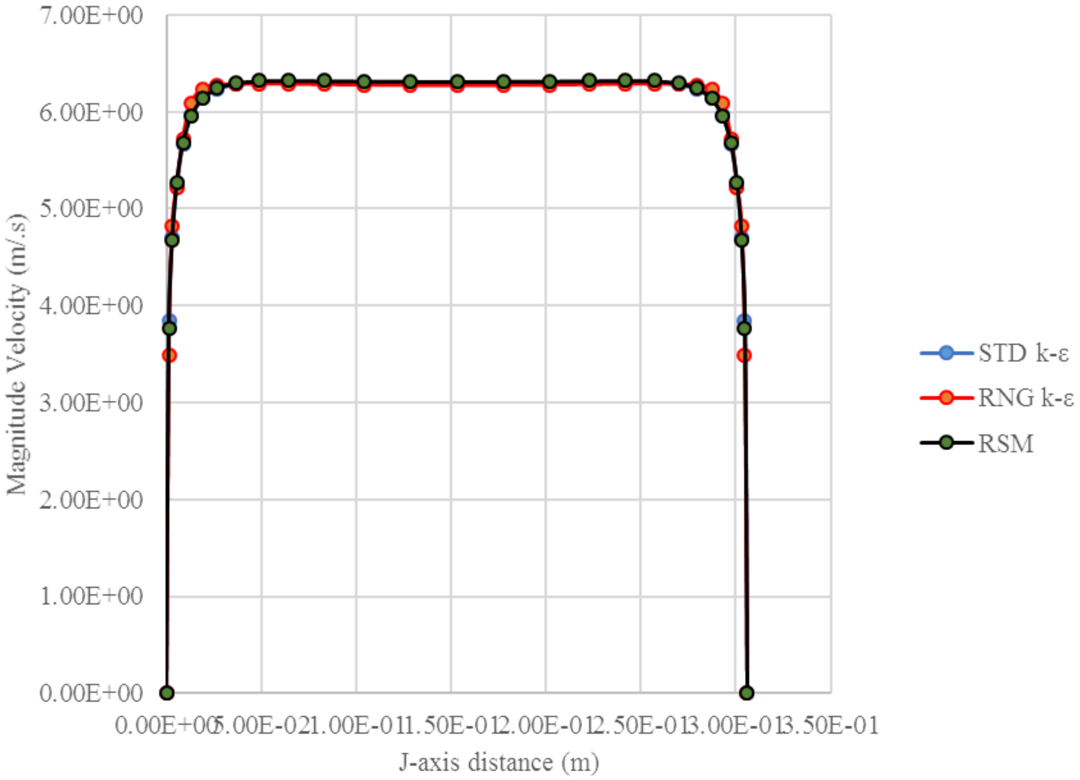

Figure 5 Magnitude velocity curve along position-I = 50 and position-K = 7

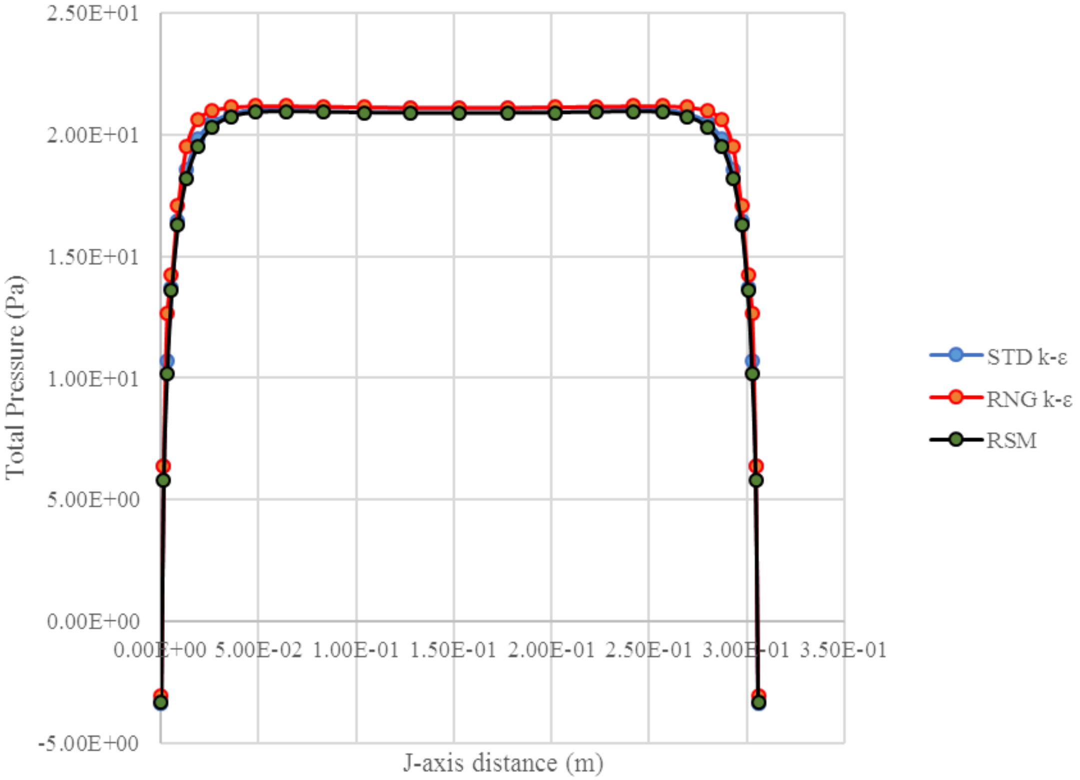

Figure 6 Total pressure curve along position-I = 50 and position-K = 7

The simulation results for magnitude velocity and total pressure contour were also identical for all three turbulence models, which complements the plot curve magnitude velocity and total pressure results. Figure 7 and Figure 8 provide these simulation results. Two types of turbulence models are not shown because they had an identical contour shape.

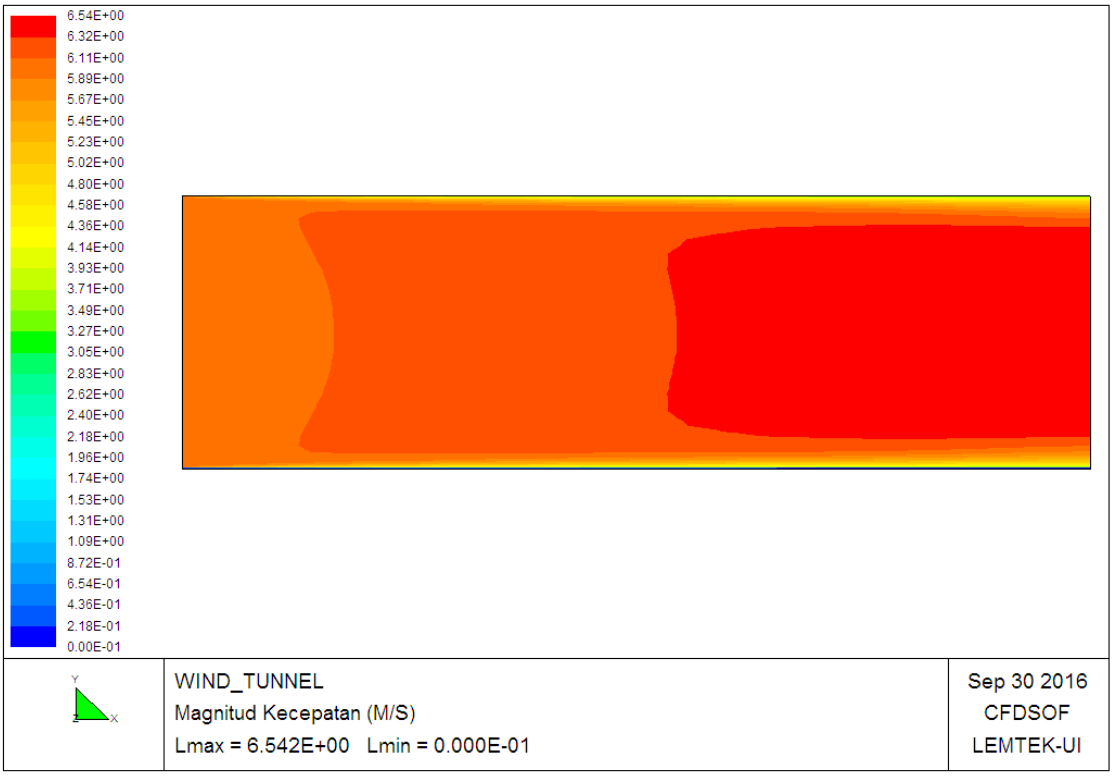

Figure 7 Magnitude velocity contour for position-K = 7

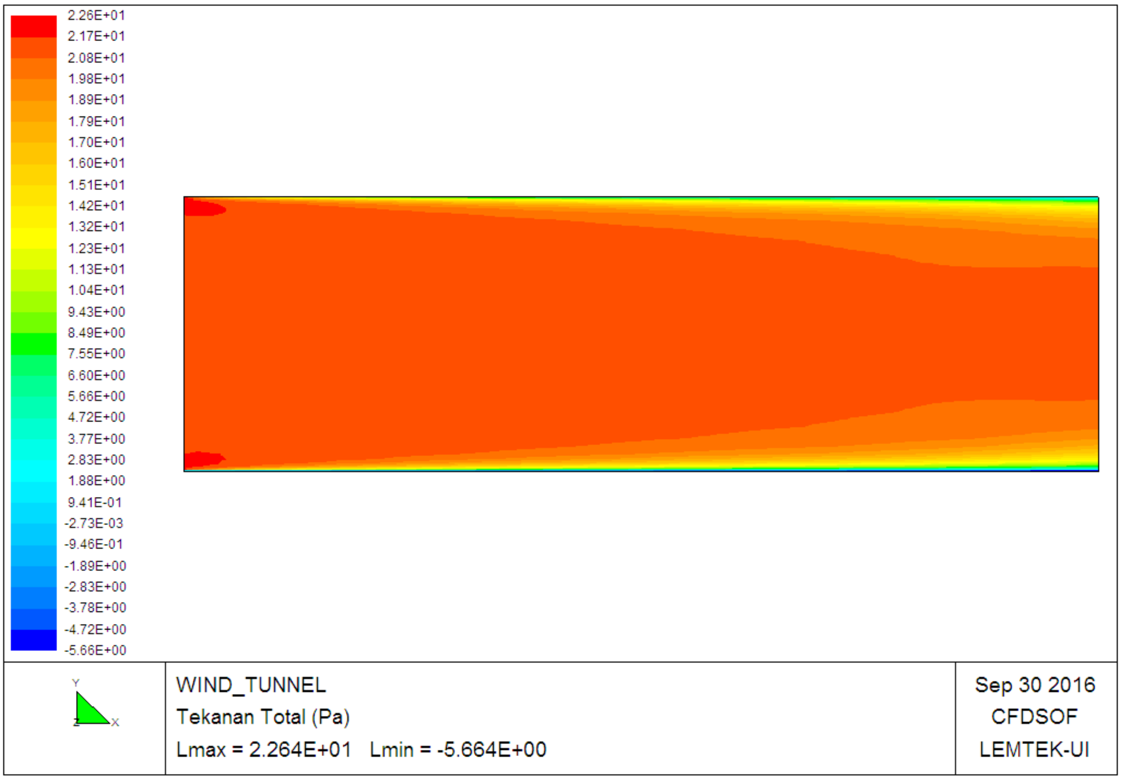

Figure 8 Total pressure contour for position-K = 7

Figure 9 shows the contours of the turbulent kinetic energy of position-K = 7. Unlike the magnitude velocity and total pressure contour, where the three types of turbulence models showed identical results, the contours of the turbulent kinetic energy of the three types of turbulence models showed different results. This difference was mainly in the lower and upper walls. The highest value was given by the RNG k-ε turbulence model in the amount of 3.049231 m^2/s^2, and the lowest value was given by the STD k-ε turbulence model in the amount of 0.6181944 m^2/s^2, while the RSM turbulence model had a value of 0.6625272 m^2/s^2.

Figure 10 shows the curves of the turbulent kinetic energy for position-I = 50 and position-K = 7. The patterns of these curves tended to be similar, but the curve of the RNG k-ε turbulence model was higher in the wall and lower in the middle of the channel compared to the STD k- ε and RSM turbulence models. As we know that the RSM turbulent model is a model that provides more accurate results for simple to complex applications when compared with the STD k-ε or RNG k-ε turbulence models, while the STD k-ε turbulence model is superior because of its simplicity and cheap and adequate results for many applications, these results were not very precise for the flow, which had a large Reynolds strain. While the RNG *k-ε* turbulence model is an improvement from the STD k-ε turbulence model, accounting for the Reynolds strain, the RSM turbulence model will most likely give better results for calculations of turbulent kinetic energy than the RNG k-ε or STD k-ε turbulence models. The RSM turbulence model accounts for the Reynolds stress in all directions, so its simulation results are considered best, followed by RNG k-ε and STD k-ε turbulence models. As shown in Figure 11, the patterns for turbulent dissipation rate and turbulent effective viscosity also tended to have similar curves.

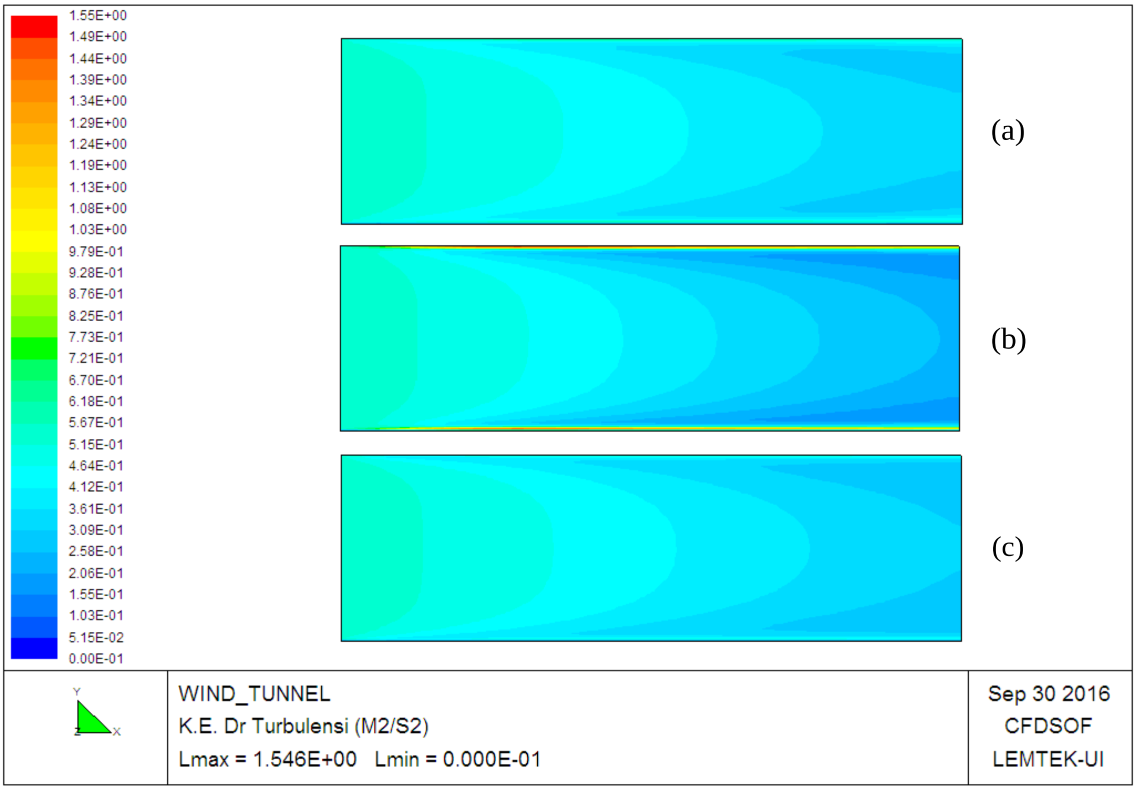

Figure 9 Turbulent kinetic energy contours for position-K = 7: (a) STD k-ε model; (b) RNG k-ε model; and (c) RSM model

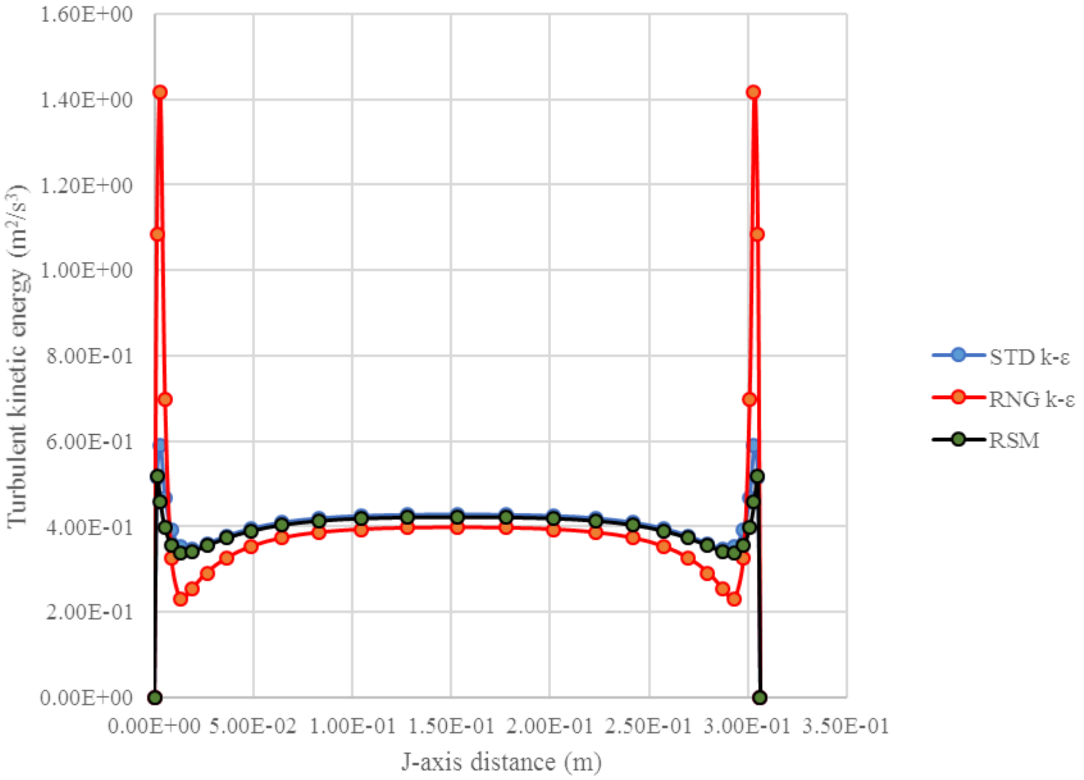

Figure 10 Turbulent kinetic energy curve along position-I = 50 and position-K = 7

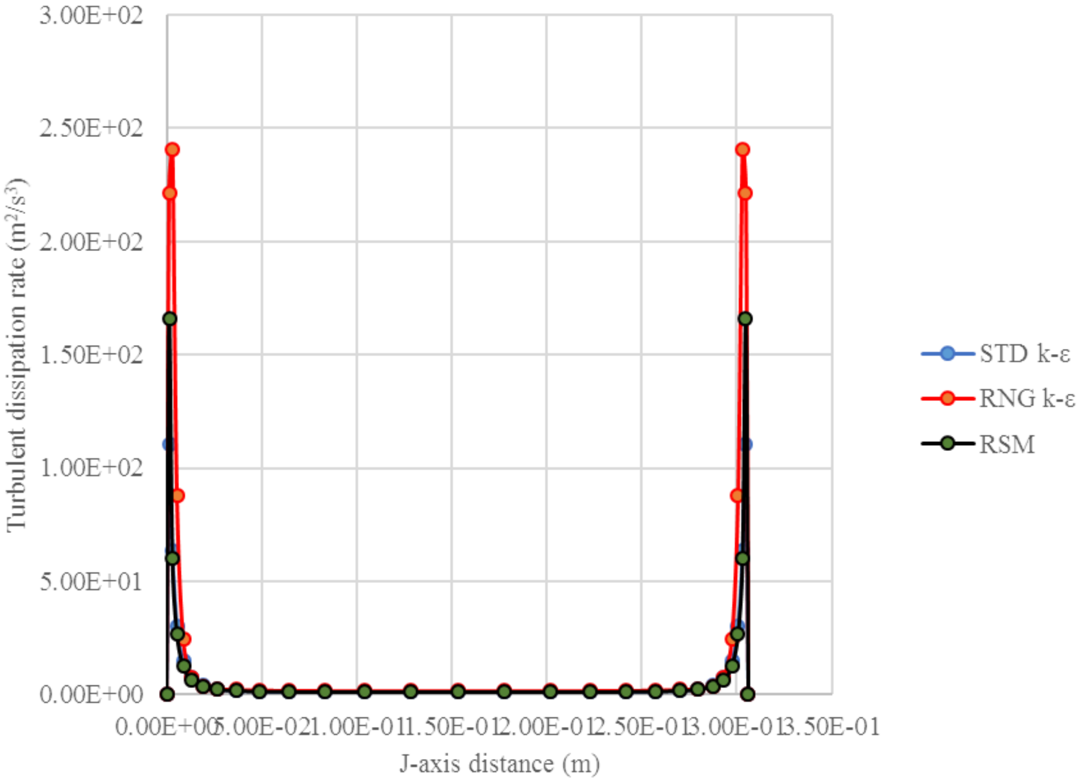

Figure 11 Turbulent dissipation rate curve along position-I = 50 and position-K = 7

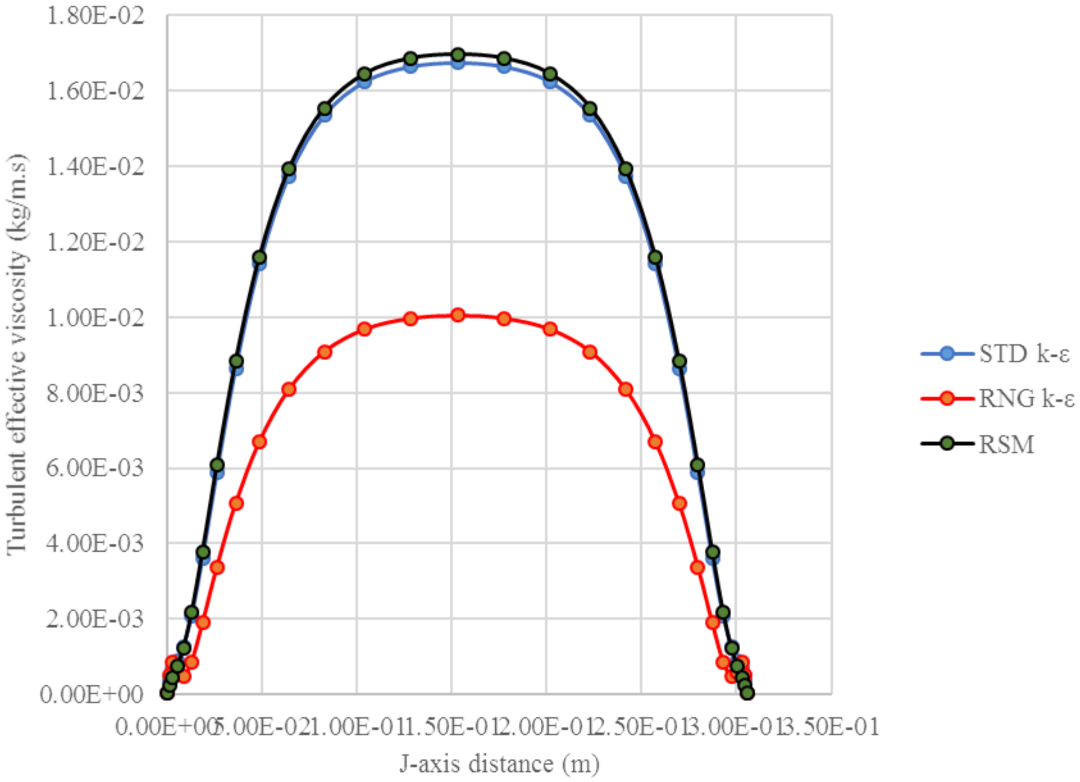

Figure 12 Turbulent effective viscosity curve along position-I = 50 and position-K = 7

4. CONCLUSION

Each specific fluid flow case requires a certain turbulence model to be able to better calculate its flow properties. Thus, this paper attempted to compare the characteristics of three turbulent models, i.e., standard (STD) k-ε, renormalization group (RNG) k-ε and reynolds stress model (RSM), simulating flow in a wind tunnel. The simulation results can be concluded: (1) The distribution of magnitude velocity and total pressure showed that all three models were identical in terms of turbulent results; (2) Turbulent kinetic energy contours showed the same results for all three turbulence models. However, the RNG k-ε turbulence model provided the greatest turbulent kinetic energy value, while the STD k-ε turbulence model provided the lowest. The maximum turbulent kinetic energy value was 3.049 m^2/s^2 for the RNG k-ε turbulence model, 0.663 m^2/s^2 for the RSM turbulence model and 0.618 m^2/s^2 for the STD *k-ε* model. In this case, the RSM turbulence model gave more accurate results; (3) From the results, it can be concluded that the third turbulence model gave good results to predict the distribution of speed and pressure of the fluid flow in the wind tunnel. As for predicting the turbulent kinetic energy, turbulent dissipation rate and turbulent effective viscosity, the STD k-ε turbulence model was effectively used with comparable results to the RSM turbulence model.

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