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Comparison of Turbulence Models for Turbine Stator Optimized For Producer Gas Using CFD Analysis

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ABSTRACT
Efficient energy conversion devices are the most important need of the hour looking at the global energy scenario. Catering to this need, better and more efficient designs are been put forward regularly. New and better methods of energy conversion are also been proposed. The use of Turbocharger in an engine is an example of the same. But the critical examination and of these devices is of utmost importance. Simulation is a tool that can reduce the efforts that need to be put in physically and can carry out virtual calculations and can respond the results too. There are various pre-programmed software that contain a variety of models that can be employed to study the parametric variation and carry out the simulation. This paper deals with study of three such turbulence models namely the k-epsilon, k-omega and the Shear Stress Transport model. A number of parameters will be considered and simulations will be carried out on all the three models with the view of determining the most suitable model among the three with the ability to provide optimum results for the study of a turbocharger turbine stator optimized for producer gas. The results will be obtained in the form of graphs and contour images which will be studied to determine the most suitable model for further use. Based on the results, suitable conclusion will be drawn and stated towards the end.

1. Introduction

Turbocharger is a device used in engines to increase the efficiency of energy conversion by means of forcing the air into the combustion chamber. This increases the quantity of air intake per cycle and thereby carries out efficient energy conversion. A typical turbocharger comprises of an air compressor which is powered by a turbine which in turn is rotated by the difference of enthalpies at the inlet and outlet of the exhaust gases. The enthalpy of exhaust gases is converted to rotational work to drive the turbine which drives the compressor, compressing the air thereby. The turbine of a turbocharger comprises of two important components; one being the rotor and other, the stator. Stator mainly forms the casing of the turbine. The most important function of the stator is to efficiently convert the pressure energy of the incoming exhaust gases into kinetic energy so that the exhaust gases can expand over the blades of the rotor with a high velocity. There are various types of stators available. Some have the provision for a dual flow by means of a partition while others allow a single stream of flow. The following work deals with the study of a turbocharger casing modeled, whose initial dimensions are obtained using coordinate measuring machine (CMM) and by further creating a CATIA model of the same. Among other parameters studied, emphasis is laid on the comparison of different turbulence models for stator. The approach used is by computational fluid dynamics (CFD) and associated simulations.

2. Methodology

The stator is initially checked for grid independence and other necessary parameters. Thereafter three turbulence models, namely, k-epsilon (k-ε), k-omega (k-ω) and shear stress transport (SST) are considered for the comparative study. Parameters including pressure ratio, exit velocity, total temperature, turbulent kinetic energy, eddy viscosity distribution, Mach number and convergence criteria are varied against mass flow rate and critical study of the results is carried out. Conclusions are drawn based on the closeness of a particular model to the realistic values.

3. Turbulence Models

Turbulence models refer to the flow models that are available with the software. They include various pre-programmed parameters that can be used while carrying out the analysis. The turbulence model study should be carried out in such a way that the simulation must be done using nearly realistic turbulence model. The turbulence models are generally classified as, Reynolds's Averaged Navier Stokes (RANS), Large Eddy Simulations (LES), Detached Eddy simulations and other hybrid models, Direct Numerical Simulations (DNS). The most popular models are from RANS. The three most popular turbulence models from RANS that are used for turbocharger analysis are k-epsilon, k-omega and Shear Stress Transport (SST). Features of these models are as follows.

3.1. k-epsilon Model:

This is the most commonly used turbulence model. In this, 'k' refers to turbulent kinetic energy while 'epsilon' refers to the rate of dissipation of kinetic energy. This model has the property of fast convergence and low system requirements.

For turbulent kinetic energy

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$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k+P_b-\rho\epsilon-Y_M+S_k \quad (1)$$

For dissipation ϵ

$$\frac{\partial}{\partial t}(\rho\epsilon)+\frac{\partial}{\partial x_i}(\rho\epsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right]+C_{1\epsilon}\frac{\epsilon}{k}(P_k+C_{3\epsilon}P_b)-C_{2\epsilon}\rho\frac{\epsilon^2}{k}+S_\epsilon \quad (2)$$

3.2. k-omega Model:

In this model, 'k' refers to turbulent kinetic energy as earlier while 'omega' refers to the specific rate of dissipation of kinetic energy. This itself shows that the calculations are more complex in nature and the model requires more time and larger number of iterations to converge to a desired value. This model uses the concept of wall function and is suitable for internal flow study. It has large memory requirements and is difficult to converge.

Turbulent Kinetic Energy-

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=\tau_{ij}\frac{\partial U_i}{\partial x_j}-\beta^* k\omega+\frac{\partial}{\partial x_j}\left[(\nu+\sigma^*\nu_T)\frac{\partial k}{\partial x_j}\right] \quad (3)$$

Specific Dissipation Rate-

$$\frac{\partial \omega}{\partial t}+U_j\frac{\partial \omega}{\partial x_j}=\alpha\frac{\omega}{k}\tau_{ij}\frac{\partial U_i}{\partial x_j}-\beta\omega^2+\frac{\partial}{\partial x_j}\left[(\nu+\sigma\nu_T)\frac{\partial \omega}{\partial x_j}\right] \quad (4)$$

3.3. Shear Stress Transport Model:

This is a combination of both the above models. It uses the properties associated with k-epsilon for free stream and k-omega for walls. Precise flow simulation for complex geometries can be obtained.

Turbulent Kinetic Energy-

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=P_k-\beta^* k\omega+\frac{\partial}{\partial x_j}\left[(\nu+\sigma_k\nu_T)\frac{\partial k}{\partial x_j}\right] \quad (5)$$

Specific Dissipation Rate-

$$\frac{\partial \omega}{\partial t}+U_j\frac{\partial \omega}{\partial x_j}=\alpha\frac{\omega}{k}\tau_{ij}\frac{\partial U_i}{\partial x_j}-\beta\omega^2+\frac{\partial}{\partial x_j}\left[(\nu+\sigma\nu_T)\frac{\partial \omega}{\partial x_j}\right] \quad (6)$$

Equations (1) to (6) are pre-programmed in the system software in the form of suitable logic and mathematical models. The convergence of the solutions is governed by these equations themselves. Having understood the basic turbulence models under study, our next objective is to finalise a certain model out of the three which is compatible in all respects and gives the most desirable and precise simulations and results.

4. Parametric Study for Comparison of Various Turbulence Models

The three models are studied at a constant speed. Following are parameters considered for comparison study.

4.1. Pressure Ratio Variation

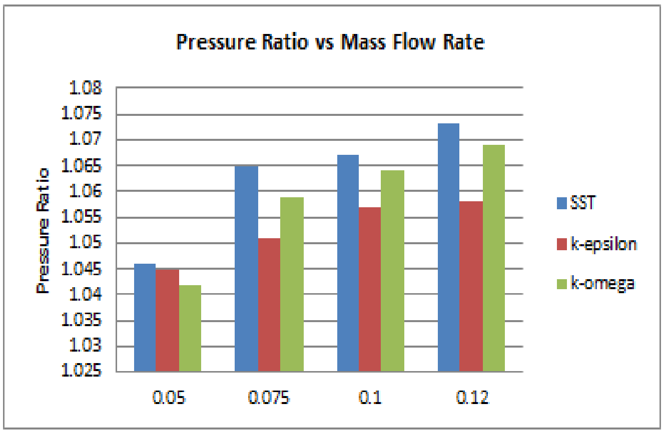

Figure 1. Variation of pressure ratio vs. mass flow rate for different turbulence models.

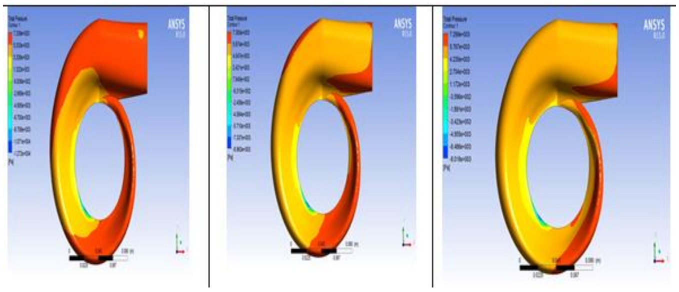

Figure 2. Total pressure distribution contour for stator under k-ε, k-ω and SST models.

From the plot of pressure ratio against mass flow rate for various turbulence models, it is observed that for all the models under study, the value of pressure ratio increases with the increase in mass flow rate. The mass flow rate is varied between 0.05 to 0.12 kg/s. The k-epsilon model depicts a pressure ratio ranging from 1.045 to nearly 1.058. The increase in the value is steady and for larger mass flow rates, the increase is not that large revealing attainment of maximum possible value. The value of pressure ratio as depicted by this model is least among the three if observed as overall consideration. For the k-omega model, the value of pressure ratio ranges from 1.043 to 1.069. The increase in the value is large for smaller values of mass flow rate and further becomes almost constant rate of increase with respect to mass flow rate. The value of pressure ratio as depicted by this model is intermediate as compared to the values given by the other two models. The Shear Stress Transport model (SST) depicts a range of pressure ration as 1.045 to 1.073. The variation with respect to mass flow rate is increasing rapidly at first, and then gradually for larger values of mass flow rates. Figures 1 and 2 show the distribution of pressure across the stator and it can be observed that the SST model gives better distribution with larger conversion efficiency. Further it can be observed that, how uniformly the pressure is being converted into kinetic energy gradually over the contour or surfaces. Thus the pressure energy is efficiently been converted to kinetic energy at the stator outlet.

4.2. Outlet Velocity

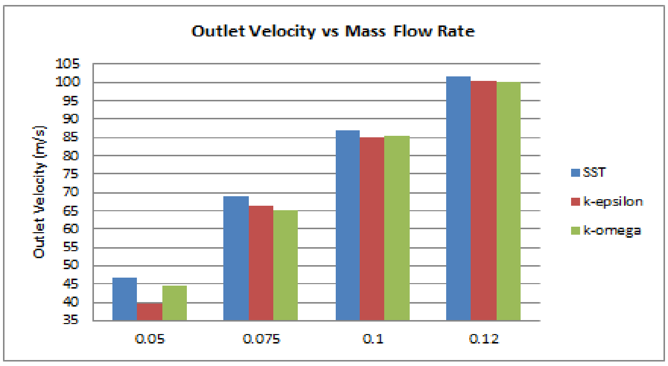

Figure 3. Variation of outlet velocity vs. mass flow rate for different turbulence models.

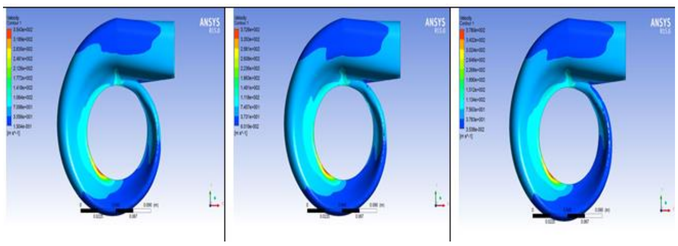

Figure 4. Velocity distribution contour for stator for k-epsilon, k-omega and SST models.

The next parameter to be analyzed is the variation of the outlet velocity with the increase in the mass flow rate. It is known that as the pressure decreases from inlet of stator to the outlet of stator, the outlet velocity increases from the inlet to the outlet of the stator. This paves way to a optimum outlet velocity that can rotate the turbine rotor at the required optimum rotational speed. The three turbulence models are put to simulation with various values of mass flow rates and the outlet velocity is determined. It is observed from the Figure 3 that for the SST model, there is a constant increase in the value of outlet velocity against increasing mass flow rates. The mass flow rate is varied from 0.05 kg/s to 0.12 kg/s. It is observed that the value of outlet velocity for the SST model varies from 47m/s to 102 m/s. The variation is almost constant. As in case of the k-epsilon model, the value of outlet velocity increases rapidly at lower mass flow rates from 0.05 kg/s to 0.075 kg/s. Further a steady increase in the value is observed from 0.075 kg/s to 0.12 kg/s. For the k-omega model, a similar variation as that of k-epsilon is observed. There is a sudden increase at lower values of mass flow rates and thereafter the increase in value is steady.

Thus it can be clearly observed that the SST model shows the highest value of outlet velocity which is in accordance with the theoretical concept of having a high outlet velocity for imparting optimum rotational speed for the turbocharger-turbine rotor. Figure 4 shows the distribution of velocity along the flow passage. It can be observed from all the three plots that the velocity at inlet is very small of the order 0.03m/s to 0.15 m/s. However on account of the stator geometry and flow passage thus created the velocity at outlet increases to a much larger value of the range 354 m/s to 378 m/s. These plots are obtained for a constant value of mass flow rate and are sufficient to clearly depict the velocity distribution. The maximum velocity value as in case of the k-epsilon model is 354.3 m/s while that for k-omega is found to be 372.6 m/s and the maximum value of outlet velocity for the SST model is found to be 378 m/s. The increase in the outlet velocity indicates the efficient conversion of the pressure energy into kinetic energy.

4.3. Total Temperature

According to theoretical considerations, the temperature of the frame of the stator is supposed to be constant since adiabatic conditions are assumed and there is theoretically no heat transfer that has to take place. However due to actual physical conditions and the practical parameters, there is certain heat that is transferred to the surrounding. The following figure illustrates the temperature variation across the flow passage.

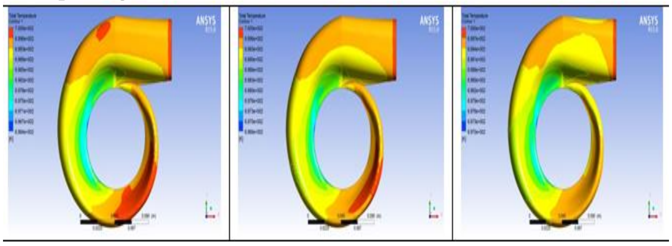

Figure 5. Total temperature distribution contour for k-epsilon, k-omega and SST turbulence models.

The defined adiabatic temperature for the study is 700 K. From Figure 5 it can be observed that an almost constant temperature profile is observed for the SST model. The SST model also shows a smaller range of temperature variation.

The range of variation of temperature is 696.4 K to 700 K for the k-epsilon model, while foe the k-omega model the range is 696.6 K to 700 K and for the SST model, the range of temperature variation is 697 K to 700 K. Thus comparatively, the SST model is seen to work with least heat loss and thereby adhering to the adiabatic conditions to the maximum extent. The k-omega model is found to be better than the k-epsilon on comparison of the range of temperature variation and the overall profile. Heat loss mainly occurs at the larger surface areas exposed on account of convection heat transfer. The adiabatic temperature distribution provides insulation to heat loss and carries out efficient conversion of Pressure energy to Kinetic Energy.

4.4. Turbulent Kinetic Energy Study:

Turbulent kinetic energy refers to the kinetic energy of the fluid on account of turbulence caused during the flow. Also it is noteworthy that higher values of turbulent kinetic energy refer to more efficient conversion of pressure energy to kinetic energy of the fluid leaving the stator. Higher velocity results in higher turbulent kinetic energy. The following figure depicts the variation of the turbulent kinetic energy along the profile of the stator.

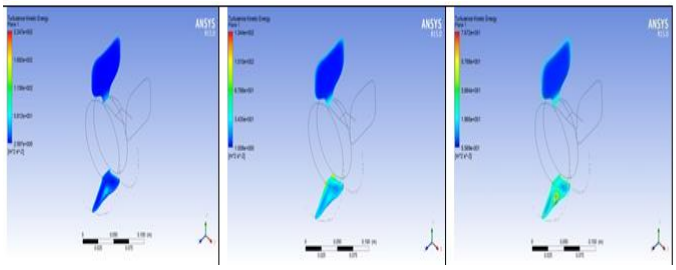

Figure 6. Distribution of turbulent kinetic energy across a plane for k-epsilon, k-omega, SST model.

From Figure 6, it is observed that the SST model has the highest distribution of turbulent kinetic energy which shows efficient energy conversion at a major portion of the stator as compared to the other two models. The range of turbulent kinetic energy is seen to be the least for the SST model while the range is highest for the k-epsilon model. The value of turbulent kinetic energy is calculated in units of m^2/s^2. For the k-epsilon model, the range is found to be from 2.597 m^2/s^2 to 224.7m^2/s^2, while that for the k-omega model is found to be 1.008 m^2/s^2 to 134.4 m^2/s^2. The SST model depicts a range of values from 0.5569 m^2/s^2 to 76.72 m^2/s^2. This clearly shows that highest distribution of the turbulent kinetic energy is found in the study carried out with the SST turbulence model.

4.5. Eddy Viscosity Distribution:

There is formation of eddies which adds on to the flow resistance in the flow path. These eddies are formed due to irregularities in the geometry. This is quite a practical situation of consideration since there cannot be a completely even surface that can be obtained by any of the manufacturing operations or processes. Certain imperfections are existent although utmost care is always taken in order to avoid the same. The following figure depicts the eddy viscosity distribution.

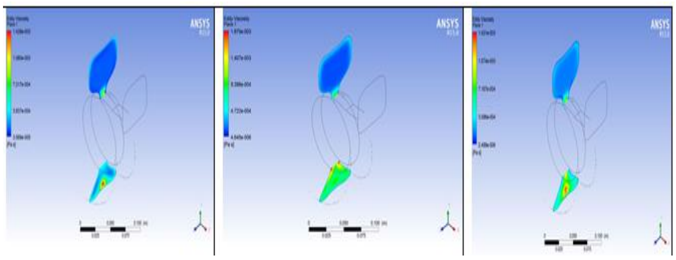

Figure 7. Distribution of eddy viscosity across a plane for k-epsilon, k-omega and SST models.

The eddy viscosity is a measure of overall resistance offered to the fluid flow within the casing of the stator. The value of eddy viscosity varies for all three models. The SST model shows least effects of eddy viscosity, as shown in Figure 7, on the flow path and thus is found to be the most efficient model with minimum resistance to the fluid.

4.6. Variation of Mach number:

Mach number is a dimensionless number defined as the ratio of speed of fluid through a medium to the speed of sound. For sub-sonic flows, the Mach number value is less than 1 while for supersonic flows, the value of Mach number is greater than 1. Higher Mach number corresponds to higher outlet velocity. The variation of Mach number for the three turbulence models is as shown in Figure 8.

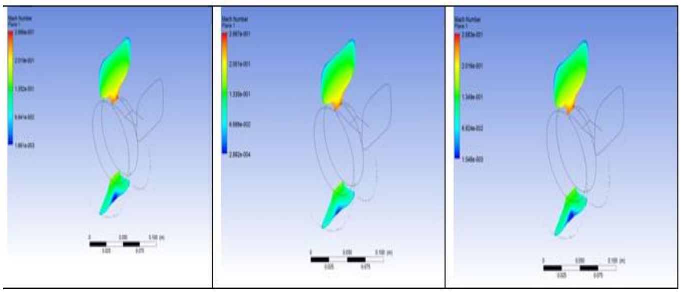

Figure 8. Distribution of Mach number across a plane for k-epsilon, k-omega, SST models.

The Mach number is found to vary at various sections of the stator. The ranges of Mach number as observed in the simulation for the three turbulence models are as follows. For the k-epsilon model, the Mach number ranges from 0.001661 to 0.2686, while for the k-omega model, the value ranges from 0.0002882 to 0.2667 and for the SST model, the value of Mach number ranges from 0.001548 to 0.2683. It is noteworthy that the upper limit of the Mach number is almost the same for all the three models. It can also be observed that at the outlet region, the value of Mach number is highest for SST as compared to the other two. The overall flow as observed from all the models is sub-sonic in nature. The higher value of Mach number indicates higher outlet velocity thus validating the results as obtained from the variation plots of outlet velocity v/s the mass flow rate. Also that high outlet velocity indicates better pressure conversion and thus higher efficiency of energy conversion.

4.7. Convergence Criteria

Convergence iteration is that at which the simulation is free for the equation imbalances. It indicates the minimum number of outer loop iterations to be performed in order to reach a point where simulation and theoretical results are in good agreement with each other. The following figures depict the convergence study for the three models.

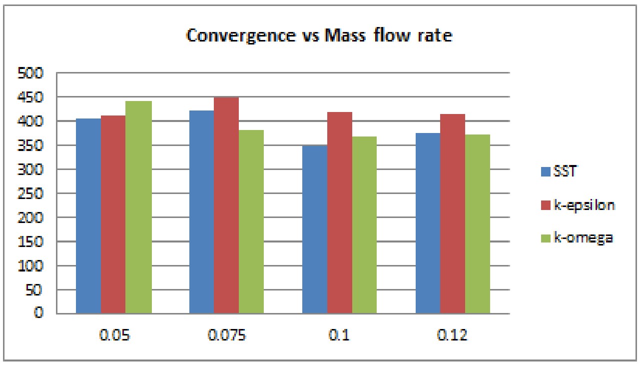

Figure 9. Convergence iteration trend with respect to mass flow rates for different turbulence models.

As observed from Figure 9, for mass flow rates varying from 0.05 kg/s to 0.12 kg/s, for a majority of cases, it is the SST model which is observed to converge the earliest as compared to the other two models. The k-epsilon model requires the largest number of iterations to converge to a particular value. Lesser value of number of convergence iterations refers to lesser time required for the simulation. This is also an indication of optimum time in which the study can be carried out for better validation of the results close to the theoretical ones. For the range of mass flow rates as considered in the above shown Fig. 9, the SST model is seen to converge between 350 to 425 iterations which shows the optimum value for proper simulation.

5. Conclusion

Thus from the study of various graphs and contour images for variation of various parameters as considered for the turbulence model comparison, it can be concluded that the Shear Stress Transport (SST) Model is the most suitable and ideal model that can be used to carry out any of the future study with respect to the parametric study of a turbocharger-turbine stator. As per the proposed grid independence study results and other fundamental considerations of parameters like the operating speed etc, various simulations were carried out to study parameters like the Pressure Ratio variation, Outlet Velocity, Total Temperature, Turbulent kinetic energy study, Eddy Viscosity Distribution, Mach number variation and Convergence criteria, it has been prominently observed that the Shear Stress Transport Model (SST) has proved to be the most suitable one for the simulations. The results obtained from the employment of the SST model are the closest to the desired theoretical values. This makes the SST model to be the most realistic model for the purpose of experimentation. Therefore for further detailed parametric study of Turbocharger Turbine Stator optimized for Producer Gas, the Shear Stress Transport (SST) Model can be used to obtain the most optimum results which are in good agreement with the theoretical values.

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