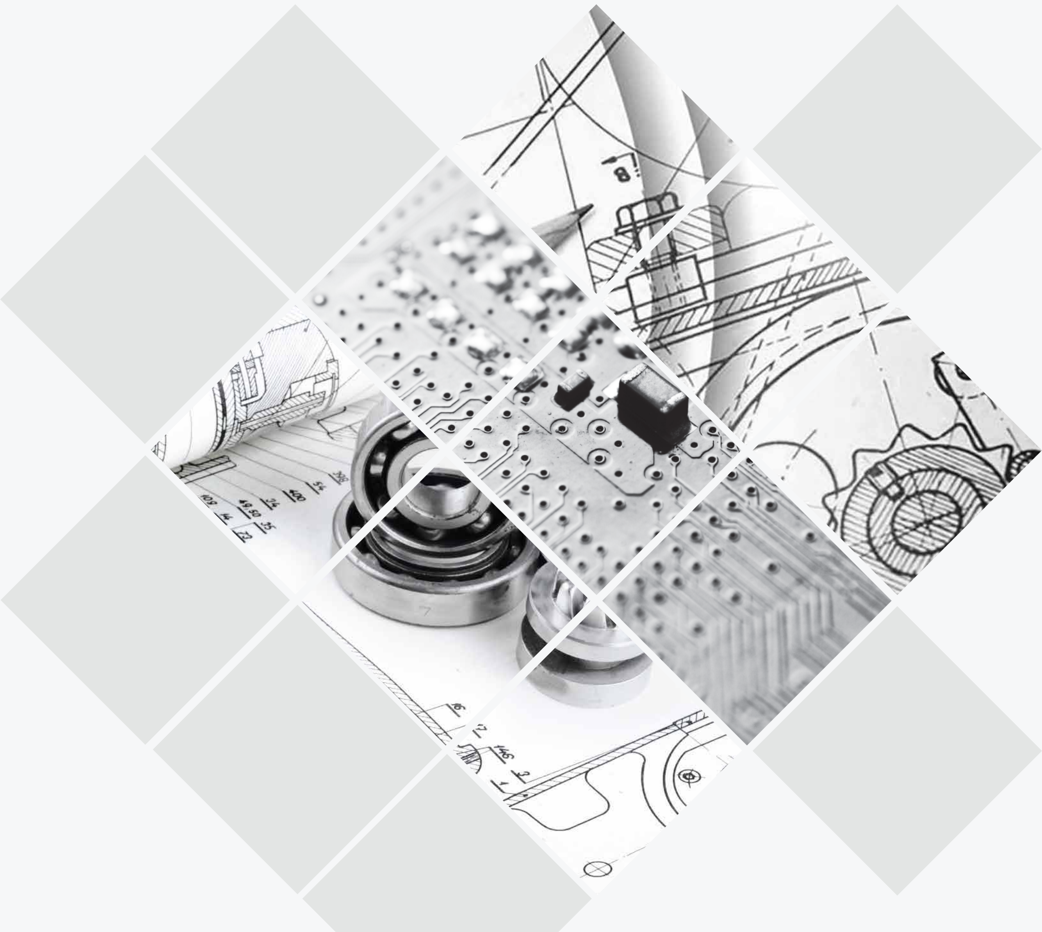
studies on impact of inlet viscosity ratio, decay rate & length scales in a cooled turbine stage

Modern aircraft engine designs are driven towards higher operating temperature and lower coolant flow requirements. During the flight mission, the hot gas path components encounter flows at different pressure, temperature and turbulence conditions.



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Abstract

Modern aircraft engine designs are driven towards higher operating temperature and lower coolant flow requirements. During the flight mission, the hot gas path components encounter flows at different pressure, temperature and turbulence conditions. During design of such components, there is always an interest towards fundamental understanding of the impact of inlet turbulence on overall performance. The paper presents aerodynamic performance (stage efficiency) impact of stator inlet viscosity ratio, decay rate and length scales in a cooled turbine rig, based on CFD studies only. Through CFD studies, it is observed that an inlet length scale variation by 10 times could impact the aerodynamic efficiency by ~0.5% to 4% depending on the size of the length scale. Efficiency drops with higher flow length scales and turbulence intensity. The length scale effects are observed to be more predominant with high turbulence intensities than at low turbulence intensities. Similarly a viscosity ratio increase by 1000 times can decrease efficiency by < 0.5% in the lower bounds and can drastically increase to ~ 3% at higher bounds. The efficiency drop can be as much as 2.5 % for a decay rate change from 0.01 to 1 for viscosity ratio of 10000.

Nomenclature

U_1	Laminar viscosity
n_{st}	Stage efficiency
u_t	Turbulent viscosity
Cax	Axial chord
DR	Decay rate $= \epsilon \, \tilde{L}_d \; k{*}U_{ave}$
H_0	Total enthalpy
i	Index
k	Turbulent kinetic energy
L_d	Length of Domain
LS	Length scale
m_c	Coolant mass
m_{in}	Inlet mass flow
N_c	Number of coolant flows

P_{stage}	Stage Power
TI	Turbulence intensity
U_{ave}	Average inlet velocity
VR	Viscosity ratio = u_t/u_1
ϵ	Dissipation rate of turbulent kinetic energy

Subscripts

C	Coolant
ex	Exit
ideal	Ideal Condition
in	Inlet

Introduction and Background

Ever since the inception of gas turbines, there has been a drive to increase the output and efficiency. This output here refers to power in case of land based gas turbine or specific thrust in case of aircraft gas turbine. The aircraft gas turbines experiences a wide range of operating conditions and has been pushed to higher limits of operational flexibility, with more stringent environmental friendly requirements and operational costs. A clear understanding of the factors impacting the gas turbine performance is necessary in carrying out the design and development of these sophisticated systems. There are numerous parameters that impact the efficiency of a gas turbine. An aircraft gas turbine encounters different levels of pressure, temperature, flow and turbulence in the atmosphere as it flies. As in any new design and development, the process consists of performing a set of sensitivity studies for different turbulence inlet conditions.

Based on CFD predictions of Boyle [1], the impact of length scales is observed to be significant. He also reported a better match with smooth vane data with use of smaller length scales. Brookfield et. al. [2] studied the effect of free stream whirl on the rotor blade wake decay in the flow field. Other sensitivity studies, by Carullo [3] and Dring et. al. [4] with turbulence intensities and length scales were more focussed on heat transfer.

The effect of large scale high free stream turbulence and vane exit mach number on a turbine vane heat transfer was presented by Shakeel et. al [5]. Turbulence intensity as high as 16% and integral length scale as big as 0.23 times of the vane pitch were used for the study. Thole and Bogard [6] showed that relatively large-scale turbulence has a reduced effect on turbulent boundary layer heat transfer augmentation. A study on various turbulence closures was presented by Rene et. al [7] and their observation stated that the SST komega model and the V2F model efficiencies differed by around 1%. Interestingly, the impact of inlet turbulence intensity on the efficiency has also been presented. The V2F model prediction had ~0.8% drop in efficiency with increase in turbulence intensity from 2% to 25%. Detailed boundary layer measurements on a stator vane were carried out by Radomsky and Thole [8] at elevated freestream turbulence intensities. The impact of turbulence on the suction side and pressure side surface pressure has also been narrated in the paper.

A lot of literature materials are available on CFD analysis carried out on gas turbine stages, concentrated on heat transfer and secondary flow features. However, a systematic study of impact of basic turbulence quantities and flow variables on gas turbine performance are few or rather not available handy and hence the interest. The paper deals with identifying the impact of stator inlet flow and turbulence parameters on gas turbine performance. In this report efficiency has been of primary focus. The turbulence quantities studied are intensity, length scale, and viscosity ratio and decay rate. The study is only about the effect of inlet conditions and hence the variation of turbulence quantities and length scales in the domain are not in the scope of the context being discussed in this article.

Computational Domain

A meridional view of the computational domain used for the analysis is shown in Figure 1. The inlet extends from ~ 1.5 times axial chord upstream of the nozzle guide vane. The outlet is positioned at a location far away from the blade trailing edge and has a constant annular area for some distance. The nozzle guide vane is featured with surface film and trailing edge slot cooling (not visible in the picture). The hub and tip end walls are profiled to minimize secondary flow losses. The rotor blade is featured with surface film and tip shroud cooling holes. The end wall profiling is also considered for blade hub and tip shroud walls along with fence in the tip. Purge flows from upstream and downstream of the rotor blade are captured by including a portion of the cavity.

The computational domain is meshed with hexahedral elements using in-house tool. The near wall resolution, characterized by y+ value is maintained between 1 and 5 so as to resolve the viscous sublayer sufficiently. The analysis is carried out using in-house flow solver, HYDRA.

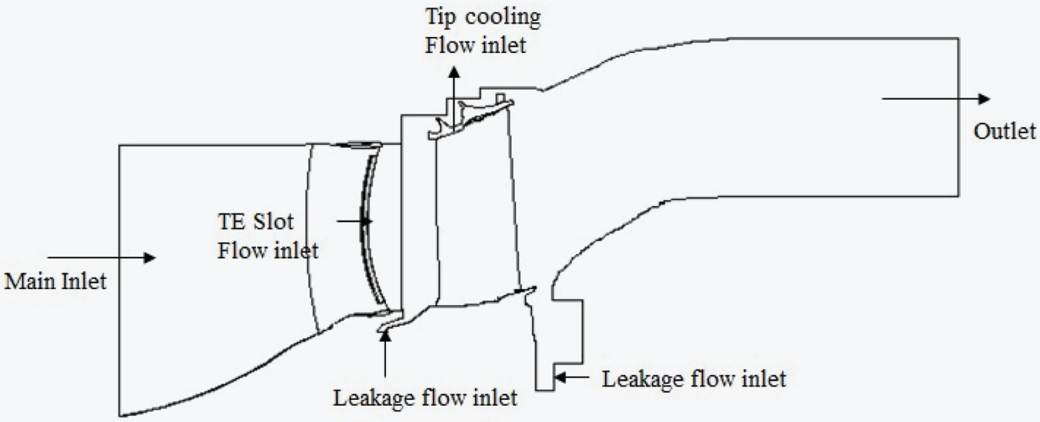

Figure 1. Computational domain used for analysis

The inlet boundary conditions were varied to account for the variation of inlet turbulence quantities. Prior to embarking on detailed comparisons, sufficient care was taken to ensure grid sufficiency by doing mesh sensitivity analysis. The mesh sensitivity analysis and the results are not provided here for brevity. The study revealed that ~ 5 million meshes for the stage was optimal. The analyses were carried out for a nozzle exit Mach number close to unity. The analysis is categorized into two groups; one carried out with intensity and length scale specification and other group is carried out with viscosity ratio and decay rate specification. The two-equation k-omega model is used for turbulence closure.

Effect of Length Scale & Turbulence Intensity

The energy from the flow is cascaded across length scales. The largest length scale of flow transfers energy to the smaller length scales and these cascades to smallest length scale where energy is dissipated. Under test conditions, the length scales can be estimated approximately, using the auto-correlation technique. In the case of limited availability of test data, trial and error methods are adopted to arrive at a particular value of length scale and intensity, and its adequacy is decided based on the quality of the data match obtained. This method assumes that all other flow variables are deterministic and the turbulence parameters are varied to obtain a better match. Although not true, the procedure provides a reasonably good match with justifiable results. Under experimental conditions, the length scales can be controlled. With turbulent grid generators, the length scales can be increased and usually without grids, they are smaller [9]. In the present cases, the length scales investigated are of sizes 1%, 10% and 30% of the vane axial chord (Cax). It is desired to study the impact of these length scales on the turbine performance for three different turbulence intensities; 5%, 15% and 30%. The range covers the minimum turbulence to maximum turbulence conditions in a general operating condition. As mentioned here, stage efficiency is of primary focus here and the results of the 5% turbulence intensity with 1% inlet length scales are considered as benchmark and the delta values are studied as shown in Figure 2. The stage efficiency used here is calculated as shown in Equation 1.

$$\eta_{stage} = \frac{P_{stage}}{\dot{m}_{in}\left(H_{0in} - H_{0ideal\,ex}\right) + \sum_{i=1}^{N_C} \dot{m}_{Ci}\left(H_{0C\,in_i} - H_{0C\,ideal\,ex_i}\right)}$$

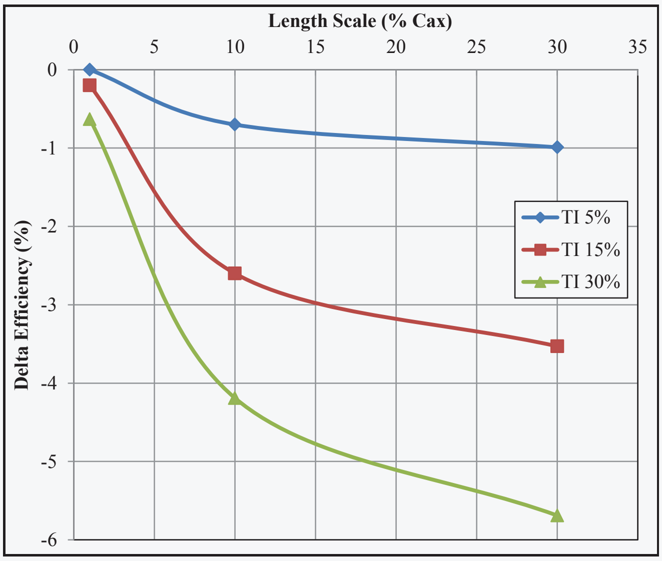

Figure 2. Impact of inlet length scale on efficiency (Linear X Scale)

There are few things that could be interpreted from the Figure 2.

1. For a given turbulence intensity, the decrease in efficiency is less with increase in inlet length scale for low turbulence intensity, the drop in efficiency is higher with increasing length scale. increase in turbulence intensity, while it is higher with higher turbulence intensity.

Applying energy cascade mechanism to explain the phenomenon, it is known that the energy dissipation happens at the smallest length scales. Let this be referred to as 'sink' length scale while, the source length scale is the biggest length scale. When the difference between the source and the sink length scale is higher, the energy cascade through more intermediate length scales until it finally dissipates.

It could be observed that the drop in efficiency is becoming lower with further increase in length scale. Similar effect has been reported by Thole and Boggard [6], with respect to heat transfer.

Additionally, the variation in efficiency with length scale is plotted on a logarithmic scale as shown in Figure 3.

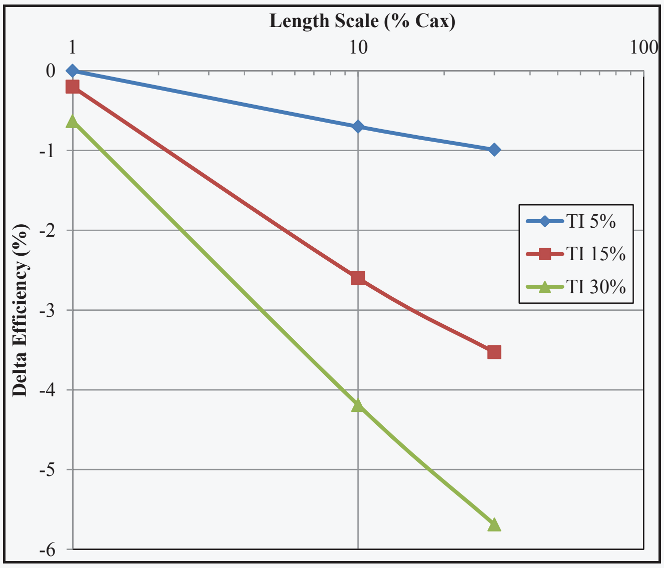

Figure 3. Impact of inlet length scale on efficiency (Logarithmic X Scale)

The variation is linear, with a logarithmic X scale. However, the slope of the curves does change for various turbulence intensities. The slope characterises the 'rate' at which losses increase with change in length scale. The same set of data is plotted to study the impact of turbulence intensity as shown in Figure 4.

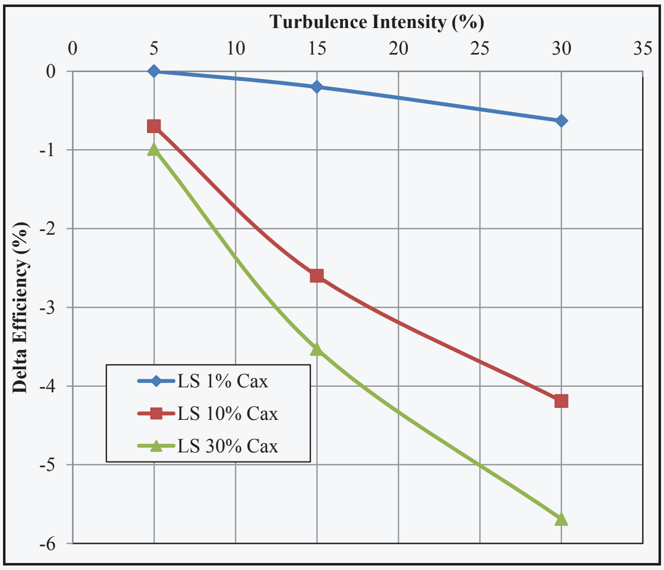

Figure 4. Impact of turbulence intensity on efficiency (Linear X Scale)

As expected, with increase in turbulence intensity, the aerodynamic loss increases. A steep fall in efficiency is observed with higher turbulence intensity, especially with larger length scales. In general, if the length scales in the flow could be contained to smaller sizes, then the efficiency fall would be lower even with higher inlet turbulence. This implies, the wake, separation flows and large scale vortices like passage vortex, tip vortex, etc., should be minimised which usually tends to increase the flow length scales. Similar to length scale, turbulence intensity is also plotted on a logarithmic X scale to identify the trend as shown in Figure 5. Unlike length scale, the variation in efficiency is 'less' linear with increase in turbulence intensity. However, in the band of interest, it could be treated more or less a logarithmic variation.

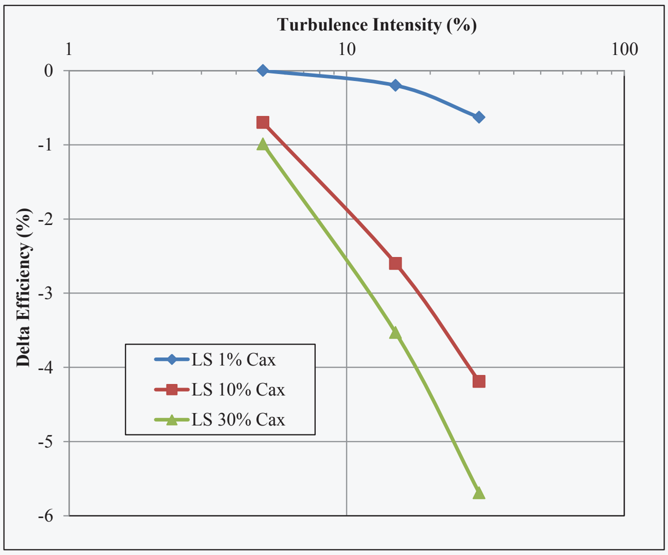

Figure 5. Impact of turbulence intensity on efficiency (Logarithmic X Scale)

To visualize the impact of the turbulence intensity in the flow field, span wise profiles of circumferentially averaged total pressure profile near the blade trailing edge is studied. Figure 6 shows total pressure profiles for various turbulence intensities. The length scale corresponding to the set of data is 10% of vane axial chord. The near wall differences in the total pressure are almost insignificant between intensities of 5%, 15% and 30%. The reason could be that downstream of the blade, the turbulence would be high, and this causes less variation between the higher and lower, inlet turbulence intensities. However, a clear drop in total pressure is observed with high turbulence and the profiles are more flat with higher turbulence, compared to that of lower turbulence intensities.

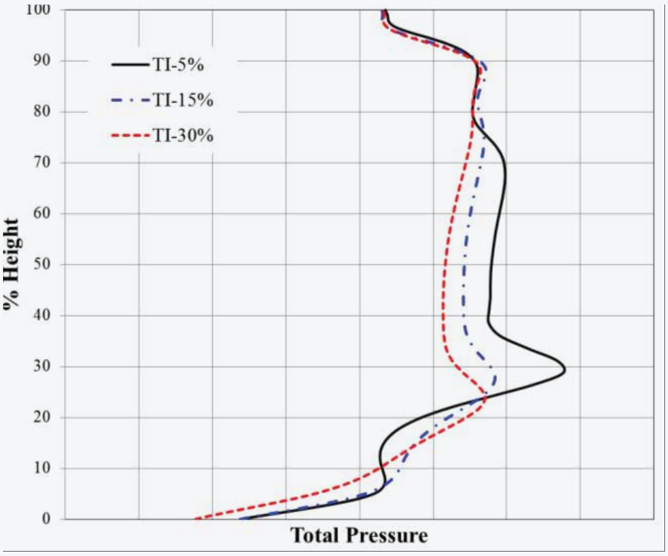

Figure 6. Comparison of total pressure profiles near rotor blade trailing edge for various turbulence intensity (LS =10% Cax)

Effect of Viscosity Ratio and Decay Rate

A number of analyses have been carried out, by varying viscosity ratio and decay rate at the inlet as against intensity and length scale model. The viscosity ratio is defined as the ratio of the turbulence viscosity to laminar viscosity. Figure 7 shows the impact of increasing viscosity ratio on the aerodynamic performance. In this case, the efficiency corresponding to the decay rate of 0.01 with viscosity ratio of 10 is considered as baseline and the relative changes are quantified and studied. Similar to the effect of the length scale and turbulence intensity, with increase in viscosity ratio, the efficiency drops. However at low viscosity ratio, the impact of decay rate appears negligible. The highest decay rate has highest drop in efficiency with increase in viscosity ratio. Similarly, the highest viscosity ratio has the highest drop in efficiency with increasing decay rate. These variations of viscosity ratio, when plotted in a logarithm scale are shown in Figure 8. The graph clearly indicates that the efficiency drop is significant, with viscosity ratios of over 1000. Figure 9 shows the impact of decay rate increase. The efficiency drop is insignificant for low viscosity ratio and with high turbulence viscosity (10000); the drop in efficiency is more than 6 times that of lower turbulence viscosity (VR 1000).

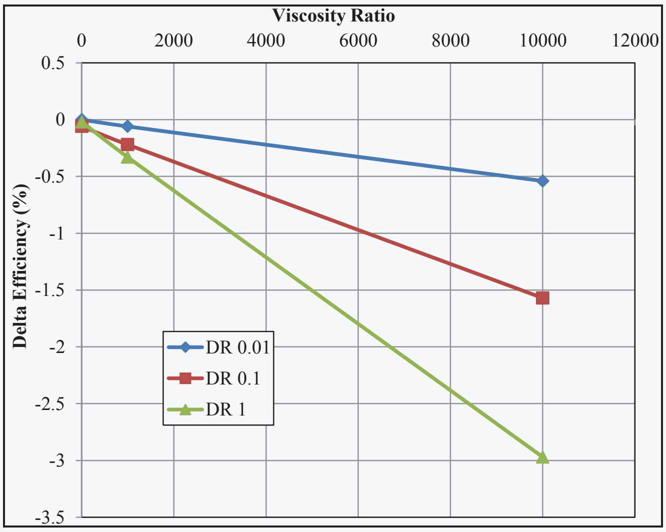

Figure 7. Impact of viscosity ratio on efficiency (Linear X Scale)

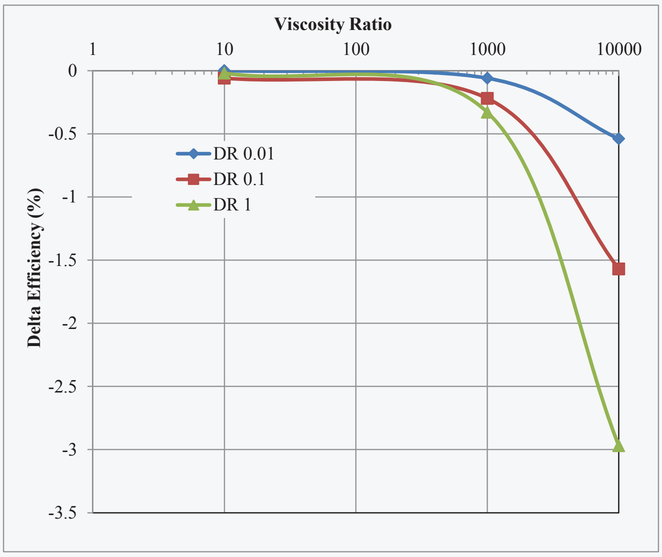

Figure 8. Impact of viscosity ratio on efficiency (Logarithmic X Scale)

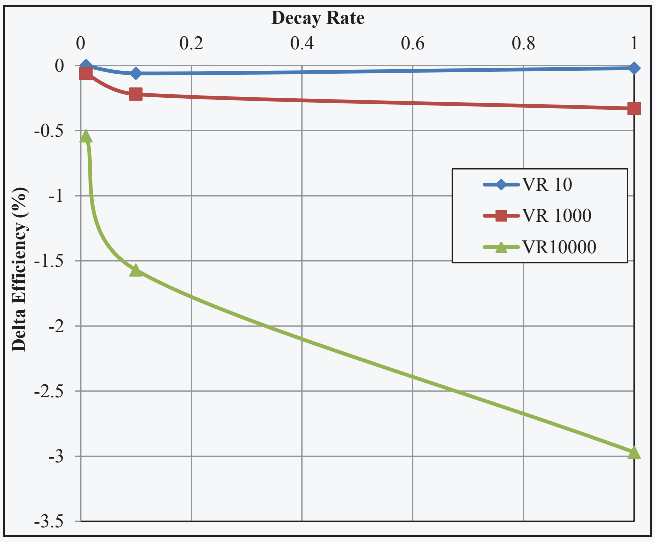

Figure 9. Impact of decay rate on efficiency

Figure 10 shows a comparison of total pressure profiles near the rotor blade trailing edge for various viscosity ratios for a constant decay rate of 0.1. It could be inferred from the profiles that peak variations in the free stream are minimised with higher viscosity ratios and the profile is more 'flat' compared to those with low viscosity ratios. It is also interesting to note that no significant changes in pressure profiles are observed near the hub between viscosity ratios of 10 and 1000 whereas the differences are appreciable in the free stream. This implies that the viscosity effects are suppressed near the walls in the high shear zones captured by near wall treatments used along with turbulence model

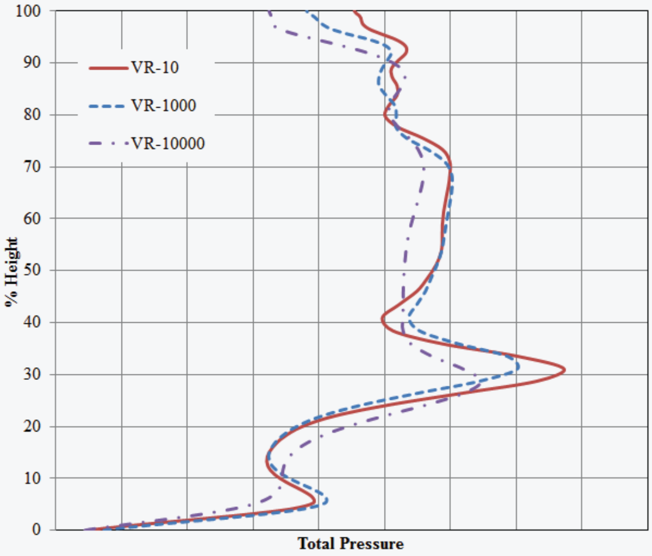

Figure 10. Effect of viscosity ratio on total pressure profile near rotor blade trailing edge (DR=0.1)

Turbulence Model Sensitivity

In order to understand the variation of the performance prediction, a set of analysis is also carried out with different turbulence models. The analysis was carried out with the two prominent turbulence models, k-epsilon and k-omega. The analysis was carried out with inlet turbulence intensity of 5% and a length scale of 1% of vane axial chord. The analysis indicated that the k-epsilon model predictions had higher loss compared to k-omega model and the efficiency was lower by ~ 1.5 %. Additionally, a variant of the k-epsilon model called CMOTT is also used to evaluate the performance.

The prediction was in between the standard k-epsilon and k-omega models. The efficiency change was observed to be around ~ 0.5%. Figure 11 shows the variation of total pressure near to the rotor blade trailing edge. It could be inferred that while the free-stream predictions are closer between the models, the pressure distribution near the walls varies. The k-omega model shows smoother variation compared to the k-epsilon model and its variants. The figure also indicates the near wall modeling difference between the k-epsilon and its variant.

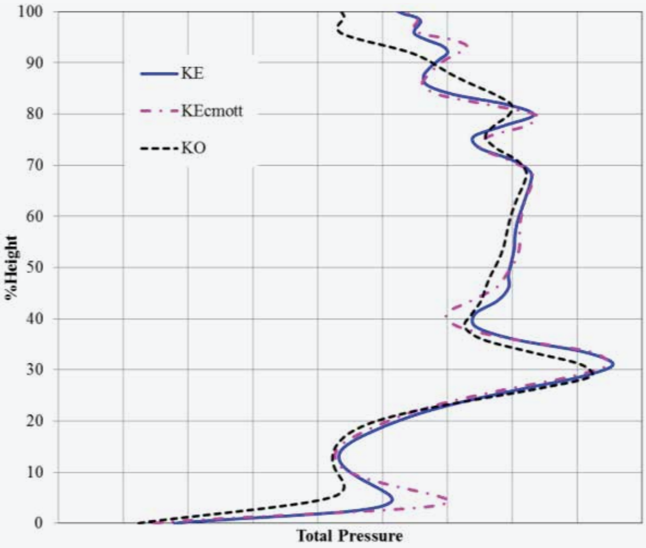

Figure 11. Comparison of total pressure near rotor blade trailing edge for different turbulence models

Conclusions

The change in aerodynamic performance with respect to change in inlet length scale and turbulence intensity is observed to be varying logarithmically. The performance loss is higher with higher inlet turbulence intensity and length scale. With smaller inlet length scale the performance penalty with increase in turbulence intensity is lower than at higher turbulence intensities. An order of magnitude change in inlet length scale can reduce efficiency by around 3% at high turbulence intensities. A comparison against the test data would reveal the implications of turbulence modeling on the solution obtained using CFD.

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