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3D-Simulation and Numerical Analysis of the Local Entropy Generation and Exergy Destruction in a Stator Vane of a Typical Gas Turbine

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ABSTRACT: Entropy serves as a key parameter in achieving the theoretical limits of performance and quality in many engineering applications. In this paper, the three-dimensional analysis of entropy generation, local entropy generation and exergy destruction of turbine stator vane by user defined function code have been done. The current innovation is to calculate the exergy destruction rate of the turbine three-dimensional vane with the help of FLUENT software. The k-ω (SST) and Spalart-Allmaras models are suitable for prediction of proper effective viscous and thermal conductivity. Due to the sensitivity to the tip of the vane and the wake flows, k-ω (SST) model obtained the mean value of entropy generation by about 85% more than the Spalart-Allmaras model. Local entropy generation has increased with respect to the scale from the root to the tip of the vane. The difference between the values of local entropy generation and the second law of thermodynamic for k-ω (SST) and Spalart-Allmaras models are 7.4% and 10.2%, respectively. Approximate turbulence coefficients have been introduced with the aid of a custom field function that increases the local entropy generation about 130%. The k-ω (SST) model calculated the exergy destruction value of a turbine stage of 1098 kW, which is 4 times the size of the two-dimensional mode due to the scale. The values of local entropy generation calculated in comparison with the stator vane of the turbine of the authentic paper are validated, which has acceptable adaptation.

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1- Introduction

Entropy, along with exergy, has been able to illuminate new aspects of various flow processes. Entropy is a useful property and is used in the analysis of industrial equipment from the perspective of the second law of thermodynamics as a valuable tool [1]. Calculating the entropy generation rate in the turbomachine canals depends directly on temperature and velocity. The total entropy generation is related to the cascade efficiency, while it depends on the local entropy generation of flow field and it is not easily recognized. Local entropy generation at each point of the turbomachinery channel represents a useful tool from various important irreversibilities in the flow [2].

In the present study, a three-dimensional transonic and compressible laboratory stator turbine vane simulation is performed to calculate the local entropy generation and exergy destruction. The selected vane is VKI-LS89, and its height is equal to the Brite Euram turbine vane and is scaled from the root to the tip of the vane 0.8. Drawing the viscous entropy generation, thermal entropy generation and exergy destruction contours, give the proper design tool to engineers, with the mention of the temperature and velocity details, and leads to detailed and proper analysis of the flow behavior around the vanes.

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2- Methodology

The selected stator vane in this study is a nozzle guide vane (combustion outlet) belonging to the Von-Karman Institute, which is called the VKI-LS89 [3]. The geometry of the vane is considered three dimensional and untwisted and the span is proportional to the transonic stator turbine vane of the von Karman institute [4]. The vane span is 0.05 m, and the tip chord is 0.8 scale of the root chord [5]. The three-dimensional schematic of the vane is shown in Fig. 1.

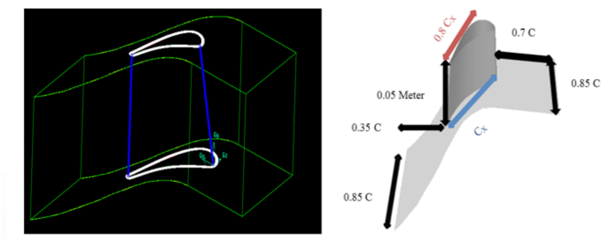

Fig. 1. Vane profile schematic

The unstructured grid has been created by the Gambit software of 2250000 cells. The boundary conditions of the flow and reference conditions are the same as the 235MUR test in transonic state.

Using the Reynolds-Averaged Navier–Stokes (RANS), the transport equation of entropy is converted into Eq. (1) [6].

$$\bar{\rho}\frac{D\bar{s}}{Dt} = \dot{s}_{mean} + \dot{s}_{turb} \quad (1)$$

The values calculated in this paper are reliable for $\dot{s}_{mean}$. In local entropy generation, the amount of entropy generation is divided into two sections: thermal entropy generation and viscous entropy generation, which Eqs. (2) and (3) depend on the local gradients of temperature and velocity. Viscous dissipation represents the mechanical energy degradation of internal energy through viscous effects. The thermal dissipation term represents entropy generation due to heat transfer across temperature gradients in the fluid. The 3D thermal and viscous entropy generations are introduced in Eqs. (2) and (3) which are per volume of fluid [7]. The variables of μ_{eff} and k_{eff} of Eqs. (2) and (3) are effective dynamic viscosity and effective dynamic conductivity. The last term of Eq. (3) is due to the compressibility that is considered in this solution [8].

$$\dot{s}_t = \frac{k_{eff}}{T^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] \quad (2)$$

$$\dot{s}_v = \frac{2\mu_{eff}}{T}\left\{\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2 + \frac{1}{2}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 \right. \quad (3)$$

$$\left. + \frac{1}{2}\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 - \frac{1}{3}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)^2\right\}$$

The unit of local entropy generation is W/m^{3}K. If it multiplied by volume, the unit becomes W/K and by integrating it, the total entropy generation is calculated.

$$\dot{s}_{gen,tot} = \iiint \dot{s}_{gen} dxdydz \quad (4)$$

The exergy destruction rate due to irreversibilities is proportional to the total entropy generation. The total exergy rate is given in Eq. (5) and its unit is in W [7].

$$\dot{E}x_{des} = T_0 \dot{S}_{gen,tot} \quad (5)$$

Various turbulence models have been used to obtain the μ_{eff} and k_{eff} values in the wake of the stator vane. The k-kl-w and Reynolds Stress Model (RSM) leads to non-physical results in the wake of vane. The (Spalart–Allmaras Simulation (SAS) and Large Eddy Simulation (LES) models need too fine grid which leads to too much computational cost. The Spalart-Allmaras and k-ω (SST) models estimate accurate results for compressible transonic vane problem.

3- 3. Discussion and Results

The viscous and thermal entropy contours in the k-ω (SST) model in 10, 50 and 90% of the vane span are shown in Fig. 2. At the 90% vane height, due to the severe drop in pressure at the leading edge, due to the high curvature of the flow, the flow pattern has changed and the entropy generation has increased significantly.

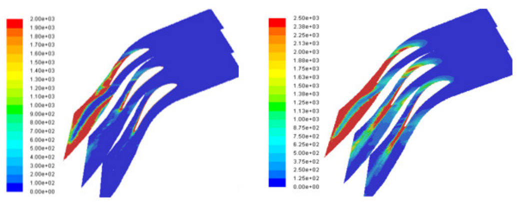

Fig. 2. Viscous (right) and thermal (left) entropy generation in k-ω (SST) model

The local entropy generation in the k-ω (SST) and SA models is shown in Fig. 3. The exergy destruction in the hub is greater than the tip of the vane, but the maximum amount of exergy destruction occurs at the tip of the vane resulting from the curvature of the vane at the tip. The maximum exergy value at the tip of the vane is shown in Fig. 4 with an oval shape.

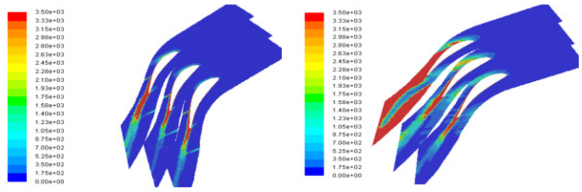

Fig. 3. Local entropy generation in K-ω (SST) (right) and SA (left) turbulence models

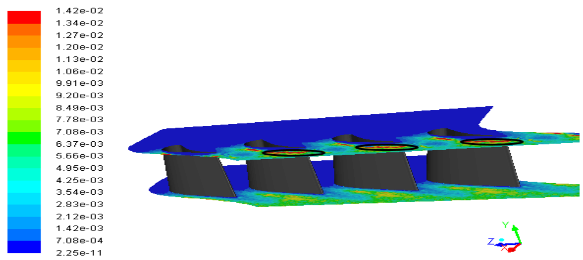

Fig. 4. Exergy destruction on the walls of the hub and tip

The amount of exergy destruction to the Brite Euram turbine vane, which uses the same airfoil of the present vane and has a scalability of 0.8 from root to tip, is calculated to be 3.625 kW. According to the advantages of the entropy generation rate, the compatibility of this parameter allows that one can calculate the exergy destruction rate in a total turbine stage. The values of the viscous entropy generation, thermal entropy generation, local entropy generation, total entropy generation and exergy destruction for the two turbulence models of the SST-kω and Spalart-Allmaras models are shown in Table 1.

4- Conclusions

The thermal and viscous entropy generations contain 28% and 72% of total entropy generation respectively, which represents the high velocity gradients in the turbine. The k-ω (SST) model predicts better the vane wake and is more sensitive to the leading edge curvature. From the point of view of improving the design of the vane, due to the 0.8 scale from the tip to root, the leading edge curvature at the vane tip is very high and this causes high destruction of exergy compared to the non-scale state. From the point of view of improving the design of the vane, due to the 0.8 scale from the tip to root and high leading edge curvature at the tip, exergy destruction is high compared to the non-scale state. Therefore it is better than not to use scale in chord from root to tip in turbine vane.

Table 1. Entropy generation value of 3D-vane

Model	Ex_{des}(W)	$s_{gen,tot}$(W/K)	s_{gen}	s_v	s_t
k-ω (SST)	3625	8.703	27623	19679	7944
S-A	1441	3.407	22639	16406	6233

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