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Numerical Study of the Effect of the Ejection Angle on the Cooling Performance of a High-Pressure Gas Turbine

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Abstract: In modern gas turbines, the purge flow plays an important role in improving the performance of the gas turbine, as it is adapted against the problem of the ingestion of hot gases in the inter-disc cavity of the turbine. The performance of this purge flow is necessarily influenced by some geometrical and physical parameters. This paper presents a 3D numerical study on the influence of the ejection angle on the cooling performance in a high pressure transonic gas turbine with the presence of the cavity. Five inclination cavity angles are compared ($\boldsymbol{\phi}$ = 30°, 45°,60°,75°and 90°) by using ANSYS Fluent, a steady flow Reynolds average Navier-Stokes equations are solved, and the turbulence model k-ω SST has been chosen based on comparison of the distribution of velocity and heat transfer convective coefficient with experimental results in a previous work. It was seen that that cooling is limited to the suction side because of the non-uniform pressure distribution of the main flow and the high pressure of the stagnation point. The optimal configuration was determined for an ejection angle of 30°.

Keywords: HP transonic gas turbine, 3D numerical study, Purge flow, Ejection angle, Cooling performance

Introduction

Today's gas turbines operate under extreme operating conditions to maximise efficiency, such that the temperature of the exhaust gases at the combustor outlet and turbine inlet exceeds 2000 K (Arts et al., 1997). Cooling air is extracted from the compressor to cool hot gas path components, such as end walls, blades and their tips using internal and film cooling, and other hot components such as the inter-disk cavity using purged air. In the turbine inter-disc cavity, a rim seal is installed between the stator and the adjacent rotor disc to prevent or at least dilute the ingress of hot main flow gases to a tolerable level which has two main causes: the pumping effect (rotationally-induced ingestion (RI)) and the non-axisymmetric pressure distribution in the annulus (externally-induced ingestion (EI)) (Gräf,., & Kleiser, 2014). The interaction between the channel flow (the purged flow) and the main flow produces an additional aerodynamic loss and a change in the thermal load distribution. This is why it seems necessary to analyse the interaction mechanisms of the flow from the inter-disc channel and to try to understand the origin of these significant losses. The article is carried out using ANSYS CFD software, it aims to clarify the effect of the ejection angle on the cooling performance in the high-pressure turbine rotor with the presence of a cavity, through analysis of the cooling efficiency contour and streamlines on different sections, and the maximum cooling efficiency values for different angles of inclination.

Computational Domain Mesh and Flow Conditions

The computational domain mesh is generated in Gambit using a multi-block topology and is illustrated in Figure 1. The domain is divided into 25 blocks and each block supports a structured mesh. The mesh resolution is very fine and consists of 1.7×10^6 elements. The walls were resolved using structured boundary layers consisting of 15 elements normal to the passage surfaces and 7 elements normal to the cavity surfaces. The maximum y + value is on the order of 5.

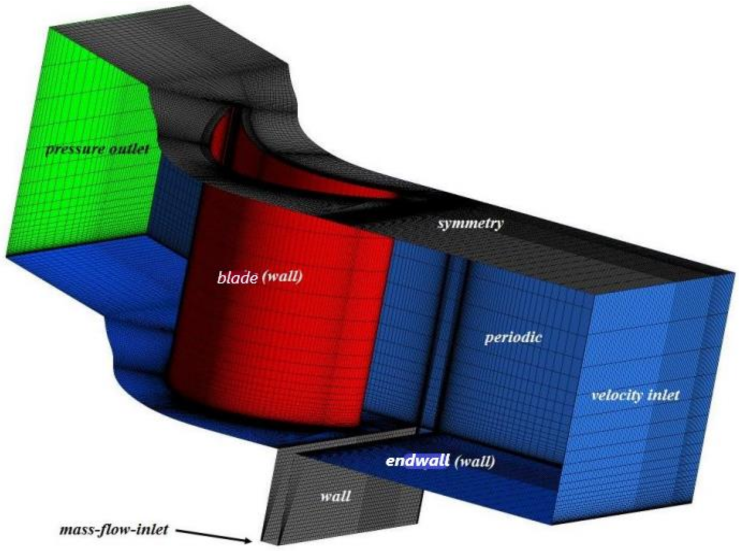

Figure 1. Calculation domain, boundary conditions and mesh

The boundary conditions are imposed as follows: at the main flow inlet, a velocity of 70 $m.\,s^{-1}$ is imposed with an angle of incidence of i = -5 °, a turbulence intensity of 5% and a warm static temperature of 1200 ° C. At the outlet, a relative static pressure of zero is imposed over the entire surface. For all walls, the non-slip and adiabatic condition is applied. At the entrance to the cavity, the mass-flow-inlet condition was imposed. At the same locations, a cooling temperature of 650°C was applied with a low turbulence intensity of 1%.

The Effect of Slot Inclination on Cooling Efficiency

In this section, we determine the influence of slot inclination on cooling efficiency (purge flow ejection angle $\boldsymbol{\phi}$) by setting slot width (E) to 4 mm and purge flow rate PF to 1%. Five ejection angles are studied $\boldsymbol{\phi}$ =30°, 45°,60°,75°,90° (Figure 2). Efficiency is analysed on the basis of the cooling efficiency parameter :

$$\theta = (T_\infty - T) / (T_\infty - T_p) \tag{1}$$

Where T_∞ is the temperature of the main flow (hot flow), T_p is the temperature of the purge flow and T is the local temperature.

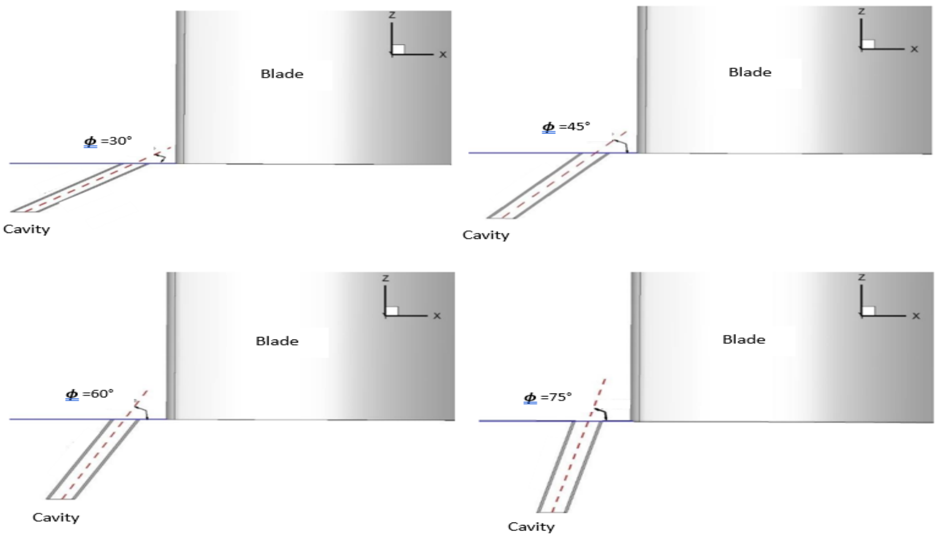

Figure 2. Geometry of the cavity

Results and Discussion

Figure 3 illustrates the cooling efficiency contours for all inclination angles, taking ϕ=90° a reference case. For all cases, film cooling is limited to the rotor's section side region, and approaches the leading edge slightly as the inclination angle becomes steeper, up to ϕ=30. All inclination angles provide superior cooling efficiency compared to the reference case. decreasing the inclination angle from 90° to 30° improves cooling efficiency by also increasing the area covered by the coolant as well as the uniformity of the coolant distribution particularly for ϕ=30°.

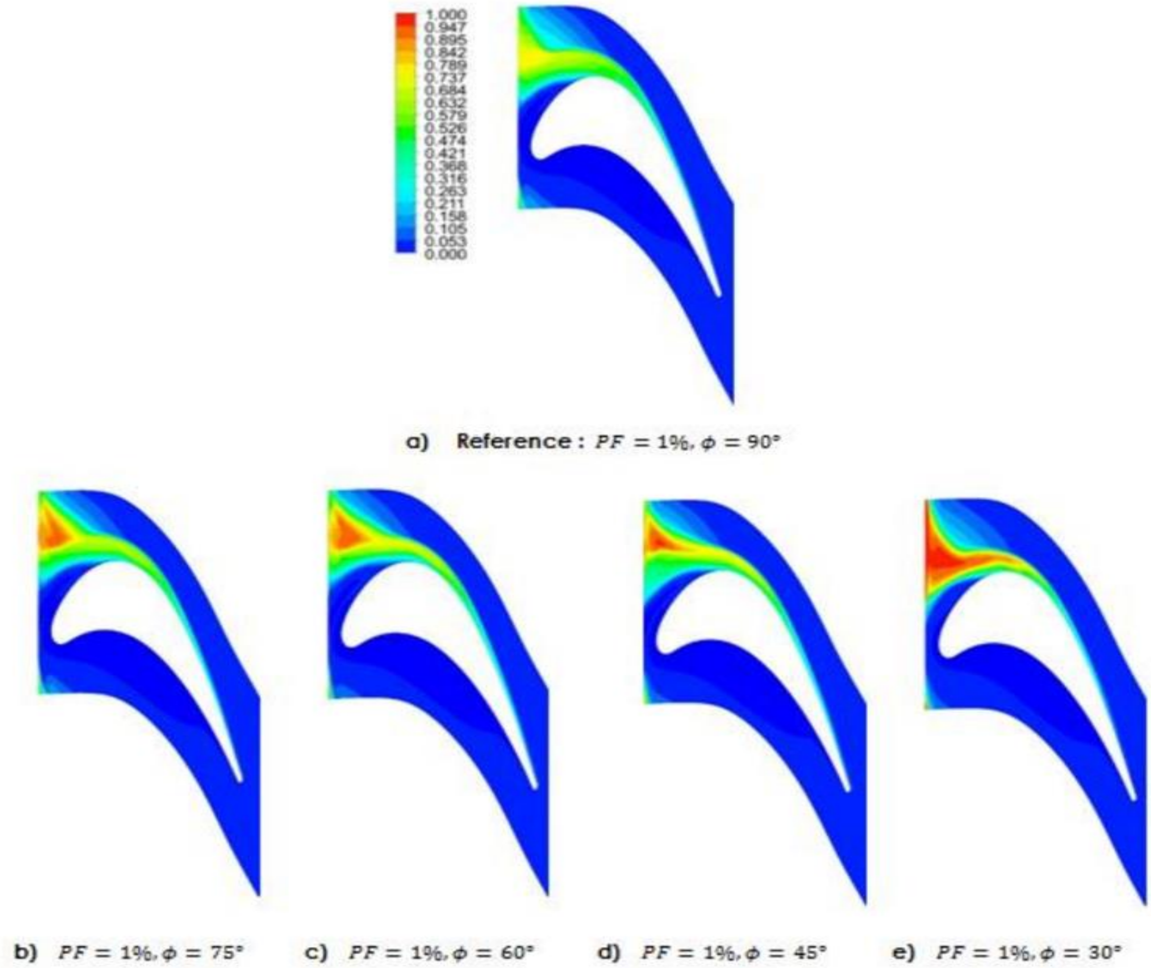

Figure 3. Contour of cooling efficiency

Figure 4 illustrates the cooling efficiency contour and streamlines on three sections for different angles of inclination. For all angles, significant differences can be found between the flow conditions of the three sections (plane 1, 2 and 3). This is due to the non-uniform pressure distribution of the main flow, as mentioned previously. For section 1 the phenomenon of main flow ingestion disappears for all angles of inclination, a more uniform distribution of film cooling efficiency is formed by decreasing the angle of inclination of the cooling fluid, and this phenomenon is particularly significant for ϕ = 45° et 30°. For section 3, the cooling efficiency is almost zero for all PF values. This is due to the high pressure of the main flow near the pressure side, where vortices are observed just downstream of the slot (return flow). The size of these vortices decreases as the angle of inclination becomes steeper.

In section 2, the main flow ingestion phenomenon can be observed, due to the high pressure at the stagnation point compared with other regions, which is responsible for the absence of a coolant ejection zone at the slot outlet shown in Figure 3. In addition, horseshoe vortices (HV) are observed downstream of the slot. Comparing the flow conditions in section 2 for the different angles of inclination, it is clear that the ingestion phenomenon is weakened and begins to disappear for ϕ = 45° et 30°.

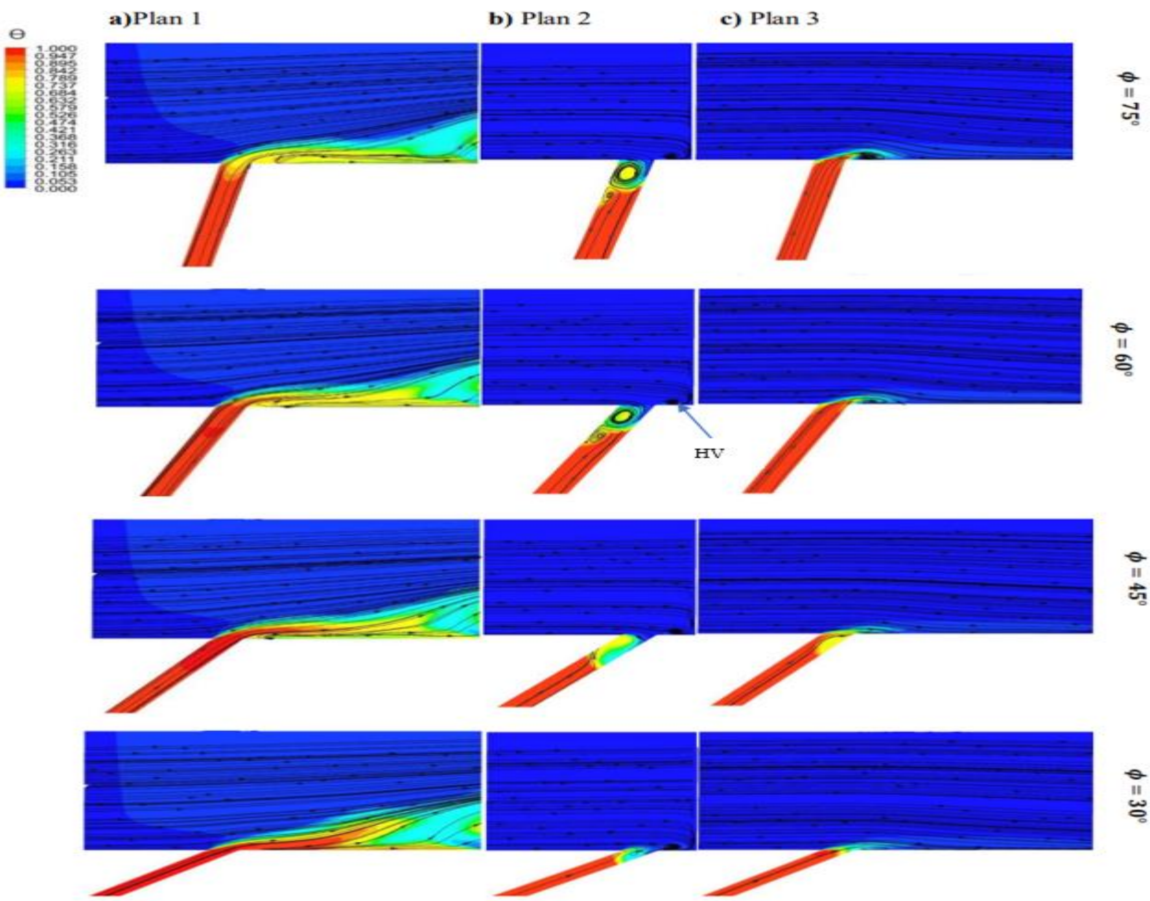

Figure 4. Cooling efficiency contour and streamlines on three sections

Figure 5 shows the maximum cooling efficiency values achieved for each angle of inclination. All the inclination cases studied give a higher cooling efficiency than the 90° reference case. The maximum θ obtained for each angle of inclination is 97.67% for an angle of 30°, 96.19% for 45°, 94.49% for 60°, 92.38% for 75° and 78.26% for 90°.The evolution of cooling efficiency is non-linear. It decreases from angle 30° to 90° with a relative difference of 1.51%, 1.76%, 2.23% and 15.28% respectively. In general, increasing the slot inclination angle has a negative effect on cooling efficiency. The best case inclination angle is 30°, with an improvement of 19.41% over the reference case.

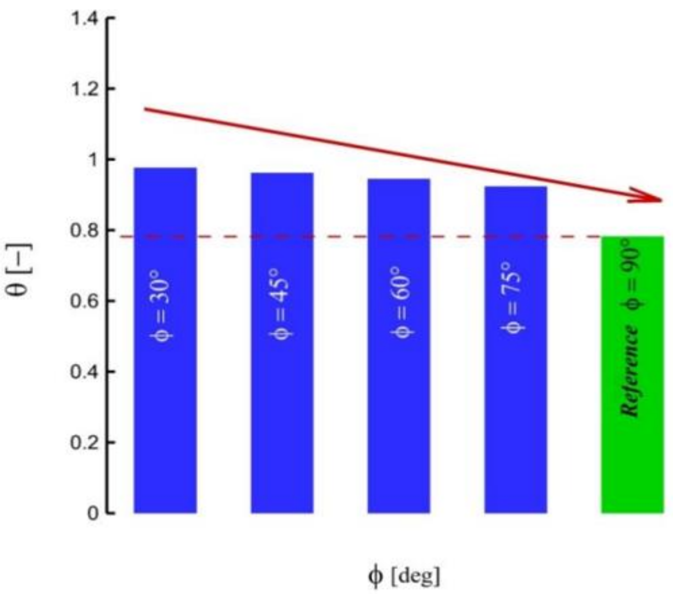

Figure 5. Maximum cooling efficiency at the hub

Conclusion

The study of the influence of the angle inclination of the cavity on the cooling efficiency is presented in this study. Five angles (ϕ =30°, 45°,60°,75°,90°) were investigated with the coupled Navier-Stokes averaged equations for a stationary and incompressible 3-D flow using the k-ω SST turbulence model.
It was concluded that:

- Cooling is limited to the suction side because of the non-uniform pressure distribution of the main flow and the high pressure of the stagnation point.
- The influence of the angle of inclination is very important on the cooling performance around the blade and on the ingestion phenomenon near the zone facing the stagnation point, which is considerably weakened with the steepest angles of inclination.
- Cooling efficiency and uniformity of coolant distribution are improved by reducing the angle of inclination from 90° to 30°, such that the cooling efficiency increases by 19.41%. The optimum thermal design choice adopted for this study is 30°.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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