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# Numerical study on the effects of multiple inlet slot configurations on swirl cooling of a gas turbine blade leading edge

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ABSTRACT

In this paper, a cylindrical swirl chamber, which can be used on the leading edge of a turbine blade is numerically modeled to investigate the effects of multiple slots at each section of the swirl chamber. The RANS equations are solved using four different turbulence models, and it was found that the SST $k-\omega$ model, resulted in the reasonable agreement with the experimental data. Two different chamber types, i.e., swirl chamber (SC) and double swirl chamber (DSC), are considered to be modeled with five different inlet configurations. In all configurations, rectangular inlet slots are located at the beginning and middle sections of the swirl chamber, but the number and direction of inlet slots will change in each configuration. SC and DSC configurations are compared using two different scenarios, where the width of both chamber types are identical in the first scenario and the hydraulic diameters are assumed to be identical in the next one. It is concluded that the comparison according to the identical width is more reasonable in the case of gas turbine blades. Results for the same Reynolds number and coolant mass flow rate confirm that the multiple inlets at each section with proper direction creates stronger vortices, which enhances the Nusselt number by 33% as compared to the base inlet configuration.

## 1. Introduction

Turbine inlet temperature (TIT) has been increased significantly in recent years in order to increase the gas turbine efficiency and output power. This temperature is limited by the materials maximum allowable temperature, but the TIT is far beyond this maximum limit in the advanced gas turbines, and its value is increasing rapidly. Therefore, high-temperature material development such as thermal barrier coatings (TBC) or advanced turbine blade cooling technologies is required to safeguard turbine vanes and other parts of the turbines from this high temperature. Both methods have been improved significantly in recent years; however, rising the rate of the maximum allowable temperature is much slower than enhancement in the cooling technologies. Different cooling technologies, which are described by Han et al. [1] could be implemented to gain maximum efficiency and power output.

Because of the high temperature and high gas velocity of the mainstream near the blades leading edge, this region is most critical in blade cooling strategies. Several internal cooling methods such as pin-fin cooling, ribbed channels and impingement cooling combined with film-cooling are usually used in this area of turbine vanes to reduce its temperature. Bunker [2] has reviewed some of the most important film-cooling technologies used for gas turbine blades, and the use of jet impingement heat transfer as an effective internal cooling method for gas turbine blade is described by Han and Goldstein [3]. However, impingement cooling cannot lead to a uniform temperature distribution in the blade and excessive film cooling flow rate can adversely affect the mainstream aerodynamic efficiency. Use of swirling flow in the blade internal cooling near leading edge can be used to reduce the temperature gradient in the blade while keeping the required flow rate by film cooling at the low levels.

Hay and West [4] are among the first, who study the use of swirling flow in cooling of turbine blade leading edge. They presented a correlation for the local Nusselt number as a function of local Swirl number and observed an augmentation of heat transfer as much as eight times compared with the non-swirling flow. Chang and Dhir [5] conducted an experiment on swirling flow in a cylindrical pipe with four tangential injections and divided the swirl flow into two different regions according to the local swirl intensity. Later, they investigated the mechanisms of heat transfer enhancement using swirling flow [6]. Ligrani et al. [7] presented an experimental study of the heat transfer in a swirl chamber with two rectangular tangential inlets and observed the streamwise development of arrays of Gortler vortex pairs, which are developed along the concave surfaces. Using the same geometry, Hedlund and Ligrani [8] studied the effect of Reynolds number on the

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**Nomenclature**

| | |
|---|---|
| $b$ | inlet slot width (mm) |
| $b_0$ | outlet slot width (mm) |
| $D$ | swirl chamber diameter (mm) |
| $d$ | inlet slot height (mm) |
| $D_{h,i}$ | inlet slot hydraulic diameter (mm), $= 2bd/(b+d)$ |
| $d_0$ | outlet slot height (mm) |
| $H_1$ | inlet slot length (mm) |
| $H_2$ | outlet slot length (mm) |
| $i$ | number of the configuration model |
| $j$ | number of inlets in each section |
| $k_{air}$ | thermal conductivity of air |
| $L$ | swirl chamber length (mm) |
| $\dot{m}$ | total mass flow rate at outlet (kg/s) |
| Nu | general Nusselt number |
| $Nu_D$ | Nusselt number based on swirl chamber diameter, $= hD/k_{air}$ |
| $Q$ | total wall heat transfer rate (W) |
| $Q_0$ | total wall heat transfer rate in base configuration (W) |
| Re | general Reynolds number |
| $Re_D$ | Reynolds number based on swirl chamber diameter, $= \overline{U}D/\nu_{air}$ |
| $Re_i$ | Reynolds number based on inlet slot hydraulic diameter, $= V_i D_{h,i}/\nu_{air}$ |
| $T_i$ | air inlet temperature (K) |
| $T_m$ | mean temperature of inlet air and swirl wall $T_m = T_i + T_w/2$ |
| $T_w$ | swirl chamber wall temperature (K) |
| $\overline{U}$ | average velocity in swirl chamber after the second inlet (m/s), $= 4\dot{m}/\rho_{air}\pi D^2$ |
| $V_i$ | average velocity of inlet (m/s) |
| $Y^+$ | non-dimensional wall distance |

*Greek symbols*

| | |
|---|---|
| $\beta$ | angel in swirl chamber (rad) |
| $\nu_{air}$ | kinematic viscosity of air |

*Abbreviations*

| | |
|---|---|
| CFD | Computational Fluid Dynamics |
| DSC | Double Swirl Chamber |
| SC | Swirl Chamber |
| TIT | Turbine Inlet Temperature |
| RANS | Reynolds-averaged Navier-Stokes |

improvement of local and globally-averaged heat transfer rate. Bhuiya et al. [9] investigated the effects of helix angle on the heat transfer augmentation of a turbulent flow through a tube by using a double helical tape. Hedlund et al. [10] experimentally analyzed the effects of Reynolds number and the ratio of the inlet temperature to the wall temperature on the globally-averaged Nusselt number and presented a correlation for these variables in an acceptable range of *Re*. Later, Ling et al. [11] used the liquid crystal technique to measure the circumferentially and axially averaged *Nu* near the swirl chamber walls. They used a cylindrical vortex chamber with two rectangular inlet slots similar to experiments of Hedlund et al. [10] and showed that the results are in good agreement with Hedlund's correlation for the globally-averaged Nusselt number. Swirling flow in two parallel swirl tubes connected with a bent duct using a heat and mass transfer analogy is investigated by Wasserman et al. [12] experimentally. They have observed an enhanced heat transfer in the swirling flow compared to the non-swirling flow. Looking for further improvements of the cooling performance, some researchers [13–15] combined the impingement cooling and the swirl cooling methods, and experimentally investigated the characteristics of swirling impinging jets. In a more recent experimental study, Bruschewski et al. [16] investigated the effects of Reynolds number, Swirl intensity, and geometrical parameters on the swirl cooling with water as the coolant fluid. They also simulated their experiment using a Large Eddy Scale (LES) model and validated their results with their own experimental data. Compared to the non-swirling flow, they observed that in the swirling flow, the *Nu* and the pressure drop was increased by a factor of 4.7 and 43, respectively.

Some researchers have attempted to enhance the swirl cooling applicability and effectiveness by using a new shape for swirl chamber, instead of usual circular chambers. Hwang and Cheng [17] implemented a triangular duct with tangential injections near leading edge of a turbine blade and presented a correlation for Nusselt number as a function of Reynolds number. Bovand et al. [18] utilized the swirl cooling for refrigeration purpose and they numerically investigated the effects of vortex tube curvature on the cooling performance. They observed that straight vortex tubes and 150° curved vortex tubes have higher performance as refrigerators compared to other curved tubes. Kusterer et al. [19] investigated another swirl cooling configuration named Double Swirl Chamber (DSC) which consists of two parallel swirl chambers merged to each other. They compared the results of heat transfer in DSC and single Swirl Chamber (SC) configurations and observed up to 41% locally and 34.5% globally improvement of the rate of heat transfer. Khalatov et al. [20] performed an experiment on a novel three passage serpentine cyclone cooling scheme and obtained correlations regarding heat transfer and flow parameters. Kusterer et al. [21,22] enhanced their DSC design using a Computational Fluid Dynamic (CFD) model and compared DSC and SC configurations with impingement cooling and obtained superior results using DSC configuration.

Swirl cooling, as a promising internal cooling method, can be implemented with or without the film cooling method. Qian et al. [23] experimentally studied the benefits of using both swirl and film cooling methods on a blade trailing edge, where space limitations make it difficult to cool that area by using an internal or film cooling method exclusively. They also observed 20% increase in average heat transfer coefficient when swirl cooling used as an internal cooling method, compared to impingement cooling. Lerch et al. [24] conducted an experiment on combined swirl-film cooling on a blade leading edge. They found that the swirl cooling can enhance the internal cooling of a blade, but it has consequences on film cooling performance which might be undesirable. By different swirl chamber configurations, adiabatic film effectiveness values are obtained from 0.3 up to 2 times the reference configuration. Fan et al. [25] studied a steady state case numerically to find the effect of film hole geometry on the performance of the swirl cooling.

With current advances in CFD methods and increasing the computational capacity of typical computers, many researchers have started to simulate and optimize the swirl cooling in different working conditions. Liu et al. [26] numerically simulated the swirling flow in both geometries of Hay and west [4] and Ling et al. [11] with four different turbulence models and found that the SST $k-\omega$ results to the best accuracy among them. Later, Liu et al. [27,28] utilized CFD modeling to find the effects of inlet nozzle height and inlet nozzle spacing on swirl cooling heat transfer coefficient and pressure drop. In similar researches, Du et al. [29,30] numerically studied the effects of jet nozzle geometry, number, and angle on the swirl cooling characteristics. In a recent study, Damavandi et al. [31] performed a multi-objective optimization in order to find the maximum heat transfer rate and the minimum pressure loss in a swirl chamber. They observed 12.6% enhancement of the thermal-hydraulic parameter at the breaking point of