Int. Symp. on Heat Transfer in Gas Turbine Systems
9*14 August 2009, Antalya, Turkey

EFFECT OF INTERNAL RIB CONFIGURATIONS ON THE DISCHARGE COEFFICIENT OF A 30-DEG INCLINED FILM COOLING HOLE

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ABSTRACT

This paper presents the discharge coefficients of 30° inclined cylindrical film cooling holes with a length to diameter ratio of 6. Measurements have been performed varying the position of quadratic ribs positioned normal to the flow direction inside the coolant supply channel and the crossflow Mach number at the hole inlet (Ma_c=0-0.3). The external crossflow Mach number has been kept constant at Ma_m=0.3. The internal and the external flow have been oriented parallel and perpendicular to each other. The lateral hole angle has been set to 0°, 45°, and 90°. The results given in terms of discharge coefficients versus the pressure ratio show a decrease of the discharge coefficient by placing ribs into the internal channel in case of a parallel orientation of internal crossflow, hole axis and external crossflow. This effect is more pronounced the closer the last upstream rib to the hole inlet is. In case of a perpendicular orientation some rib configurations even show a benefit compared to the reference case without internal ribs. The combined effect of internal crossflow Mach number, orientation of internal crossflow and hole axis and rib configurations on the discharge coefficient has been correlated using the jet-to-internal crossflow momentum flux ratio. Excellent agreement has been found comparing measured and predicted data.

INTRODUCTION

Film cooling is the state-of-the-art technology for cooling hot gas components in modern gas turbines. Comparatively cool air, taken from the compressor and bypassed to the first turbine stages, is blown out from coolant supply channels through discrete film cooling holes onto the hot gas surface. To increase the convective heat transfer in the internal channels, turbulators like ribs can be inserted. Placing the turbulators at different positions relative to the film cooling holes strongly influences the flow properties at the inlet regions of the holes and thus affects the mass flux through the holes. Since the cooling performance strongly depends on the flow rate ejected through the film cooling hole, the knowledge of the discharge coefficient is crucial for the design of a film cooling configuration. The discharge coefficient is defined according to the following equation:

$$c_D = \frac{\dot{m}_h}{\dot{m}_{ideal}} = \frac{\dot{m}_h}{p_{tc}\left(\frac{p_m}{p_{tc}}\right)^{\frac{\kappa+1}{2\kappa}}\sqrt{\frac{2\kappa}{(\kappa-1)RT_{tc}}\cdot\left[\left(\frac{p_{tc}}{p_m}\right)^{\frac{\kappa-1}{\kappa}}-1\right]}\cdot\frac{\pi}{4}D^2} \qquad (1)$$

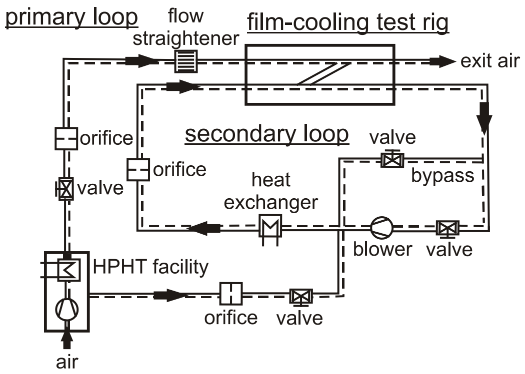

Figure 1. Test facility

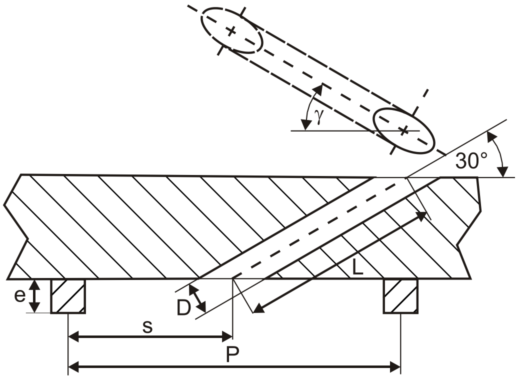

Figure 2. Hole geometry

In recent decades lots of studies have been performed investigating the effect of various geometric as well as aerodynamic influencing factors on the discharge coefficient. A comprehensive review of published data has been given by Hay and Lampard [1998]. Cylindrical holes have been tested by Burd and Simon [1999] regarding the hole length-to-diameter ratio, by Hay et al. [1983] and Gritsch et al. [2001] regarding the inclination angle, the lateral hole angle, and the influence of internal and external crossflow. Different hole shapes in combination with crossflow have been presented by Hay and Lampard [1995] and Gritsch et al. [1997]. Correlations predicting the discharge coefficient depending on internal and external crossflow have been developed by Hay et al. [1994] and Gritsch et al. [1998] for cylindrical holes, and by Gritsch et al. [2000] for shaped holes. In spite of the large number of investigations concerning the discharge coefficient of film cooling holes, less attention has been given to the influence of the geometry of internal turbulated channels. Only Bunker and Bailey [2001] presented a study in which the effect of square turbulators on the discharge coefficient is discussed.

EXPERIMENTAL APPARATUS

The tests have been carried out in a continuous operating wind tunnel. The internal and external crossflow situation - present at the hole inlet and exit region of a film cooling hole - has been modelled by two square channels. The external channel is directly supplied by the high pressure high temperature facility (HPHT). The internal channel is part of a closed loop also supplied by the HPHT facility and driven by an extra blower (Figure 1). By doing so two decisive advantages have been realised. First, the pressure and the Mach number of the coolant crossflow can be adjusted independently. Second, the mass flux through the film cooling hole can be measured directly with high accuracy by an orifice at the supply to the closed loop. The internal and the external channel have been oriented parallel (β=0°) and perpendicular (β=90°) to each other, representing the flow situation in a turbine blade and vane, respectively. They are connected by a scaled-up film cooling hole with a diameter of D=10mm (Figure 2). The hole has an inclination angle of α=30° and a length-to-diameter ratio of L/D=6. The lateral hole angle has been set to γ=0°, 45°, and 90°. Six ribs upstream of the hole inlet and one rib downstream of it have been placed at the top wall of the internal channel to guarantee periodic flow conditions. All ribs have a quadratic cross-section with an edge length of e/D=1 and are placed orthogonally to the internal flow direction. The pitch-to-edge length ratio is P/e=10. The position of the hole inlet has been varied in three discrete steps: Just downstream of a rib (s/D=2.5), in the middle between two ribs (s/D=5D) and just upstream of a rib (s/D=7.5D). Additional reference cases without ribs have been measured for all geometrical configurations.

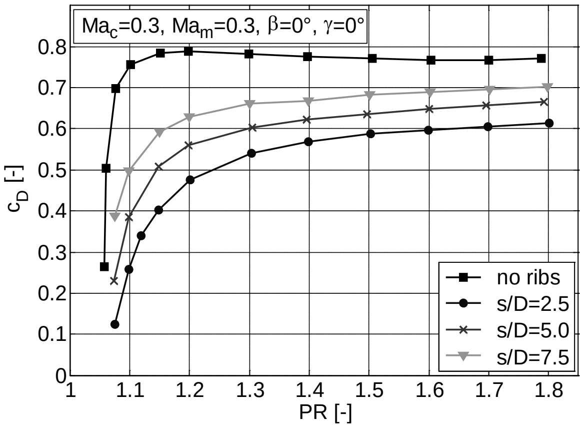

Figure 3. Discharge coefficient versus pressure ratio, effect of rib distance, parallel orientation

EXPERIMENTAL RESULTS

The effect of different positions of the hole relative to internal ribs on the discharge coefficient is shown exemplarily in Figure 3 for parallel orientation of internal and external flow (β=0°). It can be seen clearly, that reducing the distance of the last upstream rib relative to the hole inlet strongly decreases the discharge coefficient, particularly at low pressure ratios. In case of a parallel arrangement of internal flow and hole axis, an additional momentum in hole axis direction results from internal crossflow and thus supports the coolant to enter the hole. By placing ribs inside the coolant supply channel the flow downstream of a rib is highly turbulent and recirculation regions form. The velocity component in hole axis direction is reduced which leads to decreased discharge coefficients. This effect is more pronounced the closer the last upstream rib to the hole inlet is.

CORRELATION PROCEDURE

First of all a baseline discharge coefficient c_{D0} has been measured at internal plenum conditions. As presented by Gritsch et al. [1998], the influence of internal crossflow can be correlated by plotting the normalized discharge coefficient c_D/c_{D0} versus the jet-to-internal momentum flux ratio. As the deflection of the flow entering the hole is the most distinctive parameter, an individual correlation function must be drawn for each total deflection angle ($|\beta-\gamma|$ = 0°, 45°, 90°). The effect of internal ribs has been taken into account by a smoothing function Γ, which has been defined according to:

$$\Gamma\left(I_{Jet/IntCr},\frac{s}{D},\beta,\gamma\right)=\begin{cases}1 \quad \text{, in case of no ribs}\\ 1+H\left(\frac{s}{D},\beta,\gamma\right)\dfrac{\exp\left[-0.2\cdot\left(I_{Jet/IntCr}+1\right)\right]}{\left\{1+\exp\left[-\left(I_{Jet/IntCr}+1\right)\right]\right\}^{2}}\end{cases} \tag{2}$$

Applying the smoothing function to the rib cases and plotting all measured discharge coefficients with a deflection angle of $|\beta-\gamma|$ = 0° versus the jet-to-internal crossflow momentum ratio, the scatter plot shown in Figure 4 can be drawn. A rational correlation function matches quiet well the data. Analogue functions can be drawn for the remaining deflection angles. Applying the correlation to an arbitrary geometrical configuration and different rib positions, and comparing the predicted discharge coefficient with measured data, an excellent agreement can be found as shown in Figure 5.

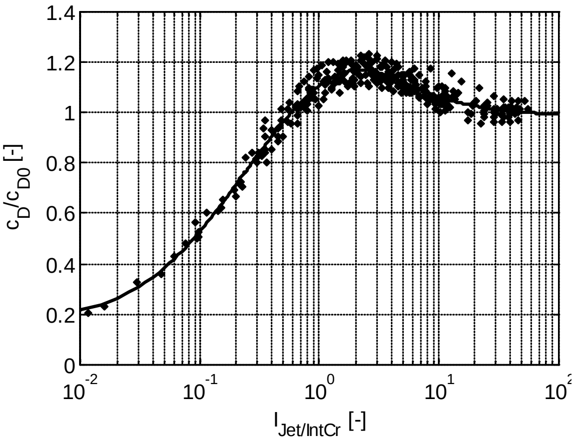

Figure 4. Correlation function for deflection angle |β-γ|=0°

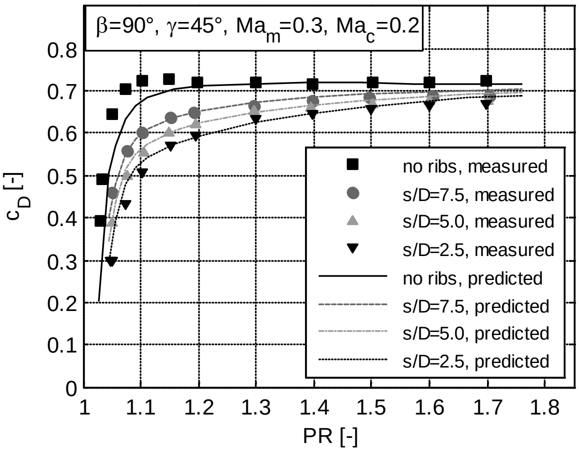

Figure 5. Comparison of measured and predicted discharge coefficients

CONCLUSIONS

The influence of quadratic ribs inside the coolant supply channel on the discharge coefficient of film cooling holes has been presented. It could be shown that the deflection of the flow entering the hole is crucial for the inlet flow losses and thus the discharge coefficient. Internal ribs have a negative effect on the discharge coefficient as long as the internal crossflow induces an additional momentum in hole axis direction for the reference case without ribs. A discharge coefficient correlation has been introduced using the jet-to-internal momentum flux ratio. Excellent agreement has been found comparing measured and predicted discharge coefficients.

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