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TRAILING EDGE FILM COOLING OF GAS TURBINE AIRFOILS – EFFECTS OF EJECTION LIP GEOMETRY ON FILM COOLING EFFECTIVENESS AND HEAT TRANSFER

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The present paper concentrates on trailing edge film-cooling of modern high-pressure turbine blades using coolant ejection through planar slots with a pressure side cutback. The experimental test section consists of a generic scaled-up trailing edge model. The effects of different geometric configurations on the structure and the performance of the cooling-film are investigated in terms of film-cooling effectiveness, heat transfer coefficients, and discharge behavior. The interaction between an internal turbulator array of ribs with the ejection slot lip is of major interest. Different designs of the coolant ejection lip are applied. Four different ratios of lip thickness to ejection slot height (t/H = 0.2, 0.5, 1.0, 1.5) are investigated and three different lip contours representing typical manufacturing imperfections and wear. The experiments are performed at engine-realistic density ratios. The blowing ratios are varied between 0.2 < M < 1.25.

INTRODUCTION

Due to structural and aerodynamic constraints the application of trailing-edge film-cooling in first stage high-pressure turbines still holds many challenges in order to enhance the thermodynamic efficiency. One major goal is the reduction of coolant mass flow for a given cooling performance. The latter even needs to be increased, when higher turbine inlet temperatures are considered. The film-cooling performance in this context is characterized by the isoenergetic heat transfer coefficient h_f with

$$h_f = \frac{\dot{q}_w}{T_{aw} - T_w} \tag{1}$$

and the adiabatic film-cooling effectiveness η_{aw} defined as

$$\eta_{aw} = \frac{T_{rec} - T_{aw}}{T_{rec} - T_c} \tag{2}$$

Numerous studies on film cooling have been published in the past. Only few publications exist, those deal with coolant ejection on a trailing edge pressure-side cutback. The effects of the lip thickness on the film cooling effectiveness have been experimentally investigated by Taslim et al. [1990]. Besides the ejection angle, slot width and density ratio, they varied the slot lip thickness to height ratio between 0.5 and 1.25 and concluded that the film cooling effectiveness decreases as the lip thickness is increased due to intensified shedding effects on the ejection lip. Numerical and experimental studies were done by Holloway et al. [2002] who identified unsteady vortex shedding at the ejection lip to be the major driving mechanism for the mixing of the cooling film with the hot gas. Martini et al. [2003, 2004, 2006a] presented various numerical and experimental studies on the variation of internal cooling designs including pin fins and rib arrays. An increasing number of authors utilize numeric methods to visualize and analyze the mixing processes involved in film cooling. Martini et al. [2006b] and Joo and Durbin [2009] use hybrid numerical approaches for film cooling investigations, since the complex three-dimensional mixing flow structure cannot reliably be predicted by conventional statistical methods (RaNS). An important goal is still to improve the understanding and control of the coolant mixing processes. In order to do so, the main focus of this study is on the interaction between internal geometries and the ejection lip. It is to be observed, how the lip shape can affect the mixing and how this knowledge can be used to improve the cooling performance in future designs.

EXPERIMENTAL SET-UP

The experiments are conducted in an atmospheric open loop wind tunnel. The test rig is supplied by a radial compressor that delivers air of up to 140kPa absolute pressure. The air is heated up to 500K in an electric heater unit, and passes an arrangement of mixers and flow straighteners. Upstream of the test section, a turbulence grid is inserted to control the turbulence level at the slot exit. The coolant air is supplied by an additional compressor at ambient temperature (300K). With this arrangement engine realistic density ratios and blowing ratios can be applied at the same time. A schematic view of the test section is given in Figure 1. The modular design allows for an easy assembly of different cooling configurations. In the present study, a double in-line rib array is inserted. Besides the above described parametric study of the lip thickness, the shape of the ejection lip is varied. The rounded contours represent typical features of manufacturing (Shape B) and wearing (Shape C).

The measurements concentrate on the cooled surface in the near slot region up to 15 times the slot height downstream of the slot. The thermographic measurements are done using an infrared camera above the test section at two different thermal conditions on the test surface. An in-situ calibration method applied to the camera’s raw signal provides for very accurate surface temperature measurements. The superposition approach of film cooling is used to obtain film cooling effectiveness and heat transfer coefficients.

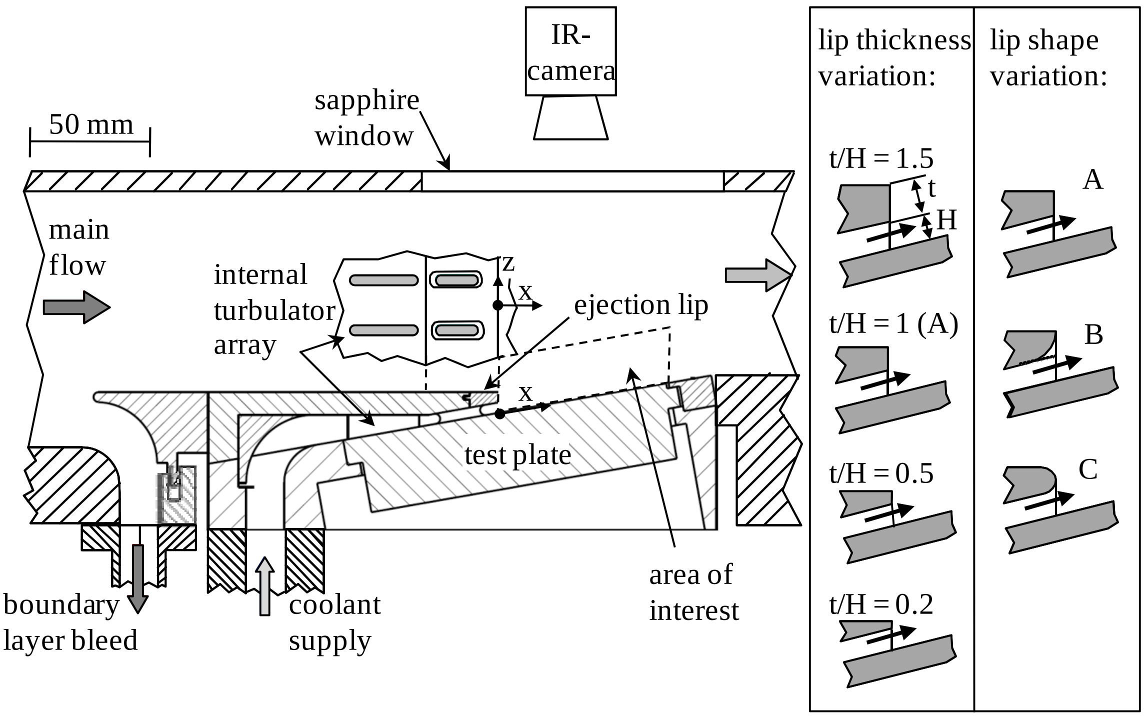

Figure 1. Generic test section for trailing film cooling experiments with varying ejection lip geometry

RESULTS

The contours of local film cooling effectiveness given in Figure 2 demonstrate the qualitative effect of the ribs on the film cooling performance for two different lip thicknesses and three different blowing ratios. In the wake region of the ribs the mixing of the cooling film is increased due to higher turbulence levels within this region. Looking at the thin ejection lip (x/H = 0.2) this leads to lower film cooling effectiveness downstream of the ribs compared to the space between the ribs. At an increased lip thickness (e.g. t/H = 1) an inverse effect can be observed. Vortex shedding from the blunt ejection lip causes a drop of film cooling effectiveness, whereas the wake region behind the ribs suppresses the vortex shedding and, therefore, stabilizes the cooling film.

The laterally averaged values plotted versus blowing ratio are given in Figure 3. Starting from M = 0.8 the film cooling effectiveness drops and recovers again at the highest investigated blowing ratios. This effect is in close accordance to the measurements of Martini et al. [2006a]. It is not visible with the thin lip geometries (x/H = 0.2; 0.5). Even at x/H = 8 the thin lip configurations show an almost intact cooling film with an effectiveness of nearly unity. Looking at the heat transfer coefficients, the thickness seems to play a minor role. However, a slight tendency to higher heat transfer coefficients with thicker lips can be observed, which is mainly caused by increased turbulence levels.

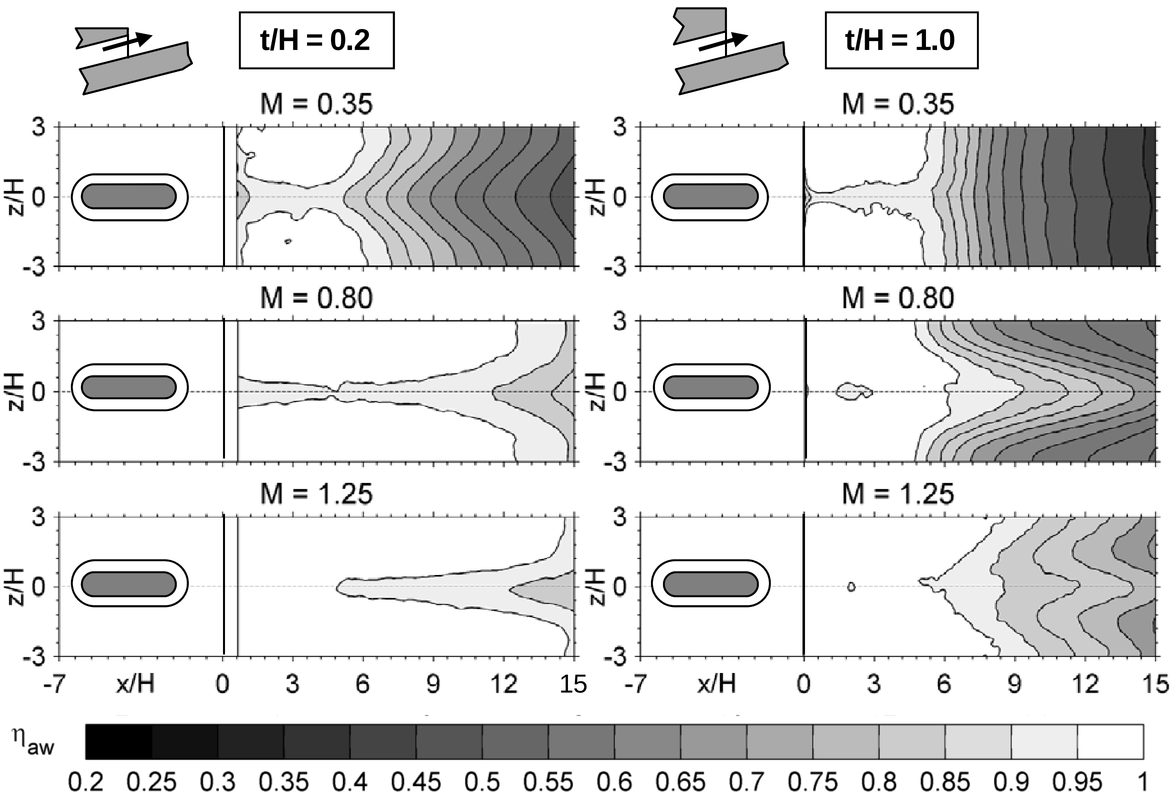

Figure 2. Contours of local film cooling effectiveness downstream of the ejection slot at different blowing ratios for two different lip thicknesses

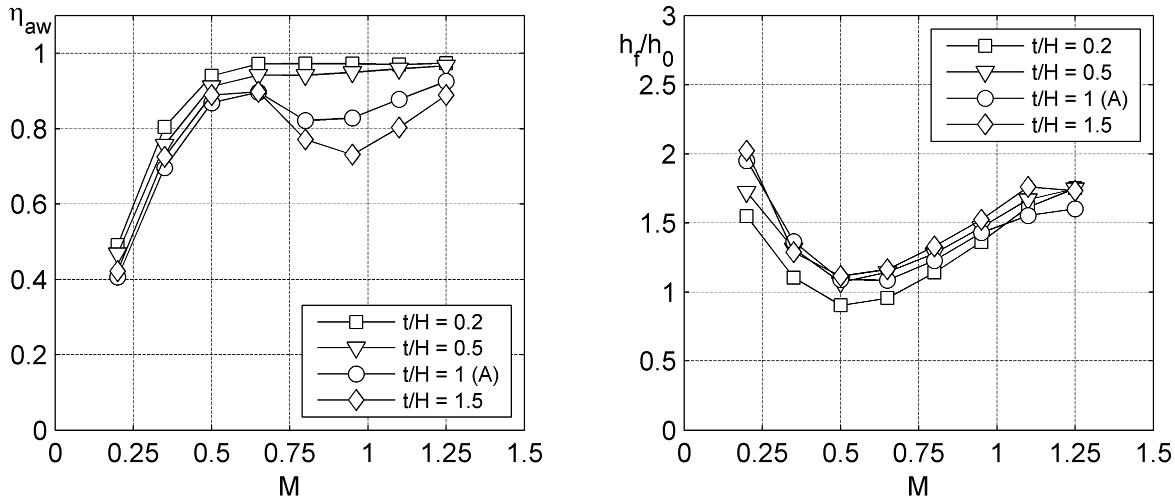

Figure 3. Laterally averaged adiabatic film cooling effectiveness and normalized heat transfer coefficient distributions at x/H = 8 downstream of the slot

CONCLUSIONS

Experimental data on the variation of the ejection lip thickness and shape of a trailing edge have been presented. The variation of the ejection lip thickness has a pronounced effect on the mixing process of the cooling film, as well as on the discharge coefficients. Moreover, the cooling performance depends on the blowing ratio and can locally be supported by internal ribs. The parametric modifications show only minor influences on the heat transfer. A tendency to increased heat transfer coefficients with thicker lips can be observed.

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