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AN EXPERIMENTAL STUDY OF AIRFOIL AND ENDWALL HEAT TRANSFER IN A LINEAR TURBINE BLADE CASCADE – SECONDARY FLOW AND SURFACE ROUGHNESS EFFECTS

Marco Lorenz[1,*], Achmed Schulz[1] and Hans-Jörg Bauer[1]
[1] Institut für Thermische Strömungsmaschinen
Universität Karlsruhe (TH), 76131 Karlsruhe, Germany
([*]Corresponding author: lorenz@its.uka.de)

The present study is part of a comprehensive heat transfer analysis on a highly loaded turbine blade and endwall with varying surface roughness. In this paper a smooth airfoil with an endwall of varying surface roughness is considered in order to investigate secondary flow and surface roughness effects on airfoil and endwall heat transfer. The measurements have been conducted in a linear cascade at several freestream turbulence levels (Tu_1 = 1.4% to 10.1%) and varying inlet Reynolds numbers. Aerodynamic measurements on the airfoil at midspan have been carried out. Heat transfer on both the full-span suction and pressure surfaces of the airfoil and endwall is shown for smooth surfaces. Furthermore, rough endwall surfaces are compared to the smooth reference case showing a maximum increase of local heat transfer up to 240% due to surface roughness.

INTRODUCTION

In modern gas turbines high thermodynamic efficiency is reached by increasing turbine inlet temperature, which is far beyond the material's melting point and, thus, requires sophisticated cooling concepts. In order to predict lifetime of turbine components under such severe operating conditions and for optimizing the cooling, an exact knowledge of surface heat transfer in the turbine is necessary. Heat transfer is affected by various factors, like pressure distribution, wakes, surface curvature, free-stream turbulence, secondary flow effects, and surface roughness. In contrast to the first five factors surface roughness is not constant during the lifetime of gas turbines but changes due to erosion, corrosion or particle deposition.

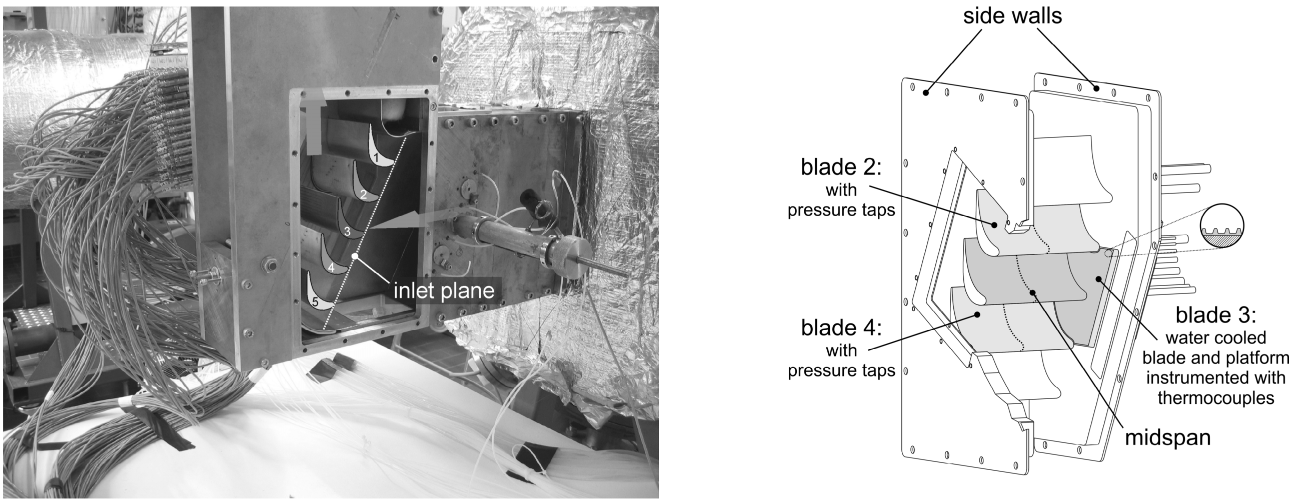

Fig. 1: Test facility (left) and cascade with instrumented airfoils (right)

Extensive investigation on heat transfer at midspan of airfoils has been made e.g. by Dullenkopf et al. [1992], Schiele et al. [1995], Lorenz et al. [2008]. Bons and McClain [2003] show flat plate heat transfer measurements of real turbine roughness. Stripf et al. [2005] systematically investigated surface roughness effects on midspan heat transfer. Since in modern gas turbines the endwall region becomes more and more thermally loaded increasing focus lies on airfoil heat transfer in the close vicinity of the endwall and on the endwall itself, where secondary flows dominate the heat transfer behavior. The complex vortex pattern of these secondary flows has been investigated by Langston et al. [1977] and summarized by Wang et al. [1997]. Detailed external heat transfer measurements on a smooth turbine blade and endwall by Graziani et al. [1980] show strong secondary flow effects on airfoil and endwall heat transfer. Blair [1994] investigates airfoil and platform heat transfer for a smooth reference case in comparison to a roughened surface and reports an increase in heat transfer of up to 40% due to surface roughness. Further work by Stripf et al. [2007] systematically examines different surface roughness and its effect on heat transfer on an airfoil close to the endwall. The present experimental study is part of a comprehensive heat transfer analysis on a highly loaded turbine blade and platform with varying roughness. Whereas a first publication [Lorenz et al. 2008] concentrated on midspan heat transfer of a smooth airfoil, in this paper the full-span heat transfer distribution on the blade and on its platform will be analyzed. Furthermore, a variation of surface roughness and its effect on external heat transfer will be shown.

EXPERIMENTAL SETUP

The measurements are conducted on a highly loaded linear turbine cascade in a hot wind tunnel as shown in Fig. 1. The cascade consists of five untwisted turbine blades of which the inner three blades are instrumented as shown in Fig. 1. Blade 2 and 4 are equipped with pressure taps for measuring the pressure distribution. Blade 3 is instrumented for heat transfer measurements. Both airfoil and platform are water cooled and contain approx. 150 thermocouples in order to measure the surface temperature distribution as well as the cooling water temperature. The local heat transfer is determined with the gradient method using the measured temperature distribution as boundary condition for calculating the local wall heat flux [Stripf et al. 2005]. Two different turbulence grids with rectangular bars can be placed at two different locations upstream of blade 3 in order to generate different freestream turbulence levels. Thus, the turbulence intensity in the cascade inlet plane Tu_1 can be varied from 1.4 % (without grid) up to 10.1%. From measurements of the decay of turbulence intensity downstream of each grid by means of hot wire constant temperature anemometry the turbulent dissipation length scale at the cascade entry $L_{\varepsilon,1}$ is determined. In order to investigate varying surface roughness smooth or rough metal foils can be glued on the airfoil and its platform by a vacuum bagging technique. The roughness consists of arrays of truncated cones.

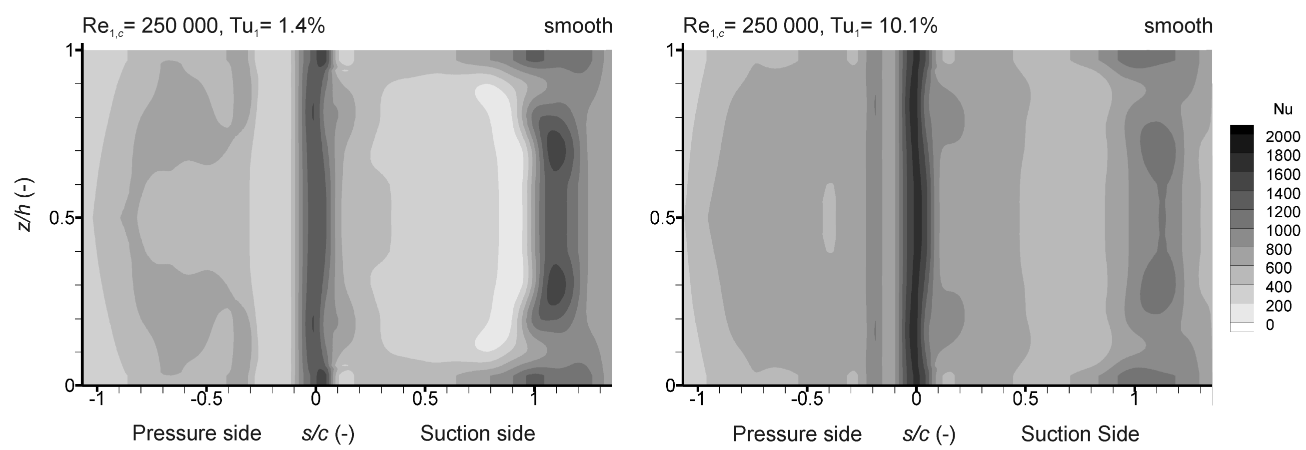

Fig. 2: External heat transfer distribution on a smooth airfoil at different freestream turbulence levels

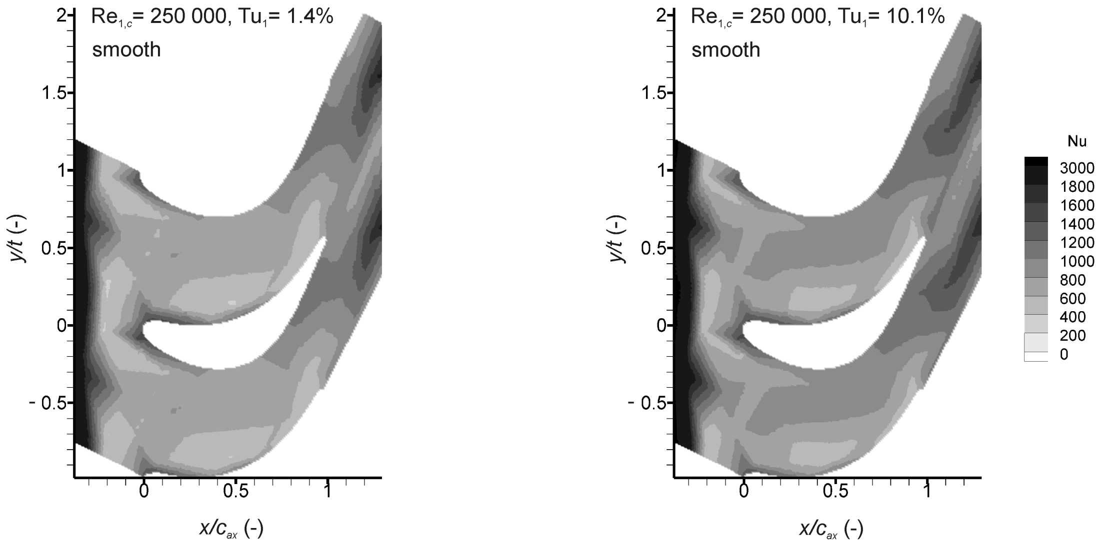

Fig. 3: External heat transfer distribution on a smooth endwall at different freestream turbulence levels

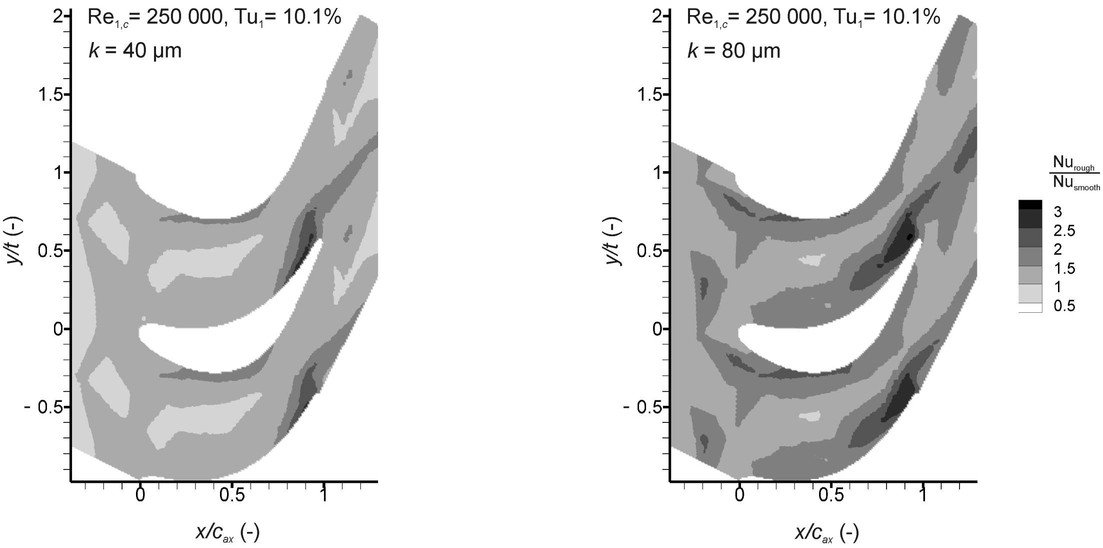

Fig. 4: External heat transfer augmentation due to surface roughness for different roughness heights *k*

RESULTS

External heat transfer for both airfoil and endwall is shown in terms of Nusselt number distributions as indicated by Equation 1. The Nusselt number is determined using the local heat transfer coefficient h, the airfoil chord length c and a constant thermal conductivity for air k. The heat transfer coefficient h is referring to the temperature difference between total inlet temperature $T_{tot,1}$ and wall temperature T_w.

$$\mathrm{Nu} = \frac{h \cdot c}{k} = \frac{\dot{q}}{T_{tot,1} - T_w} \cdot \frac{c}{k} \tag{1}$$

As can be observed in Fig. 2 turbulence intensity has a large impact on heat transfer in the stagnation point, on the pressure side as well as on the suction side of the airfoil. A detailed discussion about the influence of freestream turbulence on heat transfer at midspan is given in Lorenz et al. [2008]. Fig. 2

additionally reveals the influence of secondary flow effects on airfoil heat transfer near the platform on the suction side (for $z/h < 0.2$).
In contrast to airfoil heat transfer the Nusselt number distribution on the endwall does not depend as strongly on the level of freestream turbulence as can be seen in Fig. 3. In the measuring setup an adiabatic wall upstream of the cooled platform is provided ensuring a well defined start of the temperature boundary layer at the left boundary of the endwall. This leads to a comparably high heat transfer in this region. Mainly it can be observed that heat transfer increases as the flow accelerates from the left to the right because of the decreasing cross section through the passage.
In Fig. 4 it can be seen that endwall heat transfer is highly affected by surface roughness. Even if the roughness consisting of truncated cones with a height k of 40 µm and 80 µm respectively is equally distributed over the platform its effect on heat transfer is quite non uniform. Besides a tendency to higher local Nusselt numbers due to surface roughness it can be seen that the roughness induced heat transfer is largest near the airfoil reaching a maximum increase of about 240%.

CONCLUSION

Measurements on a highly loaded turbine blade and its platform have been presented accounting for secondary flow effects on external heat transfer. Surface roughness effects on endwall heat transfer have been investigated. It has been shown that airfoil heat transfer is highly affected by secondary flow effects near the endwall. Moreover, airfoil heat transfer is strongly influenced by freestream turbulence. It has been shown that freestream turbulence does not affect endwall heat transfer to the same extent. However, surface roughness increases endwall heat transfer dramatically, leading to a maximum Nusselt number augmentation of 240% in some regions of the platform.

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