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Coherent structures in trailing-edge cooling and the challenge for turbulent heat transfer modelling

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ABSTRACT

The present paper tests the capability of a standard Reynolds-Averaged Navier–Stokes (RANS) turbulence model for predicting the turbulent heat transfer in a generic trailing-edge situation with a cutback on the pressure side of the blade. The model investigated uses a gradient-diffusion assumption with a scalar turbulent-diffusivity and constant turbulent Prandtl number. High-fidelity Large-Eddy Simulations (LES) were performed for three blowing ratios to provide reliable target data and the mean velocity and eddy viscosity as input for the heat transfer model testing. Reasonably good agreement between the LES and recent experiments was achieved for mean flow and turbulence statistics. The LES yielded coherent structures which were analysed, in particular with respect to their effect on the turbulent heat transfer. For increasing blowing ratio, the LES replicated an also experimentally observed counter-intuitive decrease of the cooling effectiveness caused by the coherent structures becoming stronger. In contrast, the RANS turbulent heat transfer model failed in predicting this behaviour and yielded significantly too high cooling effectiveness. It is shown that the model cannot predict the strong upstream and wall-directed turbulent heat fluxes caused by large coherent structures, which were found to be responsible for the counter-intuitive decrease of the cooling effectiveness.

1. Introduction

Film cooling is an important technology for enhancing the performance of gas turbines for power generation and aircraft propulsion because it allows to increase the maximum allowable turbine inlet temperature, and hence, the overall thermal efficiency and power output. In the high-pressure turbine, both the leading and trailing-edge section of the blades are exposed to very high temperatures and, therefore, require extensive cooling (Bogard and Thole, 2006; Cunha and Chyu, 2006). In the present study, the focus is on film cooling of the trailing-edge with cutback on the pressure-side of the blade. For this configuration, the cooling air passes through the interior of the blade, which represents an internal convective cooling system with arrays of ribs or pin–fins. Subsequently, the cooling air is ejected onto the exterior cutback surface over which it forms a protective cooling film as shown in Fig. 1. In experiments, the blowing ratio M is often taken as a measure for the amount of coolant. M is the ratio of coolant mass flux $(\rho U)_\mathrm{c}$ to hot gas mass flux $(\rho U)_\mathrm{h}$ and depends for incompressible flows on the ratios of bulk velocity $U_\mathrm{c}/U_\mathrm{h}$ and bulk density $\rho_\mathrm{c}/\rho_\mathrm{h}$, respectively bulk temperature $T_\mathrm{c}/T_\mathrm{h}$ for ideal gases:

$$M = \frac{\rho_\mathrm{c}}{\rho_\mathrm{h}}\frac{U_\mathrm{c}}{U_\mathrm{h}} = \frac{T_\mathrm{h}}{T_\mathrm{c}}\frac{U_\mathrm{c}}{U_\mathrm{h}}, \tag{1}$$

where the indices ‘c’ and ‘h’ refer to the values in the cold and hot gas streams, respectively. The degree of mixing between the two gas streams is typically quantified by the adiabatic film cooling effectiveness η_aw, which can be determined from measurements of the adiabatic wall temperature T_aw:

$$\eta_\mathrm{aw} = \frac{T_\mathrm{h} - T_\mathrm{aw}}{T_\mathrm{h} - T_\mathrm{c}}, \tag{2}$$

where the T is the bulk temperature in the respective streams.

In order to optimize the cooling performance, systematic parameter studies are required. Previous experimental studies have shown that almost any variation in the geometry of the internal or external design has an impact on the cooling performance; e.g. variations in the rib- or pin–fin-array, ejection-slot height, cutback-lip thickness or shape, and ejection angle were reported for geometries with and without so-called land extensions, (see e.g.

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Taslim et al., 1992; Martini et al., 2006a; Fiala et al., 2010; Horbach et al., 2011; Benson et al., 2012). The large number of influence parameters makes experimental studies very expensive. Moreover, experiments are often subject to constraints, so that numerical prediction methods, namely Computational Fluid Dynamics (CFD) methods, became an important complementary tool in the development of optimized cooling designs.

The standard CFD modelling approach for optimizing a cooling design is to employ methods based on Reynolds-Ageraged Navier–Stokes (RANS) turbulence closures. These closures are generally used for preliminary design studies and are cost-efficient compared to more advanced approaches, such as Large-Eddy Simulations (LES), see e.g. Pope (2000) for an overview of RANS and LES. In the RANS approach, a turbulence model is provided for (1) the unknown Reynolds-stresses in the momentum transport equations and for (2) the unknown turbulent heat fluxes in the energy transport equation. The Reynolds-stresses can be determined via a turbulent-viscosity model (e.g. k—ϵ- or k—ω-model) or via the solution of modelled Reynolds-stress transport equations, e.g. model of Launder et al. (1975, LRR) or Speziale et al. (1991, SSG). On the other hand, the turbulent heat fluxes are typically determined via a gradient-diffusion assumption with a scalar turbulent diffusivity and constant turbulent Prandtl number, Pr_t. Such a model will be denoted for brevity as the Pr_t-model. For the Pr_t-model, the underlying modelling assumptions postulate a direct analogy between the momentum and heat transfer, i.e. the so-called Reynolds analogy. While the above turbulence closures for the momentum transfer can deliver acceptable results even for practical flows, the Pr_t-model can be used to compute only relatively simple boundary-layer, channel or pipe flows (Kays, 1994). For many practical flows, the Pr_t-model fails in predicting the heat transfer correctly. However, it remains the most widespread model employed and is the default model in virtually all CFD codes, although there exists a wide range of more sophisticated alternatives (Launder, 1978, 1988; Speziale and So, 1997; Hanjalić, 2002). Fairly recent overviews are provided by Grötzbach (2007) and Hanjalić and Launder (2011).

The failure of a typical RANS approach in replicating the measured film cooling effectiveness along a turbine trailing-edge model was reported by Medic and Durbin (2005), Martini et al. (2006b), and Egorov et al. (2010). The above studies proposed that large-scale unsteadiness played an important role for the mixing between the hot and the cold gas streams, which motivated the use of unsteady RANS (URANS, Medic and Durbin, 2005; Joo and Durbin, 2009) and hybrid LES/RANS methods (Martini et al., 2006b; Joo and Durbin, 2009; Egorov et al., 2010); see Fröhlich and von Terzi (2008) for a review on hybrid LES/RANS methods. When using unsteady RANS, the authors found that their computations still significantly overpredicted the cooling effectiveness when compared to the experiments. In contrast, the use of a hybrid LES/RANS method including the Scale-Adaptive Simulation (SAS) method of Menter and Egorov (2010) allowed to capture the large-scale unsteadiness and its effect on heat transfer more realistically, so that the calculations yielded a significantly better agreement with the corresponding experiments (Martini et al., 2006b; Joo and Durbin, 2009; Egorov et al., 2010).

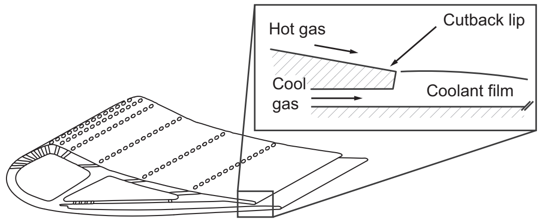

Fig. 1. Schematic of high-pressure nozzle guide vane with trailing-edge cutback film-cooling on pressure side of the blade.

Schneider et al. (2010) investigated by means of highly-resolved LES the role of large-scale unsteadiness for a trailing-edge design without internal turbulators corresponding to an experiment of Martini (2008). For the two blowing ratios $M = 0.5$ and 1.1 considered, an experimentally observed counter-intuitive behaviour could be reproduced, i.e. that the film cooling effectiveness can in fact decrease with increasing blowing ratio (Martini, 2008; Schneider et al., 2012). The LES data have shown that the counter-intuitive behaviour was related to a change in the type and strength of large coherent structures that were formed behind the blunt cutback-lip and, thereby, confirmed earlier conjectures of Martini (2008). In order to investigate further the reasons for this behaviour, Schneider et al. (2011) performed highly-resolved LES for a wider range of blowing ratios. Results from this study are presented in Fig. 2(a) and (b) to effectively illustrate the counter-intuitive decrease of η_{aw} within a limited range of blowing ratios. It is seen that while η_{aw} continuously increases for increasing M within the regions R1 $(0.35 < M \leqslant 0.65)$ and R3 $(0.95 < M \leqslant 1.25)$, it decreases within the region R2 $(0.65 < M \leqslant 0.95)$. In this context, it is also important to note that the counter-intuitive behaviour is generally suppressed or significantly attenuated in experiments with turbulators in the upstream section of the ejection slot (Martini et al., 2006a; Martini, 2008; Horbach et al., 2011). Schneider et al. (2011) describe a mechanism that can explain the counter-intuitive behaviour in the absence of internal turbulators: the decrease of the cooling effectiveness was related to strong coherent structures that caused strong turbulent heat fluxes directed not only towards the wall, but also against the mainstream direction.

The causes for the suppression of the counter-intuitive behaviour in the presence of internal turbulators were further investigated in the work of Schneider (2013). Internal turbulators were found to generate high levels of turbulence which were specifically characterized by frequency, amplitude, and phase difference of the dominating lateral velocity-fluctuation component. The characteristics depended on coolant mass flux and could result in a deformation and subsequent break-up of the large coherent structures. Because the break-up of the flow structures was associated with a decreased probability of strong vertical fluctuations, the vertical component of the turbulent heat flux vector was reduced compared to the cases without turbulators and, therefore, the counter-intuitive behaviour was suppressed.

1.1. Motivation and objectives

From the literature, it emerges that large coherent structures can play a dominant role for the film cooling of a turbine-blade trailing edge. In particular, the findings of Schneider et al. (2011) and Schneider (2013) highlight that turbulent heat fluxes require realistic modelling if one wants to optimize the cooling design by using the RANS approach. Until now, it is not clear whether the poor RANS predictions noted are caused by the turbulence model for the momentum transfer or by the model for the heat transfer. What if the turbulence model for the momentum transfer were to predict a perfect flow field and the turbulence model for the heat transfer causes the poor predictions? This is not a mere academic question, but one that has important implications for the industrial design process.

Considering market-dominating commercial CFD codes, these provide several options with varying level of sophistication for calculating the turbulent momentum transfer: e.g. the one-equation Spalart–Allmaras model, the two-equation k—ϵ- and k—ω-models, and the Reynolds-stress models of LRR and SSG. In contrast, the codes offer almost exclusively only a single option for calculating