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Evolution of jets effusing from inclined holes into crossflow

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Abstract

The turbulent flow structure and vortex dynamics of a jet-in-a-crossflow (JICF) problem, which is related to gas turbine blade film cooling, is investigated using the particle-image velocimetry (PIV) technique. A cooling jet emanating from a pipe interacts with a turbulent flat plate boundary layer at a Reynolds number $Re_\infty = 400{,}000$. The streamwise inclination of the coolant jet is 30° and two velocity ratios (VR = 0.28, VR = 0.48) and two mass flux ratios (MR = 0.28, MR = 0.48) are considered. Jets of air and CO_2 are injected separately into a boundary layer to examine the effects of the density ratio between coolant and mainstream on the mixing behavior and consequently, the cooling efficiency. The results show a higher mass flux ratio to enlarge the size of the recirculation region leading to a more pronounced entrainment of hot outer fluid into the wake of the jet. Furthermore, the lateral spreading of the coolant is strongly increased at a higher density ratio. The results of the experimental measurements are used to validate numerical findings. This comparison shows an excellent agreement for mean velocity and higher moment velocity distributions.

Keywords: Film cooling; Velocity ratio; Density ratio; Mass flux ratio; Particle-image velocimetry (PIV)

1. Introduction

To improve the efficiency of gas turbine engines the gas inlet temperature has to be increased beyond the failure temperature of the turbine blade and vane material. In other words, gas turbine blades have to be protected from the hot gases using a thin fluid film that is wrapped around the blade. To achieve such a protective layer cooler air is injected through discrete holes on the blade surface.

This problem has been analyzed by numerous numerical and experimental studies like, e.g., Guo et al. (2006), Renze et al. (in press), Walters and Leylek (2000) and Baldauf et al. (2001). The experiments, however, used intrusive techniques such as hotwires, cold wires, and thermocouples to obtain local, time resolved point measurements of the velocity, temperature, and mixing of the film-cooling mechanism. With these measurement methods the spatial structure of the flow field of a jet emanating from a hole into a turbulent boundary layer can only be resolved on a point by point basis. A better spatial resolution of the flow field can be achieved by the particle-image velocimetry (PIV) technique that has been used by Peterson and Plesniak (2004) and David et al. (2004) to study flow structures like the counter-rotating vortex pair (CVP) or wake vortices that appear in a JICF problem. Most of the PIV investigations as for instance Jovanovic et al. (2006) consider variations of parameters like the Reynolds number, blowing ratios, and the influence of jet shapes in a range that is relevant for the cooling process. However, the density difference between the coolant and the crossflow that appears in a gas turbine engine due to the temperature ratio is only considered in a recent publication by Bernsdorf et al. (2006), who discussed mean flow measurements but no turbulence statistics.

It is evident that experimental investigations of turbine blade flows at real temperatures, i.e., in the range of $1300 \leqslant T_G \leqslant 1600$ K, require extremely complex and expensive wind tunnel equipment. To circumvent problems due to the high temperatures investigations of effects of density differences between the coolant and the crossflow through the use of a denser cooling gas were carried out.

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Nomenclature

D	cooling hole diameter
DR	jet-to-mainstream density ratio $= \rho_j/\rho_\infty$
f	mixing fraction $= \rho_n/\rho_{tot}$
H	vertical distance between the surface of the plate and the top of the chamber
IR	jet-to-mainstream momentum ratio $= \rho_j u_j^2/\rho_\infty u_\infty^2$
MR	jet-to-mainstream mass flux ratio $= \rho_j u_j/\rho_\infty u_\infty$
Re_∞	local Reynolds number based on the distance from the leading edge
R_Θ	momentum thickness Reynolds number at the point of injection
H_{12}	shape factor at the point of injection
u_j	jet velocity
u'_{rms}	streamwise fluctuation velocity
u_∞	streamwise mean velocity
VR	jet-to-mainstream velocity ratio $= u_j/u_\infty$
X	streamwise distance based on hole center line
Y	vertical distance based on hole center line
Z	spanwise distance based on hole center line
δ	boundary-layer thickness
ρ	density

Subscripts

j	jet conditions
n	species index
∞	mainstream conditions
rms	root mean square
tot	total

The first experimental studies investigating the density influence on a film-cooling problem has been done by Goldstein and Eckert (1974) using Freon vapor to provide a denser coolant. A mixture of air and CO_2 was injected into the mainstream by Petersen et al. (1977). Adiabatic wall measurements showed that the film-cooling effectiveness through jet injection strongly depends on the density ratio. Teekaram et al. (1989) investigated CO_2 injections into the main air stream at two temperature conditions, i.e., two density ratios (DR = 1.25, DR = 1.67) were analyzed. The obtained heat transfer results showed a close agreement between the results of the injection to mainstream density ratios achieved either by changing the injection to mainstream temperature ratio or by using a foreign gas injection. Han and Mehendale (1986) studied the effect of the blowing ratio at an air and steam injection. Pietrzyk et al. (1990) conducted measurements in the flow field that resulted from cooling the air jet to obtain a density ratio of DR = 2. These measurements were carried out in the vicinity of the exit holes by means of the Laser-Doppler anemometry technique (LDA). In addition, Sinha et al. (1991) injected a cooled air stream into a crossflow and found that an increase in the coolant to mainstream density ratio leads to an improved film-cooling effectiveness. Mehendale et al. (1994) reports about the effect of density ratio on blade film effectiveness and heat transfer distributions over a linear turbine cascade achieved from CO_2 injection to produce a density ratio of DR = 1.48. Ekkad et al. (1997) confirm the higher cooling effectiveness for the CO_2 jet emanating from simple angled holes compared to compound angle injection using the transient liquid crystal technique. Applying the same measurement technique Ekkad et al. (1998) found out that an increase in coolant density caused a decrease in heat transfer coefficients at all blowing ratios. The injection of CO_2 provided an injection to mainstream density ratio of DR = 1.5 with the highest effectiveness at MR = 0.8. They also obtained an increase in coolant density had little effect on film effectiveness distributions at higher blowing ratios. Focusing on the velocity and temperature fluctuation measurements using a cold wire in conjunction with LDA have been conducted by Kohli and Bogard (2005) producing a density ratio of DR = 1.05 to study the turbulent transport of heat in a film-cooling field.

As indicated above, there has hardly been any previous experimental study using the PIV technique to analyze simultaneous the velocity and density influence on the complex turbulent flow field of a JICF problem. In addition, the other investigations that considered density ratios between the jet and the crossflow were only carried out to examine the effects of jet density on the wall temperature or the flow field on a point by point basis. They have, however, failed to describe the density effect on the vortical structures present within these flow fields. This is of particular importance as these structures dictate the final development of the flow field patterns which in turn determine the mixing process and the cooling efficiency of the JICF.

In this paper the flow pattern resulting from such an air–CO_2 mixing process will be investigated and compared against the mixing behavior of an air jet injected into an air crossflow. The turbulent flow structure and vortex dynamics that influence the cooling efficiency depend strongly on the velocity and density ratio. The measurements allow a detailed analysis of such a flow field and are used to validate numerical data presented in Guo et al. (2006) and Renze et al. (in press).

The organization of the paper is as follows: First a brief description of the experimental setup, the flow conditions and the measurement technique is given. Subsequently, the flow structure in different measurement planes in which jets emanate into an air-like crossflow is analyzed considering different velocity and density ratios. This is followed by the discussion of the experimental results and finally a comparison with numerical data investigating the same JICF problem is made.