Effect of blowing rate on the film cooling coverage on a multi-holed plate: application on combustor walls

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Abstract

Multi-holed film cooling systems are the most effective and widely used cooling techniques applied to gas turbine blades and combustor liners to obtain resistance in extremely high temperature operating conditions. This paper reports on measurements in flows generated by jets issuing from a 10:1 scaled multi-holed plate for a blowing ratio varying from 0.2 to 11. The plate geometry is similar to geometries encountered within current combustion chamber walls. The test section has 138 holes arranged on 12 staggered rows. The holes are spaced 6.74 diameters apart in the spanwise direction and 5.84 diameters apart in the downstream direction. The holes angle inclination is 30 degrees with respect to the plate surface. Mean velocity vectors and turbulent Reynolds shear stresses are measured using a two-component Laser Doppler Anemometry system. An investigation is performed to study the effects of adjacent jets flow interactions and jet-to-cross-flow combinations on the film cooling coverage, downstream from the end of the perforated zone. Results obtained are intended to help improve the aerodynamic and thermodynamic heat-transfer laws for multi-holed and near wall flows. The acquired experimental database is useful to validate different physical models and numerical codes in multi-holed flow cooling techniques.

Keywords: LDA, perforated plate, combustion chambers, blowing rate, turbulence intensity, Reynolds shear stresses, mean flow velocity, film cooling.
1 Introduction

Cooling of the hot section in gas turbine engines has become more difficult due to the rise of compressor exit temperature that has doubled over the last 30 years. In addition, gas turbine manufacturers are also striving to reach higher component lifetimes. These two factors lead to the utilisation of state-of-the-art wall cooling methods. Film cooling techniques are used for various gas turbine components, including combustion chambers, disc cavities and turbine blades. Multi-holed plates are used in different forms, such as impinging jets, wall jets, or cross-flow jets. In the film cooling application, usually, arrays of discrete holes are used to provide the cold air flow. In fact, only a few percent of the cold air coming from the compressor, passes through the perforated regions of the combustor walls. The rest of the cold air is conducted to the end of the combustion chamber, where it is used for the dilution of the burned gases, and also for the post-combustion process. In the perforated regions, jets require a distance to merge together and to form a uniform cooling film. Before the jet flows merge, hot spots exist between the jets, therefore even downstream of the jet-merging location, cooling effectiveness is not necessarily uniform. This non-uniformity may lead to thermal fatigue and thermal barrier coating spalling.

Today experiments are important to validate predictive methods for turbulent flows and especially detailed measurements of the velocity distribution in the near wall flow field are much needed for the improvement of turbulence models and the development of physically correct models. There are many film cooling studies using a single hole (Fric and Roshko [1]) or one to three rows of holes (Goldstein [2], Brown and Saluja [3]). However, little research has been performed using staggered rows of holes with a realistic cold air supply method for the perforated plate as correctly simulated by our experimental setup.

2 Experimental facility and instrumentation

A special wind tunnel working at ambient temperature was built to investigate aerodynamically the film cooling through a multi-holed plate as an application of combustor walls cooling techniques. Two multi-holed plates, 60 and 30 degrees holes angle inclination with respect to the plate surface, are available and can be mounted into the test section. In this study, only the results of the second perforated plate are shown. The low-speed wind tunnel consists of four parts: the main flow blowers, the development region, the test section and the exhaust system as described next in detail.

2.1 Main flow blowers, development flow region and exhaust system

The experiments are conducted in an open-circuit, blowing-type wind tunnel as shown in Figure 1. Two identical fan blowers provide the primary and the secondary flows through the two rectangular ducts. Before entering these ducts, the two flows pass through a 50-cm contraction segment with a ratio of 2:1 that contains a 2 cm long honeycomb section and a screen to provide uniform flows.
Next, two rectangular ducts (40 cm x 12 cm) of 2.5 m in length are connected to the test section. Flow rates through the ducts are controlled by changing the rotational speed of the blowers and a calibration with the LDA measurements velocity profiles is done. At the end of the test section, a pressure screen is used to create a pressure difference to facilitate the passage through holes into the “primary flow”, and therefore, to create a film cooling downstream the end of the perforated zone. Depending on the secondary flow rate and the flows pressure difference, a small part of the secondary flow entering the test section passes through inclined holes, and the rest exits, through the pressure screen, to the exhaust system. The primary flow passes through the test section at the atmospheric pressure and then directly into the exhaust system. A smoke generator, using white F5-Smoggy fluid is seeding both flows at the inlet blowers to ensure homogenous particle concentration in the test section.

Figure 1: Experimental setup.

2.2 Test section

The test section was designed to duplicate existing manufacturing and operating conditions of perforated plates in today’s combustion chambers. Two groups of parameters, geometrical and aerodynamic, were investigated to obtain the optimum configuration. The selection process is explained in the following sections.

2.2.1 Geometrical parameters

Many factors affect how the mixing process of the jets occurs in the film cooling region of the perforated plate. Some of the geometric parameters, (see Figure 2) like the shape of the jet issuing holes, the diameter of the jet (d), the inclination angle (α), the spacing between two adjacent jets (s), the inter-row distance (r), and the plate thickness (e), form the design parameters with respect to the jets.

These variables require a large number of combinations to be investigated. But, since our perforated plate is a 10:1 test scaled model with respect to a real perforated plate of combustor walls, the holes diameter is fixed, and the plate thickness is two-times the hole diameter. The perforated zone has 138 holes arranged on 12 staggered rows starting 20 diameters downstream the beginning of the test section. The step in the spanwise direction is $s = 6.74 \, d$ and $r = 5.84 \, d$ in the downstream direction. The inclination angle of the holes is $\alpha = 30$ degrees with respect to the plate surface.
2.2.2 Aerodynamic flow parameters

The flow parameters were identified as the blowing ratio $M = \frac{\rho_{\text{jet}} V_{\text{jet}}}{\rho_1 V_1}$, the maximum pressure difference between secondary flow and primary flow $\Delta P = (P_2 - P_1) \text{[Pa]}$, and the Reynolds number based on the duct centerline velocity and the half height of the rectangular duct $Re = \frac{V_1 H/2}{\nu}$. In order to simulate real flows inside combustors, Reynolds similarity criteria was respected. The maximum mean velocities for the flows inside the two rectangular ducts are varying from 1 to 11 m/s ($Re_{H/2} = 8000$ to 42000) and the static pressure difference between the secondary flow and the primary flow varies between 20 and 130 Pa.

2.3 Assumptions and simplifications

The named “secondary flow” is supposed to represent the cold air coming from the compressor of a gas turbine engine. Both the “primary flow”, which represents the burned gases flow inside the combustion chamber, and the “secondary flow”, are at the same ambient temperature, in our case approximately 27°C. Therefore, the blowing ratio is reduced to velocity ratio, and we have: $\rho_1 = \rho_2 = \rho_{\text{jet}} = \rho_{\text{air}}$. 

Figure 2: Perforated plate geometric parameters.
Two-dimensionality is a concession to theory - it is rare in nature and is very difficult to obtain in an experiment. However, at the entrance of the test section we have measured with the LDA system, a two-dimensional uniform flow, which spreads over 65\% of each rectangular duct width.

The development region upstream the test section was designed to be long enough to obtain a fully developed and turbulent duct flow characteristic, and thus the boundary layer thickness for both rectangular ducts is equal to the half height of the duct, $\delta = H/2$. The turbulence intensity on the duct centreline has been measured to be around 5\%.

To reduce the edge effects, the LDA measurements were conducted for three adjacent jets in the spanwise direction centred at the middle of the test section width.

2.4 Laser Doppler Anemometry system

A 5 W Coherent Argon Ion two-component laser system is used for the LDA measurements. The system operates with two blue beam lights of wavelength 488 nm and two green beam lights of 514.5 nm wavelength and allows direct measurement of the two velocity components: $u$, in the x direction, and $v$ on the y direction. The transmitter and the receiver are situated in a single probe head containing all the necessary optics to form the control probe volume and also to measure the back-scattered signal. This signal is detected by photo-multipliers by means of multimode optic fiber and is then directed as an electrical signal to the data acquisition system. These measurements are treated to correct for fast particles bias. As fast particles will pass the measurement control volume more rapidly than slow particles, there is a trend to measure more frequently fast particles, and the simple mean velocity will be higher than the true mean. The correction treatment accounts for this bias by weighting the measured velocity with the gate time of each particle passing through the probe volume. Table 1 shows the nominal optical characteristics of the LDA system used in our laboratory.

<table>
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<th>Table 1: Nominal optical characteristics of the LDA system.</th>
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<tr>
<td>Transmitter lens focal length (mm)</td>
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<td>Probe volume length (mm)</td>
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<td>Beam waist diameter ($\mu m$) green / blue</td>
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<td>Fringe spacing ($\mu m$) green / blue</td>
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3 Velocity measurements and uncertainties

The LDA system is equipped with 40 MHz frequency shifting process in order to distinguish between forward and reverse flow and to avoid fringe bias errors in measurements. The LDA probe volume is precisely positioned by a 3D computer controlled traverse system, and the positional errors are estimated to less than 1/60 mm. The measurement time at one point varied from about 10 s to 120 s, and the mean values of $u$ and $v$ velocity components were obtained from
minimum $2^{10}$ valid particles. Uncertainties in the mean velocity can be estimated for up to 1% for $u$ component and up to 2% for $v$, at the ducts centreline regions. Uncertainties in the turbulence can be estimated up to 5 percent for both $u_{rms}$ and $v_{rms}$. Velocity profiles were measured with a very high density of measuring points in the near-wall region at a minimum wall distance of $y^+ < 3$.

4 Results and discussions

As shown in Figure 3, LDA measurements were conducted in three principal zones: upstream the perforated zone, downstream the perforated zone and in the middle of the perforated zone.

Figure 3: Test Section flows, dimensions and LDA Measurement Zones.

Instantaneous velocities $u$ and $v$, as well as turbulent Reynolds shear stresses are measured simultaneously in vertical planes, in the longitudinal and then normal directions to the flow. Since the primary flow is fully developed and has perfect longitudinal centreline symmetry, the experimental grid domain was reduced to the superior half of the primary rectangular duct. At the entrance of the test section, LDA measurements were conducted ten diameters, upstream the perforated zone, in order to verify the fully developed duct flows hypothesis. Figure 4 shows the mean velocity profiles and the turbulent Reynolds stresses normalised by the friction velocity against $y^+$. 
Figure 4: Mean velocity profiles and normalised turbulent Reynolds stresses.

These results are totally in agreement with the universal von Karman log-law velocity profile for an incompressible turbulent boundary layer near the plate surface (see, e.g. theoretical fundamentals in texts of Pope [4] and Rohsenow et al [5]). In the perforated zone, for the mean velocity profiles there is a high similarity starting from the seventh row of inclined holes. All velocity profiles measured at three hole diameters downstream hole centre axes, and for each even row, are characterised by two velocity picks, like in Figure 5.

Figure 5: Mean velocity contours a), and velocity profiles for even rows b).

The first pick represents the jet core and is obtained as a result of the interaction between the jet issued from the hole and the primary free stream flow. The normal coordinate of the maximum velocity represents the jet penetration. The second pick represents the film cooling core, which is obtained from the previous interactions between the upstream jets and the primary free stream flow. The film cooling thickness is defined as the normal coordinate where the local mean velocity starts to be greater than the unperturbed upstream mean velocity.
Downstream the perforated zone, after the twelve staggered rows of holes, the jets are totally merged and a film thickness of about six times hole diameters is obtained and maintained for more than 24 diameters in the downstream direction.

Figure 6: Mean velocity contours in: a) normal and b) longitudinal to flow plan.

Figure 6-a shows the well-known kidney shape of jet in cross flow for a normal plan (y, z) at 3d downstream the number eight row and Figure 6-b shows a mean velocity contour plot of the film, downstream the number twelve row. To compare different aerodynamic flow configurations and to study the influence of the blowing ratio on the film cooling characteristics, a normalisation by the duct centerline velocity of the primary flow was used. Figure 7-b, shows normalised velocity profiles for some flow configurations with the blowing ratio varying from M = 1.69 to 5.33.

Figure 7: Film thickness evolution a), and downstream velocity profiles b).

Different studies have related that the aerodynamic jet flows are very sensitive to the hole angle inclination and the hole exit shape as well as to the hole diameter and compound angle injection of the cold air, see Lee et al [6].
one can see, in Figure 7-a, increasing blowing rate has little influence on jet penetration in the primary flow. Meanwhile, in the downstream zone of the perforated region, the film cooling aerodynamic characteristics parameters, such as the maximum velocity or the film thickness, are directly related to the blowing ratio. Also, flow configurations with high blowing ratios are dangerous for gas turbine engines because the cold air, which penetrates into the flame tube, could locally stop the combustion reactions and create unburned gas components. With the same cold air consumption, at small blowing ratios, better results for the film cooling efficiency can be obtained using different geometrical plate configurations. So, there is no need in using too much cold air coming from the compressor for the cooling process, but it is suitable rather to ameliorate the geometrical parameters of the multi-holed plates cooling configurations. These results are totally in agreement with experimental investigations of Emidio et al [7] conducted on multiholed flat plates used in today’s combustor, at a 1:1 scale and in realistic aerodynamic and thermal environment conditions.

5 Conclusions

Two components LDA measurements were conducted on a 10:1 perforated plate model in order to investigate the influence of aerodynamic flow parameters, like blowing ratio, flows pressure difference and Reynolds number, as an application to combustor walls cooling techniques. Except particular cases, the blowing ratio has little influence on the film cooling thickness downstream the perforated zone. That implies to choose for the multiholed plate flows, the minimum cold air fraction coming from compressor since a major part of the cold air is used for the combustion process, the gas dilution and the post-combustion process of the gas turbine engine. The present work reports on partial results of LDA measurements and the achieved database will be used to validate different physical models and numerical codes for multi-holed flow cooling techniques, and will serve also for future turbulent aerodynamic investigations in combustors.

Nomenclature

- d: circular diameter of the jet holes (mm)
- e: perforated plate thickness (mm)
- H: rectangular duct height (mm)
- M: blowing ratio = \(\frac{(\rho V)_{\text{jet}}}{(\rho V)_1}\)
- P: static pressure (Pa)
- r: inter-row distance (mm)
- Re: Reynolds number
- s: spanwise holes distance (mm)
- u, v, w: velocity components (m/s)
- V: mean total velocity (m/s)
- x, y, z: Cartesian coordinates
- x': local row coordinate
Subscripts

1 primary flow
2 secondary flow
air air flow
atm atmosphere
jet jet flow
rms root mean square

Symbols

α hole angle inclination (degree)
δ boundary layer thickness = H/2 (mm)
Δ pressure difference (Pa)
ρ density (kg/m$^3$)
ν cinematic viscosity (m$^2$/s)

References