Applied Thermal Engineering 62 (2014) 766–776

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Experimental flow field investigations of a film cooling hole featuring an orifice

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HIGHLIGHTS

- Anti-CRVP effect of a film cooling hole featuring orifice is examined.
- CRVP strength is greatly decreased due to double-decker vortices canceling out.
- Kidney-shaped jet merges to a round jet providing better surface coverage.
- CRVP might not have obvious impact on jet lift-off.

ARTICLE INFO

Article history:
Received 23 July 2013
Accepted 4 October 2013
Available online 18 October 2013

Keywords:
Film cooling
Anti-CRVP
Orifice
Vortex
PIV
Gas turbine

ABSTRACT

This paper presents the flow field downstream of a film cooling hole geometry featuring orifice, referred to as nozzle hole, on a flat plate using PIV. The experiments were performed with blowing ratios from 0.5 to 2.0, density ratio of 1.0 and mainstream Reynolds number of 115,000. Velocity fields and vorticity fields of nozzle hole jet are compared with that of cylindrical hole jet. The results indicate that nozzle hole jet features double-decker vortices structure, resulting in vortices canceling out and significant reduction in CRVP strength. The streamwise vorticity of nozzle hole jet averages a drop of 55% at low blowing ratio 0.5 in comparison to cylindrical case. At high blowing ratio from 1.0, 1.5 and 2.0, the average drop is 30%–40%. A round jet bulk is observed to merge from the two legs of a typical kidney-shaped jet and the merged jet brings better coverage over the surface. In addition, it is found that CRVP strength might not have strong impact on jet lift-off but influences jet-mainstream mix characteristics.

1. Introduction

In the development of gas turbines with higher thermal efficiency, advanced film cooling technology is of great demand. Higher turbine inlet temperature (TIT) is continuingly a highly effective solution to some extent, whereas by achieving higher turbine and compressor polytropic efficiency, monotonically increasing TIT doesn't promise better thermal efficiency due to the penalty for large amount of coolant injected into turbine stages. Wilcock et al. [1] provided cycle efficiency of a simple-cycle industrial turbine under various operating conditions taking into account a real gas model. Under the probable maximum achievable polytropic efficiency of around 92.5%, the current film cooling technology hinders gas turbines from achieving higher cycle efficiency at a specific TIT. Therefore advanced film cooling technology with higher cooling effectiveness and reduced coolant usage is highly requisite in high-polytropic-efficiency and high-TIT gas turbines.

In the flow field of film cooling, the interaction between jet and mainstream results in a complex flow structure downstream of injection hole. Counter-rotating vortex pair (CRVP) is a major feature in such flow interaction and recognized as critical and detrimental factor to film cooling performance. Mainstream entrainment due to vortical flow and jet lift-off due to CRVP are believed to be two major contributors to the deteriorated film cooling effectiveness. Reducing CRVP strength offers direct enhancement to cooling effectiveness. Using shaped holes is a well-adapted method. Haven and Kurosaka [2] are among the pioneers studying the vortex reducing effect of shaped holes. They suggested that a spanwisely wider hole (large aspect ratio) reduced the mutual induction between the vortex pair and weakened jet lift-off. Hyams and Leylek [3] shared a similar conclusion that lift-off could be reduced by reducing CRVP by a shaped hole. Saumweber and

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http://dx.doi.org/10.1016/j.applthermaleng.2013.10.008

Schulz [4] and Gritsch et al. [5] studied the effect of hole geometry. Lee and Kim [6] optimized various geometric variables of fan-shaped hole to increase cooling effectiveness. Compound angle film cooling holes is another option to reduce CRVP, or to break the vortex pair. McGovern and Leylek [7] and Brittingham and Leylek [8] performed CFD simulation on single row of compound angle cylindrical and shaped holes and reported this phenomenon. Aga et al. [9,10] suggested that compared with streamwise injection hole, compound angle cylindrical hole made the counter-rotating vortex pair become a single large vortex and no jet lift-off was observed up to a blowing ratio (BR) of 3. Greater lateral jet spreading and higher lateral averaged cooling effectiveness were confirmed. Kusterer et al. [11] introduced double compound angle jet on the suction side of an airfoil. Each set of holes ejected secondary stream in different directions, therefore canceling out the opposite vortices. Gräf and Kleiser [12,13] investigated two subsequent rows of compound angle holes and their anti-CRVP effect. It was found that the downstream jet had lower profile and more lateral spreading due to downwash of upstream jet vortex, which resulted in better cooling effectiveness. Anti-CRVP approaches are not limited to above. Some researchers [14,15] investigated the anti-kidney vortex by introducing additional branching holes accompanying the main injection hole. The various anti-CRVP methods can also be combined together in use. Farhadi-Azar et al. [16] investigated a vertical injection scheme of the similar concept. They confirmed that the vortices induced by the small accompanying holes reduced the CRVP strength of main injection. In Asghar and Hyder's numerical study [17], two staggered rows of semi cylindrical holes brought a weakening effect on the CRVP. The vortex strength was reduced effectively and the centerline effectiveness was reported much higher than that of typical cylindrical holes.

Summarizing previous anti-CRVP approaches, some featured different exit local blowing ratio and momentum flux ratio (I) from hole inlet, since the nominal BR and I were calculated based on the cylindrical part before the shaped part of the hole. Some injected jet fluid with an angle to mainstream direction and some employed additional holes that had multiple jets. Study focusing on the particular effect of CRVP on flow structure of single injection in a classic round-jet-in-crossflow arrangement is rare. In order to study the sole effect of CRVP strength on film cooling effectiveness, Li et al. [18] proposed a new film cooling hole scheme, referred to as nozzle hole scheme. Nozzle hole is a cylindrical hole featuring an orifice before hole exit, located 0.3 d from the leading edge of the hole exit. The geometry of the nozzle hole is shown in Fig. 1. The orifice has a width of 0.5 d, and in the present experiments, the thickness of the orifice plates is 0.0625 d. The orifice changes the in-hole flow structure before ejecting it. The round exit issues jet fluid like cylindrical hole does. This keeps blowing ratio and momentum flux ratio the same from hole inlet to exit, enabling better understanding of the particular effect of CRVP. Previous numerical investigation [18] on nozzle hole showed remarkable CRVP strength reduction and cooling effectiveness increase.

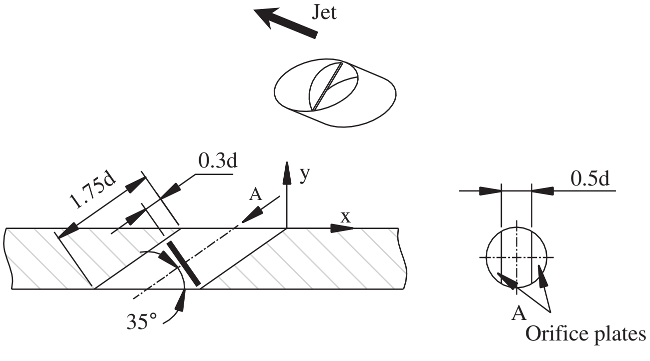

Fig. 1. Nozzle hole geometry [18].

The present study experimentally examines the flow field of nozzle hole jet on a flat plate using particle image velocimetry (PIV). Detailed flow structure of nozzle jet is presented. The velocity field and vorticity field of nozzle jet are compared with cylindrical jet. The particular fluid phenomenon due to reduced CRVP strength of nozzle jet is reported. The vortex structure of nozzle jet suggests an explanation for the CRVP suppressing effect, which is also discussed.

2. Experimental approaches

2.1. Experimental facility

The experimental facility consists of a low-speed wind tunnel with aerosol seeding generator and stereo PIV measurement equipment. Fig. 2 shows the schematic diagram of the wind tunnel. The wind tunnel has three major branches, mainstream, secondary stream and seeding particle path. A compressed air tank and a compressor supply all three branches. Mainstream airflow goes through a divergent–convergent section to damp any possible instability of the air supply system before entering a turbulence grid and a 1.6 m long entrance section. Detailed information about the wind tunnel can be found in the study of Ghorab et al. [19].

The aerosol seeding generator with Laskin nozzles seeds both main and secondary streams with 1 μm diameter vegetable oil particles. Three switches on the generator control the number of particles ejected out of the generator. The seeding flows join main and secondary streams through two adjustable gate valves, which provide the possibility of finely tuning seeding particle allocation.

The low-speed wind tunnel has a rectangular-shape open test section measuring 500 mm in length (x-direction), 99 mm in width (z-direction) and 53 mm in height (y-direction). It is made of acrylic to provide necessary optical access for laser and cameras. Fig. 3 shows the test section and the entrance section of the wind tunnel. Secondary stream is supplied into the test section from a screw-fixed plenum attached under test section bottom. Thermal couples are installed in the plenum to monitor airflow status. The hole insert is replaceable by removing the plenum. Test section top plate can be open for calibration and cleaning purposes.

The PIV system has a double pulse Nd:YAG laser, two CCD cameras for stereo PIV (2D3C) measurement, a synchronizer and a workstation. The laser and the cameras are mounted on a movable measurement platform with 4 degrees of freedom shown in Fig. 4. In the present study, the platform was limited to two movement directions. The vertical position of the laser and cameras can be adjusted through a screw bar and guide system. Streamwise movement is achieved through a slide guide. The laser launches 532 nm green laser beam, which is transformed into a light sheet by external lens attached to the laser head. The thickness of the light sheet can be adjusted through the lens. The CCD cameras feature 1344 × 1024 pixel resolution and 12 bit dynamic range. The pixel size is 6.45 μm. Each camera has a 60 mm f/2.8 macro lenses mounted on it. The cameras and the laser are connected and controlled by the workstation through the synchronizer.

2.2. Camera setup and calibration

In stereo PIV (2D3C) measurement, the two cameras were arranged at two lateral sides of test section at 30° from center plane. The measurement plane was normal to mainstream direction. Scheimpflug configuration, where lens axis deflected from camera body axis, was applied to ensure clear sight of object plane. The