International Journal of Heat and Mass Transfer 125 (2018) 1003–1016

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Unsteady analysis of adiabatic film cooling effectiveness behind circular, shaped, and sand-dune–inspired film cooling holes: Measurement using fast-response pressure-sensitive paint

Wenwu Zhou [a,b], Di Peng [a,b], Xin Wen [a,b], Yingzheng Liu [a,b,*], Hui Hu [c]

[a] Key Lab of Education Ministry for Power Machinery and Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China
[b] Gas Turbine Research Institute, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China
[c] Department of Aerospace Engineering, Iowa State University, 2271 Howe Hall, Room 1200, Ames, IA 50011, USA

ARTICLE INFO

Article history:
Received 6 December 2017
Received in revised form 4 March 2018
Accepted 24 April 2018

Keywords:
Film cooling
Adiabatic effectiveness
Vortex structure
Pressure sensitive paint

ABSTRACT

The unsteady adiabatic effectiveness behind three types of holes was measured with fast-response pressure-sensitive paint and a high-speed camera, i.e., a circular hole, a shaped hole and the sand-dune–inspired hole. During the experiment, coolant fluid (CO_2) was discharged from a single injection hole at an inclination angle of 35°. The blowing ratio (M) was varied from 0.40 to 1.40. The unsteady behavior of effectiveness was quantified clearly in terms of standard deviations (SDs), spatial correlations, and dynamic mode decomposition. In contrast to the circular hole, the coolant film injected from shaped and Barchan dune-shaped injection compound (BDSIC) holes remained attached to the surface. No separation appeared in any configuration. Especially for the BDSIC concept, significantly greater effectiveness, but a lower SD, was found behind the dune than in the other two configurations. Using two-point spatial correlation, the prominent signatures (i.e., a counter-rotating vortex pair and horseshoe-like vortices) buried in the cross-flow jet were determined, which were responsible for the enhanced SDs in the circular and shaped holes. As for the BDSIC configuration, large-scale coherent structures (i.e., such as circulations, anti–counter-rotating vortex pairs, and strong shear) were identified from the measured effectiveness at blowing ratios (M) of 0.40 and 0.90. Based on dynamic mode decomposition analysis, the corresponding dynamic modes were extracted from the instantaneous effectiveness fields. Although the circular hole featured dominant frequencies (St) of 0.026 and 0.008 at blowing ratios (M) of 0.40 and 0.90, respectively, the BDSIC configuration demonstrated a constant shedding frequency (St) of 0.009. This paper represents the first effort to use fast-response PSP sampling at a high frame rate to quantify the unsteady behavior of adiabatic effectiveness over a flat plate.

1. Introduction

Film cooling, as a state of the art, has been widely implemented in modern gas turbine engines to protect hot-section components from excessive heat. The principle of film cooling is to generate a thin coolant blanket over the protected surface to prevent it from direct exposure to hot gas, hence increasing its working hours [1–5]. A stable and continuous coverage of coolant film is of great importance to ensure the sustainable operation of gas turbine engines. In recent decades, substantial investigations have been undertaken to determine the mean adiabatic cooling effectiveness behind various cooling holes [2,3,5–7]. The mean effectiveness is affected by a series of parameters [1], including the blowing ratio, the momentum flux ratio, the coolant–to–mainstream density ratio, and the coolant hole geometry. Fundamentally, film cooling can be equivalent to a jet in cross-flow (JICF) problem [8–10]. As coolant discharges from the injection holes, it interacts extensively with the mainstream flow. This process gives rise to highly three-dimensional fluid mixing above the wall, leading to complex and unsteady coolant behaviors over the protected surface [10]. As a result, the vital components may be partially or completely exposed to the extremely hot gas due to the unsteady nature of a JICF. A sudden decrease in effectiveness immediately behind the hole may result in local overheating and concentration of thermal stress within the components. Over time, this unstable cooling

* Corresponding author at: Key Lab of Education Ministry for Power Machinery and Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China.
E-mail address: yzliu@sjtu.edu.cn (Y. Liu).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.126
0017-9310/

Nomenclature

D	diameter of coolant injection hole
D_s	concentration diffusion coefficient
DR	coolant–to–mainstream density ratio, ρ_c/ρ_∞
f	vortex shedding frequency
I	coolant–to–mainstream momentum ratio, $\rho_c U_c^2/\rho_\infty U_\infty^2$
Le	Lewis number, α/D_s
M	blowing ratio or mass flux ratio, $\rho_c U_c/\rho_\infty U_\infty$
MW	molecular weight ratio of coolant to mainstream
$(p_{o_2})_{air}$	partial pressure of oxygen with air as the coolant
$(p_{o_2})_{mix}$	partial pressure of oxygen with non-oxygen gas as the coolant
$R_{\eta'\eta'}$	correlation coefficient
St	Strouhal number, fD/U_∞
T_{aw}	adiabatic wall temperature
T_c	coolant stream temperature
T_∞	temperature of mainstream flow
U_c	coolant stream velocity
U_∞	incoming flow velocity
VR	velocity ratio, U_c/U_∞

Greek symbols

α	thermal diffusion coefficient
θ	injection angle
δ_{99}	boundary layer thickness
δ^{**}	momentum thickness
η	instantaneous film cooling effectiveness
η'	film cooling effectiveness fluctuation
$\overline{\eta}$	ensemble-averaged film cooling effectiveness

Abbreviations

BDSIC	Barchan dune-shaped injection compound
CRV	counter-rotating vortex
DMD	dynamic mode decomposition
PSP	pressure-sensitive paint
SD	standard deviation

behavior would cause fatigue of components and even failure of gas turbine engines. Therefore, a comprehensive understanding of unsteady behaviors of a coolant film over a protected surface is highly desirable.

Pertinent to JICF, several studies have focused on the unsteady behavior of vortex structures under different velocity ratios [5–8]. Karagozian [12], who studied the dynamics of the vorticity at various momentum flux or density ratios, found a jet structure change under different flow conditions. Bidan et al. [11] numerically studied the jet flow-rate modulation effect and reported the domination of shear layer vortices at low blowing ratios. Similar conclusions were reported by Dai et al. [9], who studied the influence of velocity ratios on the flow structures. However, most of those studies focused on the unsteady effect of vortex structures on the flow field, in terms of velocity, vorticity, or other associated turbulence quantities. Very little attention was paid to the unsteady behavior of the coolant film on the test surface, especially the unsteady analysis of adiabatic wall effectiveness. Kalghatgi and Acharya [13] used large eddy simulation to perform dynamic mode decomposition (DMD) of the three-dimensional flow and wall-temperature field and found that the flow structures associated with low and intermediate frequencies make the largest contribution to wall temperature fluctuations. More recently, Khojasteh et al. [14] measured the adiabatic effectiveness behind a circular jet using fast-response pressure-sensitive paint (PSP) and successfully reconstructed the adiabatic wall effectiveness using the most energetic modes of proper orthogonal decomposition. However, the camera in their study was sampling at a low frame rate. The reconstructed effectiveness field would inevitably lose the temporal information, which is highly valuable for the gas turbine community because both the spatial and the temporal variations of adiabatic effectiveness are essentially important.

We performed an unsteady analysis of adiabatic effectiveness behind three representative cooling holes: a circular hole, a shaped hole [7,15], and a Barchan dune-shaped injection compound (BDSIC) configuration [6]. Circular and shaped holes are widely used in gas turbine engines, and their cooling performances are well documented, whereas the BDSIC film cooling concept was recently proposed by Zhou and Hu [6]. Inspired by the unique shape of Barchan dunes commonly seen in deserts that prevents sand particles from being blown away, Zhou and Hu [6] proposed the BDSIC film cooling concept. Their preliminary measurements showed that this design could keep the coolant stream attached to the surface, leading to significantly greater effectiveness over the protected surface. However, spatial and temporal information regarding the adiabatic cooling effectiveness is still lacking.

In this study, while the circular hole was our baseline configuration, the shaped hole and the BDSIC concept were analyzed in detail to compare their spatial and temporal variations of cooling effectiveness over the test surface. Carbon dioxide (CO_2) was used as the coolant fluid and was discharged from a single hole at an inclination angle of 35°. Fast-response PSP measurements were performed in the region where $x/D < 9$ with blowing ratios (M) of 0.4, 0.9, and 1.4. Both the mean and unsteady quantities of adiabatic effectiveness were determined over the whole domain. Two-point spatial correlation was first used to identify the prominent signature above the wall. Dynamic mode decomposition was then performed to extract the dynamic modes associated large-scale structures. This paper represents the first effort to use fast-response PSP sampling at a high frame rate. The coherent structures and dynamic modes identified with spatial correlation and DMD analysis are expected to serve as a benchmark for validation studies in the computational fluid dynamics community.

2. Experimental setup and test models

2.1. Experimental model and test rig

The film cooling experiments were conducted in a low-speed, suction-type wind tunnel in the Department of Mechanical Engineering at Shanghai Jiao Tong University. The tunnel has a 500 × 90 mm^2 optically transparent test section. With honeycombs and multilayer screens installed ahead of the nozzle, the tunnel can supply uniform low-turbulence flow in the test section. Using the hot-wire data measured upstream of coolant hole, the freestream turbulence intensity was measured to be 1.1% with a turbulent integral length scale (i.e., L_x) of 1.5 mm, and the corresponding turbulent time scale is 110 μs.

In this study, all test models were made of a hard-plastic material and manufactured with a rapid prototyping machine. They were constructed layer-by-layer with a resolution of approximately 50 μm. Fig. 1 shows a schematic of the selected film cooling configurations: a circular hole, a shaped hole, and a BDSIC hole. A circular hole with a diameter (D) of 8.0 mm was chosen as the baseline configuration. It has an injection angle of 35° and an entry length of 5D. Fig. 1(b) shows the laidback, fan-shaped hole that