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Film cooling effectiveness enhancement using surface dielectric barrier discharge plasma actuator

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ABSTRACT

The case presented here deals with the enhancement of film cooling effectiveness using plasma flow control. In this experimental study, a jet is injected from an elongated slot into a thermally uniform cross-flow. The influence of a surface plasma dielectric barrier discharge actuator on heat transfer downstream of the slot is investigated. 2D PIV and IR-thermography measurements are performed for three different blowing ratios of $M = 0.4$, 0.5 and 1. Results show that the effectiveness can be increased when the discharge is switched-on. Whatever the blowing ratio, the actuator induces a deflection of the jet flow towards the wall, increases its momentum and delays its diffusion in the cross-flow. The best results are obtained with a blowing ratio close to 0.5 and an steady actuation without any frequency modulation.

1. Introduction

In turbojet engines, combustion chamber walls and turbine blades are subjected to high temperature combustion gases. To protect them from those high thermal stresses, one of the most frequently used technique is film cooling. In this process, cold air is injected through holes to provide a cool film along the wall, insulating it from hot gases. Keeping the coolant jet attached to the wall and reducing its mixing with combustion gases are a primary purpose and quite few researches were realized, specially dealing with flow control strategies such as the shape of injection (Sargison et al., 2002), the injection hole position (Goldstein et al., 1974) or the influence of the mass flow rate ratio between the injected air and the cross-flow (i.e. blowing ratio) (Eckert, 1970). In particular, they demonstrate that the cooling efficiency is greater with lower blowing ratios because the jet stays closer to the wall whereas its penetration into the mainstream is increased with higher blowing ratios (Goldstein et al., 1974). However, all these methods are limited and the unsteadiness of actual turbine flows requires a control mechanism of the injected jet which can be adapted in time to stay efficient, highlighting the needs for active cooling technologies.

In this way, the behaviour of film cooling efficiency under periodic excitation was explored in a variety of ways. Ekkad et al. (2006) studied the effect of low frequency jet pulsation and duty cycle on film cooling effectiveness by means of pulsed valves in the injection circuit. Results indicate that the effect of varying the pulsing frequency was not discernible beyond the level of experimental uncertainty. Using solenoid valves, Coulthard et al. (2007) observed that pulsing at high frequencies helped to improve film-cooling effectiveness in cases of blowing ratios of 1 and 1.5 by reducing overall jet lift-off. However, at lower frequencies, pulsing tended to have the opposite effect. They concluded that the best overall film cooling was achieved with a blowing ratio of 0.5 and a continuous jet. Lalizel et al. (2012) have performed a study with externally imposed pulsations using a loudspeaker. Their results confirmed that application of pulsations in the injected flow induces a reduction of the film cooling effectiveness for a blowing ratio of 0.65. They also showed that the film cooling effectiveness can be slightly increased, in case of blowing ratios of 1 and 1.25, with a periodic excitation leading on Strouhal numbers of 0.2 and 0.3.

The present experimental work investigates an active flow control strategy, using a plasma actuator, in case of a jet injected in a cross-flow through an elongated slot. For the last 15 years, surface dielectric barrier discharge (DBD) devices have proved to be one of the most promising actuator devices for flow control in a large variety of applications (Corke et al., 2010; Moreau, 2007). Unlike other type of active control devices, plasma actuators are

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List of symbols

M	Blowing ratio
ρ_j	Density of the jet (kg.m^{-3})
ρ_∞	Density of the free-stream (kg.m^{-3})
U_j	Velocity of the jet (m.s^{-1})
U_∞	Velocity of the free-stream (m.s^{-1})
U_{act}	Velocity of ionic wind (m.s^{-1})
η	Film cooling effectiveness
T_{aw}	Adiabatic wall temperature (K)
T_w	Wall temperature (K)
T_j	Temperature of the jet (K)
T_∞	Temperature of the free-stream (K)
h	Convective heat transfer coefficient (W.m^{-2}.K^{-1})
St	Strouhal number
G_η	Gain in effectiveness
V_{AC}	High voltage amplitude (V)
f_{AC}	High voltage frequency (Hz)
f_{BM}	Burst modulation frequency (Hz)
φ_{conv}	Heat flux density exchanged by convection (W.m^{-2})
φ_{cond}	Heat flux density exchanged by conduction (W.m^{-2})
φ_{rad}	Heat flux density exchanged by radiation (W.m^{-2})
φ_{elec}	Heat flux density provided by Joule effect (W.m^{-2})
Re	Reynolds number
L	Width of the slot (m)
D	Half-width of the slot (m)
x, y, z	Longitudinal, normal and span-wise coordinates (m)
u, v, w	Longitudinal, normal and span-wise velocity (m.s^{-1})
u', v', w'	Longitudinal, normal and span-wise velocity fluctuations (m.s^{-1})
J	Actuator momentum (kg.s^{-2})
C_μ	Actuator momentum coefficient
TKE	Turbulent kinetic energy (m^2.s^{-2})

lightweight, easy to use on in-lab models and able to produce a periodic perturbation with a wide range of amplitudes and frequencies. Typically, a surface DBD plasma actuator operates by applying a strong electric field between two electrodes separated by a dielectric material to create a non-thermal plasma above the dielectric surface. By the mechanism of ion collision, a momentum exchange occurs between charged particles and neutrals, inducing an electrohydrodynamic (EHD) force. The forcing takes place mainly in a small region close to the edge of the air-exposed electrode where the electric field is more intense. The result is a wall tangential jet flow, called ionic wind (Bénard and Moreau, 2014), which is used for flow control.

The concept of using plasma actuators for active flow control in case of film cooling enhancement was firstly introduced by Roy and Wang (2008). Based on numerical simulations, their results underlined that application of plasma discharges can improve the film cooling efficiency up to 26% in case of a round hole geometry. More recently, Dai et al. (2015) studied different plasma actuator configurations, using both numerical and experimental methods, in case of a jet injected in a cross-flow from a round hole. For two blowing ratio of 1 and 2, they confirmed that the jet flow can be deflected towards the wall due to the plasma actuation at the output of the jet.

Following this way, this study explores the ability of a plasma DBD actuator for film cooling efficiency enhancement through an experimental set-up including a film injection from an elongated slot into a thermally uniform cross-flow. It should be underlined that the main objective of this work is to demonstrate experimentally the abilities of a plasma actuator for film cooling effectiveness enhancement. Thus, the choice is made to inject the jet from an elongated slot to keep away the counter-rotating vortex pair, created close to the lateral edges of the slot, from the middle of the slot to better understand the influence of the actuator at this location. Furthermore, working with an elongated slot allows the use of a classical and well known plate to plate plasma actuator (Corke et al., 2010; Moreau, 2007). This study is an extension of the former results obtained in Audier et al. (2016) and goes into more details: the influence of the actuator is first investigated on the sole injected jet (without freestream flow), before focusing on the cross-flow configuration. In this latter case, three different blowing ratios of $M = 0.4$, 0.5 and 1 are investigated using 2D particle image velocimetry (PIV) and infrared (IR) thermography measurements. A parametric study about the influence of the input electrical parameters is finally performed to further analyse the capabilities of the actuator.

2. Experimental set-up

2.1. Methodology

To obtain detailed local informations on film cooling performance, the convective heat transfer coefficient h and the adiabatic wall temperature T_{aw} are conventionally used in film cooling studies (Goldstein et al., 1974). T_{aw} corresponds to the temperature of the wall without heat exchange between the fluid and the wall; it could be also interpreted as the fluid temperature close to the wall when there is no heat transfer. The film cooling effectiveness η is obtained by normalizing T_{aw} with the cross-flow temperature T_∞ and the jet temperature T_j:

$$\eta = \frac{T_{aw} - T_\infty}{T_j - T_\infty} \tag{1}$$

The closer T_{aw} to T_j, the higher the effectiveness. For the best case of $\eta = 1$, the temperature of the fluid close to the wall is equal to jet temperature, meaning that the jet flow imposes its temperature close to the wall. On the contrary, the worst case $\eta = 0$ attests that the temperature of the fluid close to the wall is equal to the one of the cross-flow. T_{aw} and h can be computed, for a given aero-thermal configuration (i.e. blowing ratio, Reynolds number, injection and ambient temperature), using the Newton's law of cooling:

$$T_w = \frac{1}{h}\varphi_{conv} + T_{aw} \tag{2}$$

where T_w is the wall temperature and φ_{conv} corresponds to heat flux density exchanged between the wall and the fluid by convection. In Eq. (2), the convective heat transfer coefficient h and the adiabatic wall temperature T_{aw} remain constant for a given aero-thermal configuration. Moreover, those conditions allow to use a heated surface to simplify the approach to simulate the film-cooling condition (Mick and Mayle, 1988). However, a heated wall can be used as the correct boundary condition only if all the heat flow directions are consistently reversed ($T_w > T_j > T_\infty$) (Wang and Zhao, 2011). Following this way, to simplify the experimental set-up, the choice is made to perform the experiments in the opposite way to a real case of film cooling: a hot jet flow is injected into a cold cross-flow and heat transfer measurements are performed on a heated test wall, set downstream the injection slot. Consequently, all heat flux directions are reversed in comparison to the real case. In this study, the effectiveness is chosen as the main criterion to assess the efficiency of the control.

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