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International Journal of Heat and Fluid Flow 28 (2007) 708–719
International Journal of HEAT AND FLUID FLOW
www.elsevier.com/locate/ijhff

Flow field analysis of a turbulent slot air jet impinging on a moving flat surface

J. Senter, C. Solliec *

GEPEA UMR-CNRS 6144, Ecole des Mines de Nantes, Département Systèmes Energétiques et Environnement,
4, rue Alfred Kastler, B.P. 20722, 44307 Nantes, France

Received 6 April 2006; received in revised form 14 July 2006; accepted 25 August 2006
Available online 17 October 2006

Abstract

The flow field topology of a confined turbulent slot air jet impinging normally on a moving flat surface has been investigated experimentally by using particle image velocimetry (PIV). Experiments were conducted for a nozzle-to-plate spacing of eight slot nozzle widths, at three Reynolds numbers ($Re = 5300$, 8000 and 10,600) and four surface-to-jet velocity ratios i.e. 0, 0.25, 0.5 and 1. The measurements of the mean velocities and turbulent quantities are presented in the following main characteristic regions of the jet: the potential core, the intermediate zone and the impinging zone. It appears that the flow field patterns at a given surface-to-jet velocity ratio are independent of the jet Reynolds number in the range of 5300–10,600. A slight modification of the flow field is observed for a surface-to-jet velocity ratio of 0.25 whereas at higher ratios of 0.5 and 1, the flow field is significantly affected.

Keywords: Impinging jet; Moving surface; PIV; Turbulence

1. Introduction

Impinging jets have received considerable research attention because of the high convective heat transfer that occurs in the impingement region (Korger and Krizek, 1966; Antonia, 1983; Viskanta, 1993; Sakakibara et al., 1997; Haneda et al., 1998; Narayanan et al., 2004). Industrial applications include tempering and shaping glass, drying textiles and paper, cooling turbine blades and electronic equipment, annealing metal and plastic sheets and some processes in the food industry. Thus, the jet flow issuing from a nozzle is often directed perpendicular to a moving impingement surface (Fig. 1). Some numerical studies have reported the strong effects of the impingement surface motion on the fluid flow (Zumbrunnen, 1991; Chattopadhyay and Saha, 2003). The flow field can be significantly affected since the impingement surface velocity can exceed the jet velocity in some applications such as the hot-rolling process. Indeed, at the impingement, the jet flow is divided into two wall jets. The wall jets behaviour will consequently be completely different given that the wall jet flow moves in the same or in the opposite direction to the moving surface. As a result, the strongly modified flow field will influence the convective heat transfer. As reported by Schlünder et al. (1970) and later by Martin (1977), the heat and mass transfer in impinging flow depends on the Reynolds number, the Prandtl number of the fluid, nozzle geometry and nozzle-to-plate spacing. Gardon and Akfirat (1965, 1966) also noticed the effect of turbulence on the local heat and mass transfer. They reported that, for a slot air jet, the absolute magnitude of the velocity fluctuations reaches a maximum in the neighbourhood of a nozzle-to-plate spacing equals to eight slot nozzle widths. This maximum occurs simultaneously with the maximum of the heat transfer coefficient at the stagnation point. It is also important to point out the role of the confinement of the jet on the flow field (Fitzgerald and Garimella, 1998). Indeed, the heat transfer distribution along the impingement surface is generally characterised by a single peak located at the

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* Corresponding author. Tel.: +33 2 5185 8265; fax: +33 2 5185 8299.
E-mail address: camille.solliec@emn.fr (C. Solliec).

0142-727X/$ - see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.ijheatfluidflow.2006.08.002

Nomenclature

e	slot nozzle width
h	heat transfer coefficient
H	impingement distance
k	turbulent kinetic energy
k'	two-component turbulent kinetic energy, $(u_{\mathrm{rms}}^2 + v_{\mathrm{rms}}^2)$
I_{U}	turbulence intensity of the fluctuating component of velocity in the x-direction
I_{V}	turbulence intensity of the fluctuating component of velocity in the y-direction
L_{C}	potential core length
l	channel width
Nu	Nusselt number, he/λ
Re	Reynolds number, $U_{\mathrm{J}}e/v$
R_{SJ}	surface-to-jet velocity ratio, $V_{\mathrm{S}}/U_{\mathrm{J}}$
U	mean velocity in the x-direction
U_J	jet centerline mean velocity at nozzle exit
u_{rms}	rms of the fluctuating component of velocity in the x-direction
V	mean velocity in the y-direction
v_{rms}	rms of the fluctuating component of velocity in the y-direction
V_{S}	mean velocity of impingement surface in the y-direction
$(U^2 + V^2)^{1/2}$	mean velocity magnitude
$\langle u'v' \rangle$	mean Reynolds shear stress
x, y	coordinates
Greek symbols	
ε	turbulent dissipation rate
λ	thermal conductivity of air
v	kinematic viscosity of air
ρ	air density

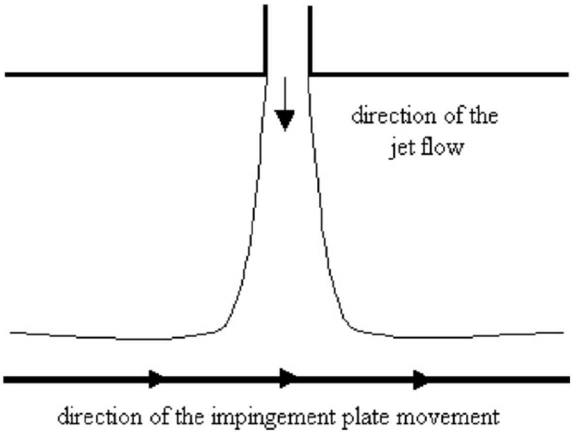

Fig. 1. Sketch showing the impingement plate movement relative to the jet flow direction.

stagnation point. However, at small nozzle-to-plate spacings, secondary peaks appear in the heat transfer distribution. They suggested that these peaks, generally understood to result from a transition to turbulence in the wall jet boundary layer, might also be due to the recirculation patterns found for the confined jet.

Among the very few experimental studies involving jets impinging on a moving flat surface, the work of Subba Raju and Schlünder (1977) concerning a moving flat surface impinged by a turbulent slot air jet can be mentioned. A mean heat transfer coefficient was calculated over the length of the impingement surface for different nozzle-to-plate spacings, several Reynolds numbers and a surface velocity V_{S} between 0.15 m/s and 5.5 m/s. However, a lack of information about the local heat transfer and the flow field prevents an understanding of the physical phenomenon. Van Heiningen et al. (1977) performed an experimental study of a turbulent slot air jet impinging on a large rotating drum. The tangential velocity of the moving surface was less than 2% of the jet velocity. Under these conditions and comparing their results with the available data for a turbulent slot jet impinging on a stationary surface, they concluded that, for low surface-to-jet velocity ratios, the wall motion seemed to be negligible in the local heat transfer.

The aim of this paper is to investigate the role of surface motion in the development of a turbulent slot air jet impinging on a moving flat and smooth surface. The relative moderate Reynolds numbers considered in this study have been chosen to enable a first comparison with different numerical simulations where the roughness is not taken into account. It also seems important to have first an accurate description of this complex flow field to enable validation of the local heat transfer in future experimental and numerical studies. In addition, future research could considered the effects of surface roughness of the moving surface on the flow field and on the local heat transfer. Indeed, Beitelmal et al. (2000) investigated experimentally the effects of surface roughness on the average heat transfer characteristics of a circular air jet impinging on a stationary surface. The roughness took the form of a circular array of protrusions of 0.5 mm base and 0.5 mm height. They showed an increased of up to 6% of the average Nusselt number due to surface roughness. Finally, Chakroun et al. (1998) also mentioned the average Nusselt number increase of a stationary surface impinged by a circular air jet due to the effects of surface roughness. In that experimental study, the roughness was composed of 1 mm cubes and was found to affect significantly both the mean velocity and the turbulence intensity of the flow.