International Journal of Heat and Fluid Flow 37 (2012) 22–36

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Fluid Flow

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

Three-dimensional vortex dynamics and convective heat transfer in circular and chevron impinging jets

Daniele Violato [a,*], Andrea Ianiro [b], Gennaro Cardone [b], Fulvio Scarano [a]

[a] Aerospace Engineering Department, Delft University of Technology, Kluyverweg 2, 2629 HS, Delft, The Netherlands
[b] Dipartimento di Ingegneria Aerospaziale (DIAS), University of Naples "Federico II", Via Claudio 21, 80125 Naples, Italy

ARTICLE INFO

Article history:
Received 14 December 2011
Received in revised form 1 June 2012
Accepted 4 June 2012
Available online 2 July 2012

Keywords:
Impinging jets
Chevron jets
Toroidal vortices
Streamwise vortices
Time-resolved tomographic PIV
Convective heat transfer
IR thermography

ABSTRACT

This paper describes an experimental investigation at Reynolds number equal to 5000 on circular and chevron impinging jets by means of time-resolved tomographic particle image velocimetry (TR-TOMO PIV) and infrared (IR) thermography. TR-TOMO PIV experiments are performed at kilo-hertz repetition rate in a tailored water jet facility where a plate is placed at a distance of 4 diameters from the nozzle exit. Using air as working fluid, time-averaged convective heat transfer is measured on the impinged plate by means of IR thermography with the heated-thin-foil heat transfer sensor for nozzle-to-plate distances ranging from 2 to 10 diameters. The circular impingement shows the shedding and pairing of axisymmetric toroidal vortices with the later growth of azimuthal instabilities and counter-rotating streamwise vortices. In the chevron case, instead, the azimuthal coherence is replaced by counter-rotating pairs of streamwise vortices that develop from the chevron notches. The heat transfer performances of the chevron impingement are compared with those of the circular one, analyzing the influence of the nozzle-to-plate distance on the distribution of Nusselt number. The chevron configuration leads to enhanced heat transfer performances for all the nozzle-to-plate distances hereby investigated with improvements up to 44% at the center of the impinged area for nozzle-to-plate distance of 4. Such enhancements are discussed in relation to the streamwise structures that, compared with the toroidal vortices, are associated with an earlier penetration of turbulence towards the jet axis and a higher arrival speed.

1. Introduction

Impinging jets have been received large research attention because of the wide variety of applicability, such as in metal and glass tempering, in paper drying and in turbine blades cooling. More efficient solutions may be implemented based on a better understanding of the influence of the flow field on the heat transfer. Discussions on this topic continue unabated.

Passive strategies to enhance the heat transfer rate between the jet and the impinged wall can be based on the modification of the nozzle geometry (Pan et al., 1992; Garimella and Nenaydykh, 1996). In an investigation on confined impinging jets, Colucci and Viskanta (1996) showed that hyperbolic shaped nozzles lead to more uniform heat transfer coefficient distributions on the impinged plate. Nozzles with chamfered outlets, instead, as reported by Brignoni and Garimella (2000) produce 20–30% increase in the heat transfer rate when compared to non-chamfered ones. Gao et al. (2003) showed that triangular tabs placed around a circular orifice lead to an enhancement higher than 25% with respect to the round configuration for a nozzle-to-plate distance of 4 diameters. The performances of elliptic nozzles with different aspect ratio were studied by Lee and Lee (2000), who, for an aspect ratio of 4, found the maximum stagnation heat transfer 15% larger than in the circular configuration. Such an enhancement was shown to result from the different spreading rates along the minor and major axis plane. A multichannel configuration (Ianiro and Cardone, 2011) and lobed nozzles (Herrero Martin and Buchlin, 2011) are also examples of nozzle configurations that lead to enhanced heat transfer properties.

The fundamental physical process at the origin of heat transfer is associated with the flow turbulence and its three-dimensional behavior in the region of impingement (Kataoka et al., 1987; Popiel and Trass, 1991; Sakakibara et al., 1997). Several studies in free jets have focused on the flow coherence and turbulence, reporting substantial changes in the transition patterns when moving from a circular to chevron. In free jets, chevron-type mixers are interesting configurations that alter the mixing process due to the generation of counter-rotating streamwise vortices at the chevron notches (Bridges and Brown, 2004; Violato and Scarano, 2011). In circular jets, mixing properties can be enhanced by placing a delta tab at the nozzle exit which, inducing low-speed region behind the tab

* Corresponding author.
E-mail address: D.Violato@tudelft.nl (D. Violato).

0142-727X/$ - see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatfluidflow.2012.06.003

Nomenclature

Symbol	quantity		
$\dot{m}$	mass flow rate	T_a	ambient temperature
Bi	*Biot* number $Bi = hs/\lambda_f$	T_{aw}	adiabatic wall temperature
d_V	vortex core diameter	T_w	wall temperature
D	nozzle diameter	T_k	temporal kernel size for velocity filtering
$f\#$	numerical aperture	TKE	turbulent kinetic energy
f	focal length	U	velocity in X direction
h	convective heat transfer coefficient	$\mathbf{V}$	velocity vector
k	air thermal conductivity	V	velocity in Y direction
$\underline{K}$	foil thermal conductivity tensor	V_r	velocity in radial direction
L	chevron length	W	velocity in Z direction
L_k	spatial kernel size for velocity filtering	W_j	average velocity at nozzle exit
λ_2	"Lambda 2" criterion	W_V	vortex convective axial velocity
Nu	Nusselt number $Nu = hD/k$	X	abscissa in the foil plane
p	chevron penetration depth	Y	ordinate in the foil plane
q''_j	Joule heating heat flux	Z	nozzle-to-plate distance
q''_k	tangential conduction heat flux	σ	Stefan–Boltzmann constant
q''_n	natural convection heat flux	ε	wall emissivity coefficient
q''_r	radiation heat flux	λ_f	foil thermal conductivity
R	radial coordinate on the target plate	μ	viscosity
Re	Reynolds number: $\mathrm{Re} = 4\dot{m}/(\pi\mu D)$	θ_e	momentum thickness
s	foil thickness	σ	velocity fluctuation
St	Strouhal number	$\boldsymbol{\omega}$	vorticity vector

and high-speed regions on each side of the tab, lead to the formation of a pair of counter-rotating vortices (Reeder and Samimy, 1996). These structures were also observed to develop in lobed jets, where, compared with circular jets, they are responsible for enhanced entrainment characteristics (El Hassan and Meslem, 2010).

The heat transfer rate performances of circular impinging jets have been reviewed by several studies, such as Martin (1977), Jambunathan et al. (1992), Viskanta (1993), among others. Early investigations on the flow field topology of circular jets have been mainly focused on the assessment of the flow statistics (Gardon and Akfirat, 1965; Gautner et al., 1970; Donaldson and Snedeker, 1971), reporting that turbulence plays the major role on the heat transfer rate, with higher levels of turbulence resulting in high heat transfer rate (Gardon and Akfirat, 1965, Fitzgerald and Garimella, 1998).

At moderate Reynolds numbers, in the region next to the nozzle exit, circular impinging jets develop Kelvin-Helmholtz instabilities which, as reported by Kataoka et al. (1987), are organized in toroidal vortices. Kataoka et al. (1987) showed that large-scale flow structures play a role in the heat transfer at stagnation, finding that the latter can be characterized by the impingement frequency of the formers. The authors explained that the stagnation heat transfer in circular impinging jets is larger for a nozzle-to-plate distance of approximately 6 jet diameters, since the large-scale structures in the region by the end of the potential core induce intermittent motions, entraining ambient air near the wall in the impingement region. By smoke-wire visualizations of a low nozzle-to plate distance impingement, Popiel and Trass (1991) showed the shedding and pairing of the ring vortices and the process of interaction with the plate. When the vortex rings approach the plate, they stretch and increase in diameter. With convective heat transfer measurements by infrared thermography (IR), Meola et al. (1996) showed that, for low nozzle-to-plate distances of 2 and 4 nozzle diameters, vortex rings cause flow separation and reattachment at a downstream location depending on the vortex strength. The point of reattachment coincides with the second peak of heat transfer distribution. Hadziabdic and Hanjalic (2008) addressed the low heat transfer at a radial distance of 1.5 diameters from the center of the plate to unsteady flow separation.

Planar PIV has been used to investigate the role of flow structures on the heat transfer performances at impingement. Sakakibara et al. (1997) combined planar particle image velocimetry (PIV) and laser induced fluorescence (LIF) to simultaneously measure velocity and temperature fields of a $Re = 2000$ jet impinging on a plate 8 diameters off the nozzle. The same authors observed that the streamwise vortex pairs are the most probable flow structure to generate turbulent heat flux as they sweep cold fluid toward the wall and eject high-temperature fluid toward the outer region. Two-component PIV was also used by Angioletti et al. (2003) who, investigating the flow field at laminar ($Re = 1500$) and transitional regime ($Re = 4000$) with a nozzle-to-plate distance of 4.5, in combination with heat transfer measurements by the naphthalene sublimation method, found that the maximum transfer coefficient is due to toroidal structures impacting on the plate. Roux et al. (2011) applied high-speed PIV and IR thermography explored the role of flow coherence on the heat transfer performances of an acoustically excited impinging jet at $Re = 28{,}000$. The same authors observed that the acoustic forcing modifies the annular vortex rings, as well as the shedding and pairing frequencies, resulting in an enhancement of the Nusselt number Nu in the at the jet axis with a smoothing of the secondary peak.

Investigations on the flow characteristics of impinging jets have mostly been focused on circular jet configurations (Kataoka et al., 1987; Hall and Ewing, 2006; Sakakibara et al., 1997; Angioletti et al., 2003, are only few example) rather than jets issued through orifices with vortex generators in the form of 'mechanical tabs'. Gao et al. (2003), who studied one of these jet configurations, discussed the flow field statistics at the region of impingement without analyzing the instantaneous patterns.

TOMO-PIV (Elsinga et al., 2006) is a suitable technique for the diagnostics of complex three-dimensional flows, such as turbulent boundary layers (Schroeder et al., 2010) and wake flows (Scarano and Poelma, 2009; Violato et al., 2011). Unlike 2D measurements, it enables the evaluation of the full velocity gradient tensor from