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Structure detection and analysis of non-circular impinging jets in a semi-confined array configuration

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Abstract

The flow structure generated by circular and oblate shaped nozzles for an impinging confined 7-by-7 jet array is investigated. Instantaneous velocity fields, obtained from Digital Particle Image Velocimetry (DPIV) along the crossflow direction are analyzed using Proper Orthogonal Decomposition (POD). Also, a vortex detection algorithm is used to locate and quantify the nature of the instantaneous vortices within the flow. The results show that an oblate shaped nozzle when oriented with its major axis aligned with the exhaust flow has flow characteristics resulting in increased turbulent kinetic energy. This has potential for increased surface transport.

Keywords: Jet; Array; Impingement; POD; Vortex detection

1. Introduction

Many engineering applications currently use jet impingement to improve the cooling capacity over a wide range of length scales and configurations. With normal impingement, jets spread symmetrically, but when arranged in an array with sidewall constraints, a directed crossflow results. In particular, sidewalls create a crossflow with increasing magnitude towards an open end, or the exhaust. The study of a single jet with crossflow has been considered in detail for a number of decades [1]. In a jet array, the flow pattern for each jet is considerably altered compared to a single impinging jet due to jet interaction and flow exhaust. In particular, in the presence of a crossflow, there is a fountain upwash that interacts with the crossflow [2–4]. Notably, is the presence of a complex three-dimensional "scarf" vortex around each impinging jet. Jet arrays in crossflow have been studied primarily for their heat transfer characteristics, with specific application to turbine blade cooling [5–10]. A review of some of these results can be found in [11], which provides a detailed description of the mean flow characteristics and heat transfer for the same jet configuration presented in this paper.

Several studies have looked at the consequences of using non-circular jets in an array. It was found that increased heat transfer rates can be obtained using non-circular jets in specific orientations [12]. Owens and Liburdy [13] demonstrated that using an elliptic jet array at low Reynolds numbers improves the average heat transfer up to 37% over a circular jet. Arjocu and Liburdy [14–16] showed that at impingement distances of four jet hydraulic diameters or more, the array of elliptic jets have streamlines that converge in the major axis planes and spread in the minor axis plane. This behavior is typical of flows through non-axisymmetric jet orifices and is part of the "axis switching" process often observed for single jets. The axis switching of non-circular jets superimposed in a jet array alters the jet column instability, increases swaying motion, and results in the presence of small-scale shear layer structures leading to a high level of turbulence and entrainment in the impingement region, which is generally thought to enhance surface cooling.

In this paper two-dimensional instantaneous velocity field data are used to better understand the flow structure

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Nomenclature

A_j	individual jet orifice area
A_s	impingement surface area
A_t	total jet orifice area $= NA_j$
A_v	area of integration for vortex detection
D	jet orifice hydraulic diameter
H	impingement distance from the jet nozzle to impingement surface
M	designation of a point in the velocity field used to determine the local vorticity
N	number of jets; number of instantaneous velocities obtained at each location
n_m	mode number
n_T	total number of modes
P	center point for vortex detection
Re	Reynolds number $= \frac{V_j D}{\nu}$
U_M	instantaneous velocity vector at point M
V_c	average crossflow velocity at a given downstream row
V_j	average jet velocity
V_r	crossflow-to-jet velocity ratio $= V_c/V_j$
x	distance along the crossflow direction
y	distance normal to the impingement surface, measured from the surface

Greek symbols

Γ_1	vortex detection function
θ_M	angle between the velocity vector U_M and the sub-area radial line PM
λ_i	POD eigenvalue
ν	kinematic viscosity of air
ρ	density of air
σ_i	POD eigenfunction
λ	total sum of all the eigenvalues $= \sum_{i=1}^{n_T} \lambda_i$

Subscripts

0	plenum chamber
j	jet
s	impingement surface

variations between circular and non-circular jets in an array with crossflow which increases in magnitude along the flow direction. The techniques used include Proper Orthogonal Decomposition (POD) and vortex detection [17–26]. Introduced by Lumley [17,18] in the context of turbulent velocity fields, POD analysis has been applied successfully to fluid engineering problems such as the turbulence diagnostics of developing boundary layer flows by Wiegel and Fischer [23] and Di Cicca and Iollo [24], but also for turbulent jets such as by Patte-Rouland et al. [25] and Gamard and George [26]. A variety of techniques have been applied to different flows to better quantify the existence and strength of vortical structures within the flow. Vortex identification methods have been used to study the formation and dynamics of vortices by Jeong and Hussain [27], Adrian et al. [28] and others. Di Cicca and Iollo [24] and Graftieaux et al. [29] have used both POD and vortex identification to study complex swirling flows.

The objective of this paper is to provide a better understanding of the flow characteristics of jet arrays from circular and non-circular nozzles. The flow studied includes a self-induced crossflow formed in the impingement region of a confined jet array. A non-circular, oblate, jet orifice geometry with two orientations is compared to circular jets with regard to the energy distribution, and the strength and location of instantaneous vortical structures in the flow. The impingement distance is selected to correspond to the location of axis switching for the elliptical shaped nozzles. Results for two jet Reynolds numbers are presented based on the jet hydraulic diameter, in the range of 8500 and 15,900. Data are confined to the centerline of the jet array, and as such does not illustrate the complex three-dimensional nature of the flow. However, this study is an initial look at flow structure differences that may occur in a jet array that results from nozzle geometry effects.

2. Experimental set-up and method

The jet orifice plate consists of a 7-by-7 array of jets with two different nozzle geometries: a circular and a cusped ellipse oblate shape. The jet array plate geometry and the circular and oblate nozzles are shown in Fig. 1. The major axis of the oblate nozzle, when aligned with the crossflow is noted as (0°) and when aligned normal to the crossflow is noted as (90°) as shown in Fig. 1. Both shapes, circular and oblate, have been designed to have the same orifice

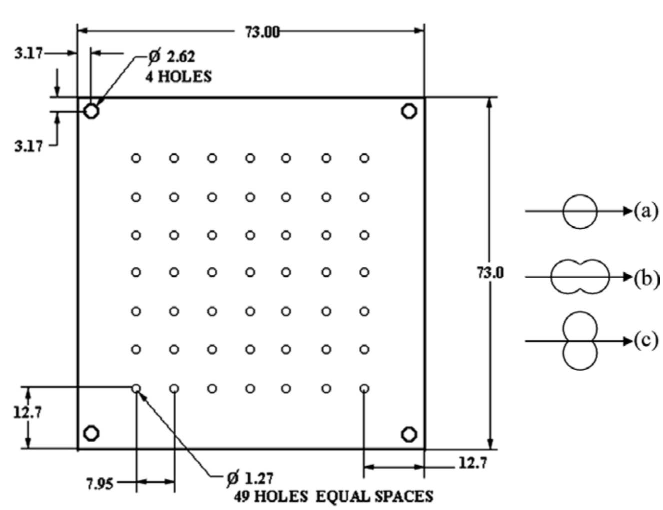

Fig. 1. Jet array geometry and orifice geometry, (a) circular, (b) cusped ellipse (0°), and (c) cusped ellipse (90°).