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Turbulent structures in the flow field of plane jet impinging on a circular cylinder

Y.M. Shim *, P.J. Richards, R.N. Sharma

Department of Mechanical Engineering, The University of Auckland, Auckland 1142, New Zealand

A R T I C L E I N F O

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A B S T R A C T

An experimental study was conducted for the structural characteristics of an impinging jet on a circular cylinder for two cases $D/h = 0.5$ and 1 at the jet Reynolds number $Re_h = 3000$, where D was the diameter of the cylinder and h was the nozzle height. The velocity field measurements were made using particle image velocimetry (PIV) in a water jet facility. The mean and turbulent flow fields of the $D/h = 0.5$ case appeared to be the replica of the wake behind the circular cylinder in cross flow. In contrast, those of the $D/h = 1$ case showed significantly different features, particularly in the Reynolds stress fields. The proper orthogonal decomposition (POD) method was applied to the two-dimensional PIV data and the 1st and 2nd modes were analysed to reveal large-scale vortical structures in the jet flow. For the $D/h = 0.5$ case, the alternate vortex shedding was formed behind the cylinder and the normalized frequency of this structure was lower than the Strouhal number of the von Kármán vortices at the same Reynolds number. This lower normalized frequency was attributed to the difference in the incoming flow conditions of the present impinging jet and cross flow over a circular cylinder. For the $D/h = 1$ case, the symmetrical secondary vortical structures were induced by the free jet vortices triggered by the initial jet instability, developed by the vortex merging process and approached to the cylinder. This induced structure has two distinct peak frequencies, which may be associated with the free jet vortices and induced secondary vortices respectively. From the present study, it was observed that the free jet vortices developed along the jet shear layers interact with the cylinder in different manners depending upon the curvature ratio, D/h and generate different flow structures. These different flow structures may cause the dependency of the averaged Nusselt number on the curvature ratio, D/h, as reported by previous studies. Therefore, it is possible to postulate that alternate vortex shedding is responsible for higher heat transfer rate and is a more efficient flow structure for thermal control.

1. Introduction

Plane jets have been studied extensively over the past several decades [1–5], because of their simple geometry and boundary conditions compared to elliptic or axisymmetric jets, practical interest in many technological applications and the presence of large-scale organized motions in the jet flow. In particular, large-scale coherent structures in plane jets have attracted many researchers. Such structures have been observed in several experiments [6–11]. It has been found that coherent structures are closely related to the main attributes of the jet flow, being able to entrain and mix with ambient fluid. From the practical viewpoint of optimal design and improvement of its performance, it is crucial to understand the physical characteristics of coherent structures and to be able to predict and control them. One way to take advantage of jet flow is through jet impingement for cooling or heating an object placed at a certain distance downstream from the jet nozzle. Since the high velocity of the jet enhances the transport of heat and mass, jet impingement yields higher heat transfer rates than are possible by most other methods of single-phase forced convection. In particular, current trends in electronic components have demanded efficient cooling systems in closely packed systems, and this need has led to the investigation of impinging jet cooling [12]. In addition, the food industry has an interest in jet impingement heating [13,14] as well. However, it should be noted that in spite of extensive prior experimental work [15–21], important information on the characteristics of the impinged jet flow on a curved surface remain unknown. The study of jet impingement on a circular cylinder will provide a better understanding of the surface curvature effects on the processes associated with the heat transfer mechanism.

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* Corresponding author. Tel.: +64 9 373 7599x88146; fax: +64 9 373 7479.
E-mail address: yshi095@aucklanduni.ac.nz (Y.M. Shim).

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Nomenclature

D	diameter of cylinder, m
$U_c(X)$	mean velocity on the jet centreline, m/s
$U_{c,o}$	mean jet centreline velocity at the nozzle exit, m/s
Re	Reynolds number, $U_{c,o}h/\nu$
Y	lateral coordinate, m
X	streamwise coordinate, m
h	nozzle height, m
U	mean streamwise velocity, m/s
u_{rms}	root-mean-square streamwise velocity, m/s
v_{rms}	root-mean-square lateral velocity, m/s
$\langle u'v' \rangle$	Reynolds shear stress, m^2/s^2
b	jet half-width in lateral direction where $U(X,Y) = \frac{1}{2}U_c(X)$, m
$\phi^{(n)}(X)$	eigenfunction
$a^{(n)}(t)$	POD coefficient
ν	kinematic viscosity of water, m^2/s

The flow in a jet impinging orthogonally on a target surface can be divided into the stagnation and wall jet regions as shown in Fig. 1. The parametric effects of circumferential distance from the stagnation point (S), jet-to-impingement surface distance ($X_o/h = 1$–13) and surface curvature ($D/h = 10.7$ and 16) on the impingement jet flow development along a semi-circular convex surface were documented into a set of mean flow and turbulence data by Chan et al. [22]. They found that the streamwise Reynolds normal stresses are strongly affected by D/h, X_o/h and S in the near wall region, compared to the transverse Reynolds normal stresses. It was also revealed that the Reynolds shear stress is much more sensitive to D/h. However, their study was limited to measuring turbulence statistics at several circumferential locations, which was not sufficient to understand the flow structures. The plane jet impinging upon a small circular cylinder ($D/h = 0.2$) located on the jet centreline within the potential core region ($X_o/h = 1.3$) was studied by Hsiao et al. [23] and Chou et al. [24]. In the jet impinging flow field behind the cylinder, both the wake and jet flow regions coexisted and a narrow accelerated region was observed near their junctions that separated these two flow regions. The pressure fluctuations on the cylinder surface were found to propagate upstream and form a feedback loop within the shear layers, leading to self-sustained oscillation flow. The measured resonant frequency of the induced self-sustained oscillating flow matched the vortex shedding frequency from the cylinder wake. In the jet region, both resonant and its sub-harmonic instabilities were observed due to the vortex merging processes as in the case of the free jet. Self-sustained oscillations have been observed for various free shear layer impingement configurations, for example, jet-flat surface, jet-slot and mixing layer-edge. These organized oscillations of an impinging flow are sustained through a series of interacting events: feedback (or upstream propagation) of disturbances from the impingement surface to the initial free shear layer; inducement of localized fluctuations; and amplification of these fluctuations in the shear layers [25]. Lucas and Rockwell [26] found that the self-sustained oscillations of a plane jet impinging on a wedge exhibited not simply a single, but as many as seven frequency components in the range of Reynolds number $250 \leqslant Re \leqslant 1150$, all of which were traceable to the nonlinear interaction frequencies of two primary components: a jet shear layer frequency (β); and a low-frequency modulating component ($\frac{1}{3}\beta$). This modulating component arose from interactions between incident vortices in the jet shear layers and induced vortices of opposite sense at the edge.

Despite the fact that many jet impingement applications for cooling/heating purpose involve a curved surface other than flat surface, jet impingement on a curved surface has not been extensively studied from a fluid dynamics perspective, compared to jet impingement on a flat surface. The purpose of the present experimental study is therefore, to provide information on the structures when the jet flows impinges on a circular cylinder, particularly focusing on the effect of the surface curvature ratio D/h of the cylinder. The PIV measurements were conducted and POD was employed to investigate the large-scale vortical structures around the cylinders.

2. Experimental set-up

The jet facility used in this study was the same as that used in the earlier study conducted by Shim et al. [27] on the flow field of a plane jet. A schematic diagram of the experimental facility is shown in Fig. 2. Details regarding the experimental facility and the PIV measurements may be found in the above reference. Only essential aspects and modifications conducted for jet impinging experiments are described here.

The X-axis is directed downstream (defined as streamwise), Y-axis is perpendicular to the streamwise direction (defined as lateral) and the Z-axis lies along the width of the nozzle (defined as spanwise). The facility consisted of a water tank and a water jet generating system. The acrylic-walled water tank had nominal interior dimensions of 1000 mm deep, 375 mm wide and 2000 mm long. The air/water interface was removed by filling water to the roof of the tank. The water jet generating system consisted of a pump, a constant-head tank, a flow conditioner and a jet nozzle. The pump supplied water from the water tank to the

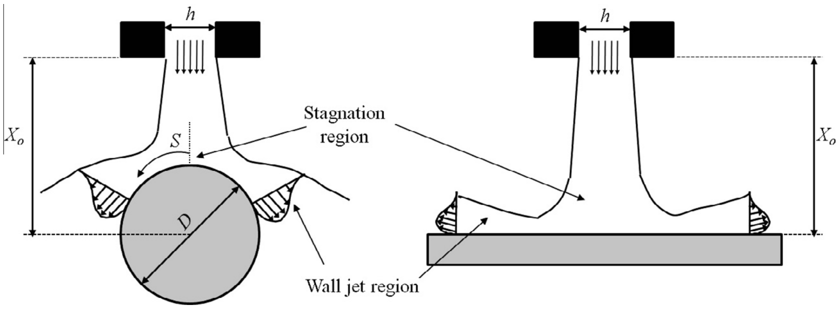

Fig. 1. Flow regions of a jet impinging on a circular cylinder and flat plate.