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2018

Long, J., & New, T. H. (2019). Vortical structures and behaviour of an elliptic jet impinging upon a convex cylinder. *Experimental Thermal and Fluid Science*, 100, 292-310.
doi:10.1016/j.expthermflusci.2018.09.002

<https://hdl.handle.net/10356/142836>

<https://doi.org/10.1016/j.expthermflusci.2018.09.002>

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Vortical structures and behaviour of an elliptic jet impinging upon a convex cylinder

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Abstract

A study on a $Re_h = 2100$, $AR = 3$ elliptic jet impinging upon different convex cylinders at a jet-to-cylinder separation distance of $H/d_h = 4$ have been conducted. Laser induced fluorescence (LIF) and digital particle image velocimetry (DPIV) techniques were utilized to investigate the effects of cylinder-to-jet diameter-ratio (i.e. $D/d_h = 1.15, 2.3$ and 4.6) and jet orientation upon the vortical structures and their behaviour. Results show that comparable flow developments occur along both convex surfaces and straight-edges when the elliptic jet minor-plane is aligned with the cylindrical axis (i.e. EJ1 configuration), while more non-uniform flow behaviour results when the elliptic jet major-plane is aligned with cylindrical axis (i.e. EJ2 configuration). Additionally, significant vortex engulfment behaviour between adjacent ring-vortices upon impingement is observed along the elliptic jet minor-plane regardless of exact impingement configuration, which subsequently lead to different flow modes. Braid vortices **play** a surprisingly interesting role, where they lead to cross-stream and upstream vortical motions for $D/d_h = 1.15$ and 2.3 cylinders under EJ1 configuration. In contrast, they interact with adjacent jet ring-vortices and rib structures for $D/d_h = 4.6$ cylinder. Proper orthogonal decomposition (POD) analyses provided additional information on the unique vortical behaviour identified in the flow fields, while momentum thickness profiles characterize the mixing layers in relation to the different configurations. Lastly, wall shear stress distributions under the above-mentioned flow conditions have also been determined and related to the vortical structures and behaviour.

Keywords: elliptic jet; impinging jet; convex cylinder; laser-induced fluorescence, particle-image velocimetry

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1. Introduction

Jet impingements have been widely studied because of their relevance to industrial applications related to achieving high heat and mass transfer rates for heating, cooling or drying purposes (Ferrari et al., 2003; Sarkar et al., 2004; Pavlova and Amitay, 2006; Zuckerman and Lior, 2006). Such a particular flow scenario also offers new cooling schemes in gas turbines to improve thermal efficiency and power density (Benini, 2011). Subsequently, most of the prior investigations focused on the heat transfer characteristics of impinging jets, looking into the effects of various flow parameters such as Reynolds number, jet-to-surface separation distance, jet and surface geometry (Cornaro et al., 2001; Lim et al., 2007; Sagot et al., 2008; Ingole and Sundaram, 2016; Penumadu and Rao, 2017, among others). Note that most of these studies made use of extensive mean flow and heat transfer results to shed light upon how heat transfer levels may be optimized.

In recent years however, it has also been gradually recognized that the flow dynamics of impinging jets have strong correlations and effects on the heat and mass transfer performances. Hadžiabdić and Hanjalić (2008) performed large-eddy simulations (LES) on a circular jet impinging upon a flat-plate at $H/d = 2$ (i.e. d and H are the jet diameter and jet-to-surface separation distance, respectively) and $Re = 20000$ to analyze the vortical structures and their relationships with the local heat transfer characteristics. The LES results attributed the appearance of a second peak in the Nusselt number distributions to reattachments of the recirculating flows and associated turbulence production. Furthermore, several studies made

use of hot-wire anemometry (Chou et al., 2002), microphone measurements and multi-channel pressure transducer measurements (Hall and Ewing, 2006) and polarographic method (EI Hassan et al., 2012; Kristiawan et al., 2012) in the investigation of impinging jets. More recently, digital particle image velocimetry (DPIV) technique has seen increasing use as a reliable quantitative technique to provide accurate measurements of the flow fields for various jet impingement scenarios, as demonstrated by Violato et al. (2012), Meslem et al. (2013), Xu et al. (2017) and Guo et al. (2017).

Despite significant progresses made in terms of understanding impinging jet vortex dynamics through the use of DPIV technique, the majority of these investigations focused on circular jets that produce axisymmetric vortical structures along their shear layers. On the other hand, noncircular jets such as cross-shaped jet, lobed jet, slot jet and elliptic jets produce comparatively far more complex vortical structures and behaviour that potentially extend their applicability towards heat transfer applications (Rau et al., 2014; Sadjavi et al., 2015; Achari and Das, 2015; Long and New, 2015; Sadjavi et al., 2016 and Trinh et al., 2016, take for instance). Among them, elliptic jet leads to non-uniform initial momentum thicknesses along its perimeter, which further results in non-uniform self-inductions and complex three-dimensional vortical motions. In particular, axis-switching behaviour is known to occur in elliptic jets, where the jet major- and minor-axis interchange as the jets convect downstream. As a result of this axis-switching behaviour, many studies have observed that elliptic jets produced enhanced mixing and entrainment ratio as compared to circular jets (Ho and Gutmark, 1987; Quinn, 1989; Hussain and Husain, 1989; Husain and Hussain, 1991, 1993; Yoon and Lee, 2003; Mitchell et al., 2013).

One of the earliest studies that investigated the heat transfer performance of elliptic impinging jets was conducted by Lee et al. (1994), where they made use an aspect ratio (AR) of 2.14 elliptic jet at $Re_h = 5000, 10000$ and 20000 , as well as $H/d_h = 2, 4, 6$ and 10 (i.e. d_h is the elliptic jet hydraulic diameter and Re_h is the jet Reynolds number based on d_h). They found higher Nusselt numbers in the impingement region as compared to that for circular impinging jet, and they attributed this finding to the higher entrainment rates at the stagnation region. In another study, axis-switching behaviour in an elliptic impinging jet was also observed through isothermal contours on a heated flat-plate (Lee and Lee, 2000). They also proposed that the Nusselt number at the impingement point could be correlated with other flow parameters as $Nu \propto (AR)^{-0.082}(H/d_h)^{-0.077}$. The study by Koseoglu and Baskaya (2008, 2010) further supported this relationship when they observed that heat transfer levels were enhanced in the impingement region when jet aspect ratio was increased. Other studies in terms of elliptic jet arrays impingement had also been investigated by Yan et al. (2004), Yan and Mei (2006) and Caliskan et al. (2014).

It should be noted that experimental endeavours emphasizing on the flow dynamics of impinging elliptic jets under different configurations are much more limited, as compared to those focused upon their heat transfer characteristics. Nevertheless, some earlier limited studies shed light on the flow phenomenon through flow visualizations (Lee and Lee, 2000), mean velocity and turbulence measurements (Koseoglu and Baskaya, 2008). In particular, extensive mean radial and axial velocity, turbulence intensity results of an $AR = 4$ elliptic jet impinging upon a flat-plate at $Re_h = 10000$ and $H/d_h = 2-6$ obtained using laser Doppler anemometry technique were reported by them. More recently, Long and New (2016) studied the effects of separation distance on the vortex dynamics of an $AR = 3, Re_h = 2100$ elliptic jet impinging upon a flat-plate through laser-induced fluorescence (LIF) and DPIV techniques. They

identified the developments of coherent vortical structures such as elliptic jet ring-vortices, rib structures, braid vortices and wall-separated vortices, as well as their corresponding influences on the instantaneous and mean skin friction coefficient levels. However, this study was limited to only flat-plate impingements, while other surface geometries are commonly encountered in real-world applications as well. As New and Long (2015) had observed, circular jet impingements upon curved surfaces lead to flow behaviour that is heavily influenced by vortex-stretching phenomenon, and hence deviates significantly from that associated with flat-surfaces. Since the flow dynamics of elliptic jets impinging upon curved surfaces are poorly understood and considering the fact that they have direct implications upon heat transfer characteristics, it will be logical and timely to take a closer look into the dynamics of such a flow configuration. The current paper reports upon the findings arising from the study, where detailed results based on LIF and DPIV techniques will be presented to reveal the intricacies associated with such a flow scenario.

2. Experimental setup and procedures

2.1 Jet impingement apparatus

Similar to earlier studies on impinging and other jet flow problems by the authors (New and Long, 2015; Long and New, 2015 and 2016; New and Tsovolos, 2009 and 2012), a recirculating water-tank facility was employed to conduct the present experiments. Water was channeled from a small reservoir into an elliptic jet apparatus, after which the freely exhausting elliptic jet would impinge upon a circular test cylinder. Flow conditioning devices were employed within the jet apparatus prior to the exhausting of the jet, in order to straighten the flow and improve its initial jet turbulence levels. In particular, they consisted of a diffuser, honeycomb flow straighteners, three layers of fine screens and a 25:1 circular-to-elliptic contraction chamber. Any excess water would overflow back into the reservoir to complete the

whole flow circuit and ensured a constant water level in the water tank. The jet flow rate was measured by an iSolv EFS800 - CFT180 electromagnetic flow meter and adjusted by a needle valve to ensure good accuracy in the jet Reynolds number used during the experiments. For more details, readers are advised to refer to the earlier studies.

The $AR = 3$ elliptic jet has a major diameter of $d_{\text{major}} = 36.7 \text{ mm}$ and minor diameter of $d_{\text{minor}} = 12.3 \text{ mm}$, with an estimated hydraulic diameter of $d_h = 17.4 \text{ mm}$. The mean jet velocity for the elliptic jet was maintained at $U_m = 0.12 \text{ m/s}$, which led to a Reynolds number of $Re_h = U d_h / \nu \approx 2100$. The fundamental frequency for the present freely-exhausting elliptic jet is 4.43 Hz along the major-plane and 3.94 Hz along the minor-plane. These frequencies are close to that associated with a freely-exhausting $Re = 2200$ circular jet with a comparable 20 mm jet diameter studied by the authors previously (New and Long, 2015), which in turn agrees well with the $St-Re$ relationship observed by Becker and Massaro (1968) for unexcited circular jets earlier. The initial momentum thicknesses measured at a location of $0.2d_h$ away from the jet exit are approximately $0.15d_h$ along the major-plane and $0.08d_h$ along the minor-plane. Further, the corresponding Strouhal number based on the initial momentum thickness and fundamental frequencies of the elliptic jet are 0.096 and 0.046 along the major- and minor-planes, respectively. Moreover, for the present elliptic jet under freely-exhausting conditions, axis-switching behaviour is present with a cross-over point in the half-jet width profiles located at approximately $5.8d_h$ away from the jet exit (Long and New, 2016). However, as the jet-to-cylinder separation distance used in the present study was restricted to $H/d_h = 4$, no axis-switching occurred prior to the jet impingements.

Three circular solid Plexiglas cylinders with diameters of $D = 20 \text{ mm}$, 40 mm and 80 mm served as impingement surfaces, with corresponding cylinder-to-jet diameter ratio of $D/d_h =$

Fig. 1 Orientation of the elliptic jet planes relative to the cylinder axis.

1.15, 2.3 and 4.6. As the present study focuses upon the effects of surface diameter-ratio, the jet-to-cylinder separation distance was kept at $H/d_h = 4$ throughout. Moreover, to minimize light reflections introduced by laser sheet illuminations, both the test cylinders and water tank bottom floor were covered with 0.09 mm thick smooth black adhesive paper (Long and New, 2015 and 2016). Another parameter of interest in the present study is the orientation between the elliptic jet and cylindrical axis. This is on the premise that numerous previous studies (Ho and Gutmark, 1987; Quinn, 1989; Hussain and Husain, 1989; Shi and New, 2013; Long and New, 2016) have reported that vortical structures and flow developments are produced to be drastically different between the elliptic jet major- and minor-planes, not to mention under impinging conditions. Hence, there is a need to address the flow effects due to the orientation of the elliptic jet relative to the cylinder. The cylinder axis was selected as the reference upon which the jet orientations were differentiated. In this case, EJ1- and EJ2-configurations refer to scenarios where the elliptic jet minor- and major-planes are aligned with the cylinder axis respectively, as shown in Fig. 1.

2.2 LIF and DPIV techniques

Details of the LIF and DPIV setups had been covered by New and Long (2015) and hence, they will only be briefly described here. For LIF system, with the use of appropriate arranged 1 W, 532 nm wavelength, LaVision continuous-wave diode-pumped solid state (DPSS) laser, beam-splitter-plate and sheet-forming optics, two thin laser sheets were generated to enter the water tank from opposite sides at the same height as the jet centreline. Hence, full visualizations of the flow fields could be obtained with negligible effects caused by cylinder shadows. Fluorescein disodium salt was selected as fluorescent dye of choice and dissolved into the jet fluid prior to exhausting into the water tank, which would show up as greenish colour after being excited by the laser. A Canon digital single-lens-reflex (DSLR) camera with an f1.4 50 mm lens was located above the water tank and LIF visualizations were recorded in 1920 px $\times$ 1080 px resolution at a frequency of 30 Hz. Thereafter, LIF images were then extracted from the digital videos for subsequent analysis in terms of the vortical behaviour in support of quantitative DPIV results.

DPIV experimental setup consisted of a Quantel Evergreen 200 mJ/pulse, double-pulse Nd:YAG laser, a four-megapixel FlowSense CCD camera, synchronization and frame-grabber cards. The acquisition frequency of the DPIV system was 14 Hz in double-frame mode with 3 milliseconds time interval between the two laser pulses throughout the experiments. A 14 Hz acquisition frequency resulted from the 2 $\times$ 1 binning of the CCD camera to 2048 px $\times$ 1024 px. Note that the 14 Hz acquisition frequency is more than three times the previously-mentioned fundamental frequencies of the present elliptic jet, as well as the fundamental frequencies of the flow behaviour along the convex surfaces and straight-edges after impingement (not described in detail here). Hence, the present acquisition frequency was sufficiently fast to track the jet impingement behaviour well. The DPIV measurement window size was approximately

76 mm × 160 mm which was sufficient to capture half of the flow field about the symmetry plane on the premise that full-view LIF visualizations present a high-level flow symmetry about the impingement axis. This in turn increased the measurement resolution that aided better capturing of the vortical structures. As such, only one laser sheet was directed into the water tank at the same height as with the jet centreline, without the use of the beam-splitter.

20 µm sized, 1.03 g/cm³ density Dantec Dynamics polyamide seeding particles were used as tracers and dispersed into the water tank and reservoir before the experiments commenced. Thereafter, 500 consecutive image pairs were acquired for each test configuration and then analysed by Dantec DynamicStudio™ software. The captured image pairs were analysed using a two-pass, multi-grid cross-correlation scheme with initial and final interrogation window sizes of 128 px × 128 px and 32 px × 32 px respectively, where they overlapped 50% in both horizontal and vertical directions. Subsequently, the raw velocity vectors were subjected to validation schemes such as peak, range and moving average validations to obtain the final vector maps as well as other associated flow quantities, such as vorticity and skin friction coefficient. For the procedures on the estimations of skin friction coefficients from the DPIV results, readers are advised to refer to New and Long (2015), as well as Long and New (2015, 2016). It should be highlighted here that the accuracy of skin friction estimations is dependent upon the accuracy and resolution of near-wall DPIV velocity measurements. While the accuracy is limited by the measurement resolution of approximately 1.2 mm here, estimations of the skin friction coefficient provided here will nonetheless provide adequate insights into the relationships between the vortical flow behaviour and the skin friction variations between the different flow configurations and test cylinder diameter-ratios.

Fig.2 Correlation coefficient between each individual POD mode 1-10 based on 350, 400, 450 and 500 snapshots for the case of elliptic jet major-plane impingement upon a $D/d=4.6$ cylinder with $H/d=4$ along (a) the cylinder convex surfaces and (b) flat edges. 500 snapshots were selected as the sampling test case.

Instantaneous velocity field results obtained in the present study were also subjected to POD analysis, where it is able to identify the most dominant flow structures and behaviour in terms of their flow energy levels. The procedures and methodologies adopted were similar to those used by Zang and New (2015) and Wei et al. (2016). To ensure that the number of velocity field results obtained for each test case is sufficiently high for satisfactory POD analysis, the convergence of the POD modes was investigated based on the procedures developed by Hekmati et al. (2011), where correlation coefficients between individual POD modes (POD modes 1-10) at different sample sizes are compared. For the sake of brevity, only the correlation coefficient results for a single test case (i.e. EJ1-configuration, $D/d_h = 4.6$, $H/d_h = 4$, along both cylinder convex surface and straight-edge) are presented in Fig. 2 to illustrate the effects of sample size on POD analysis. In particular, POD modes determined based on 350, 400 and 450 sample sizes were analysed and compared to those ascertained based on 500 sample size. The figure shows that the correlation coefficients of POD modes 1-8 are always above 0.9 and approach 1 for 400 and 450 sample sizes, which demonstrate that only incremental

improvements when the sample size increases to 500. As such, this shows that 500 velocity field results are able to produce satisfactory convergence in the POD analysis.

3. Results and discussions

3.1 EJ1-configuration impingement

Details of vortical behaviours associated with EJ1-configuration impingement upon the three present test cylinders as taken along their convex surfaces will be presented and discussed from Figs. 3 to 6. Note that key time-sequenced LIF flow images are presented in decreasing cylinder-to-jet diameter-ratio (D/d_h) for a first-hand qualitative appreciation, and time-sequenced vorticity fields derived from the DPIV measurements are subsequently presented to highlight the key vortical structures with their vorticity distributions. Full-view LIF flow images of the elliptic jet flow field presented by the authors in an earlier study (Long and New, 2016) had demonstrated sufficiently symmetrical instantaneous flow developments in terms of some key vortical behaviour like wall-separated vortex formation, vortex engulfment behaviour between adjacent ring-vortices. Hence, both time-sequenced LIF images and DPIV vorticity fields were captured with only half of the symmetrical flow fields here, as such an assumption and approach had already been successfully employed to analyse the vortex dynamics for jet impingement problems (New and Long, 2015; Long and New, 2015 and 2016).

Moreover, it should be noted that vorticity results are capable of capturing the dominant vortex cores and wall boundary layer separations within the near-field, and do not deviate too much from λ_2 -criterion based results in terms of identifying vortical changes (New et al., 2016). Hence, vorticity results are presented here to illustrate the resulting elliptic jet impingement flow fields. Furthermore, it should be highlighted that much of subsequent flow behavioural analyses upon the interactions between the elliptic ring vortices, rib structures and braid

Fig. 3 LIF flow images of EJ1-configured impingement upon a $D/d_h = 4.6$ round cylinder along the cylinder convex surface. Interactions among the primary ring-vortex, rib structure and braid vortices occur upon impingement, before a vortical structure is produced that behaves in a similar manner as the primary ring-vortex to produce a wall-separated vortex.

vortices are heavily drawn upon insights based on earlier studies conducted by Hussain and Husain (1989) and Hussain and Hussain (1991 and 1993).

For consistency, A and R indicate the anti-clockwise jet ring-vortex and rib structure, B_1 and B_2 indicate the clockwise and anti-clockwise braid vortices, and S_{B2} indicates secondary vortex due to boundary separation (i.e. wall-separated vortex) induced by braid vortex B_2 . I indicates the vortical structure resulting from the interaction process between adjacent jet ring-vortex, rib structure and braid vortices, while S_I indicates the wall-separated vortex induced by the corresponding vortical structure. It should be pointed out that the first LIF visualization image is set arbitrarily to $t = 0$ s and shows jet ring-vortex initiation which appears at approximately $2.4d_h$ downstream from the jet exit, as shown in Figs. 3(a), 4(a) and 5(a). This is similar to that of free elliptic jet exhausting along its major-plane, indicating the presenting convex cylinders do not have any effects on jet ring-vortex initiation prior to impingement regardless of the exact cylinder-to-jet diameter ratio.

Fig. 4 LIF flow images of EJ1-configured impingement upon a $D/d_h = 2.3$ round cylinder along the convex surface. Different vortical behaviours are observed between the two braid vortices.

Since the largest $D/d_h = 4.6$ cylinder deviates the least from a flat-plate here, it will be more intuitive to start with this test cylinder first. Prior to impinging upon the cylinder, Figs. 3(b-c) show that braid vortices are observed to form with a strong tendency to spread outwards away from the impingement point. This is in contrast with that for elliptic jet impingements upon a flat-plate (Long and New, 2016), which show them breaking down in a rapid manner. Thereafter, Figs. 3(d-e) show that the elliptic jet ring-vortices and rib structure, R , interact with the adjacent braid vortices, B_1 and B_2 , upon their impingements with the convex surface. At this point, the braid vortices and rib structure cannot be visualized by the fluorescent dye and could have dissipated after the interactions, until a vortical structure I , is produced, as depicted in Fig. 3(f). Subsequently, the newly-formed vortical structure continues to induce the secondary vortex to form due to boundary layer separation under the influence of an adverse pressure gradient, as shown in Fig. 3(g). Further downstream, they combined to produce a

Fig. 5 LIF flow images of EJ1-configured impingement upon a $D/d_h = 1.15$ round cylinder along the convex surface. Both braid vortices move upstream and interact with the upstream jet ring-vortices.

mushroom-shaped vortex-dipole along the convex surface, but diffuse rapidly after their formations, as shown in Fig. 3(h).

When the diameter-ratios are reduced to $D/d_h = 2.3$ and $D/d_h = 1.15$, the initial flow developments, including the formation of jet ring-vortices, rib structure and braid vortices, as well as their subsequent radial movement away from the impingement point, resemble those discussed for $D/d_h = 4.6$ test case, as shown in Figs. 4(a-d) and 5(a-d). However, they tend to behave independently along the convex surface, instead of interacting with one another. For $D/d_h = 2.3$, Fig. 4(e) reveals that braid vortex B_1 with clockwise rotational sense tends to convect in the upstream direction and interact with jet ring-vortices. On the other hand, braid vortex B_2 with anti-clockwise rotational sense tends to convect along the impingement surface independently without any significant interaction with adjacent vortical structures. Thereafter, it induces a wall-separated vortex, S_{B2} , to form as depicted in Fig. 4(f). Decreasing the diameter-ratio to $D/d_h = 1.15$ results in both braid vortices, B_1 and B_2 , to move upstream and interact with jet ring-vortices that are about to impinge upon the convex surface, as depicted in

Figs. 5(e-f). However, it is difficult to tell the subsequent flow developments of jet ring-vortices for both $D/d_h = 1.15$ and 2.3 test cases at this point, due to intense interaction with braid vortex B_1 and rapid dye dissipation. This will be further discussed utilizing time-sequenced DPIV vorticity fields shown in Fig. 6, which are in good agreement with LIF visualizations.

The first time-sequenced DPIV vorticity image for each test cylinder shows when the vortical structures (i.e. ring-vortex, rib structure and braid vortices) are about to impinge the test cylinders, which correspond well with the previous visualization images at $t = 0.13$ s. Firstly, note that visually larger vortex-dipole size and higher vorticity levels are produced along the convex surface with smaller diameter-ratio cylinders. DPIV measurements also detect some key vortical behaviour that LIF visualization cannot depict well due to fast dye dissipation, like the initiation of wall-separated vortex, not to mention the subsequent vortical behaviour of later-formed vortex-dipole along the convex surface. For instance, Fig. 6(a)(iv) shows the vortex dipole ($I-S_I$) eventually detaches from the cylinder convex surface at approximately $t = 0.84$ s after the jet ring-vortex is initiated. For smaller diameter ratios $D/d_h = 1.15$ and 2.3 , Figs. 6(b-c) clearly show the braid vortices undergoing independent vortical developments which one or both move in the cross-stream and upstream directions. In addition, wall-separated vortices that are induced by jet ring-vortices are also observed to form, at locations further away from the impingement point with smaller diameter-ratios.

To shed more light on the preceding behaviour, the vortex-core trajectories of the vortical structures discussed above (i.e. jet ring-vortex A , braid vortices B_1 and B_2 , vortical structure I , and wall-separated vortex S_A , S_{B2} and S_I , respectively) are presented in Fig. 7 for all three test cylinders. They were extracted from vortex-core locations identified through instantaneous DPIV vorticity results for the same flow sequences that were presented in Fig. 6 earlier, but

Fig. 6 Time-sequenced DPIV vorticity fields associated with EJ1-configured impingement upon (a) $D/d_h = 4.6$, (b) $D/d_h = 2.3$ and (c) $D/d_h = 1.15$ cylinders along the convex surfaces. Opposite-signed braid vortices are indicated with + and - symbols respectively.

now with vorticity results for all time intervals within the flow sequences. From the figure, it can be observed that after the initiation of wall-separated vortices due to either jet ring-vortices or braid vortices, the jet flow produces generally similar impingement behaviour for the present three cylinders in terms of vortex-dipole formation, vortex-separation and vortex-dipole breakup. In fact, they exhibit similar trends as compared to a circular jet impinging upon the

Fig. 7 Vortex-core trajectories associated with EJ1-cylinder impingements upon (a) $D/d_h = 4.6$, (b) $D/d_h = 2.3$ and (c) $D/d_h = 1.15$ cylinders along the convex surfaces.

same test cylinders previously under relatively similar conditions (New and Long, 2015), where such behaviour occurs further along the convex surfaces with a smaller diameter-ratio. On the other hand, the behaviour of braid vortices is more sensitive towards the diameter-ratio.

Take for instance, for the smallest $D/d_h = 1.15$ cylinder, both braid vortices move away from the cylinder surface without inducing any wall-separated vortices. Furthermore, the vortex-dipole produced by the jet ring-vortex and associated wall-separated vortex tends to diverge to the rear of the cylinder. In contrast, for $D/d_h = 2.3$ cylinder, braid vortex B_2 behaves like a jet ring-vortex in the sense that it induces a wall-separated vortex, with which they subsequently coalesce to form a vortex-dipole that convects more or less in the streamwise direction. For the largest $D/d_h = 4.6$ cylinder, the vortex-dipoles produced by the interactions between both braid vortices and jet ring-vortices separate away from the convex surface tangentially, after

which they appear to pair up. It can thus be discerned that the role of braid vortices differs according to the cylinder diameter-ratio. Moreover, Fig. 7 illustrates the exact convex surface locations at which wall-separated vortices are observed to form. They occur at approximately 60° , 78° and 93° locations along the convex surfaces for $D/d_h = 4.6$, 2.3 and 1.15 cylinders respectively, which subsequently leads to the increasingly further formation of the vortex dipole and eventually detaching away from the cylinder at approximately 70° , 114° and 151° along the convex surfaces.

Figure 8 shows the resulting flow scenarios associated with EJ1-configured impingement upon $D/d_h = 1.15$, 2.3 and 4.6 cylinders along their straight-edges. Their vortex dynamics largely resemble those of flat-plate impingements along the minor-plane, which has been observed by Long and New (2016), in that ring-vortices induce wall-separated vortices to form and together they produce vortex-dipoles in the initial stages of the flow phenomenon. However, vortex engulfment occurs when the impingement surface is replaced by convex cylinders, regardless of their exact diameter. And this vortex engulfment behaviour can result in different flow developments along the cylinder straight-edges, especially after vortex-separation. The larger $D/d_h = 4.6$ and 2.3 cylinders present a combination of two different flow modes after vortex-separation (i.e. continuous convections and upstream interactions), as shown in Figs. 8(a-b). In particular, interactions with the ring-vortex impingements lead to the resulting vortex-dipoles tilting back to the upstream direction and interact with their upstream neighbours shortly after vortex-separation (i.e. Flow Mode 1), as depicted in Figs. 8(a)(i) and 8(b)(i). In contrast, Figs. 8(a)(ii) and 8(b)(ii) show that the resulting vortex-dipoles behave similarly to those of flat-plate impingements and continue to convect along the straight-edges (i.e. Flow Mode 2) when vortex engulfment behaviour occurs. As for the smallest test cylinder $D/d_h = 1.15$, shown in Fig. 8(c), the resulting vortex-dipoles undergo Flow Mode 1 and do not appear to be significantly

Fig. 8 Instantaneous DPIV vorticity fields associated with EJ1-configured impingement upon (a) $D/d_h = 4.6$, (b) $D/d_h = 2.3$ and (c) $D/d_h = 1.15$ cylinders along the straight-edges, demonstrating two flow developments (i.e. upstream interactions and continuous convections).

affected, regardless of whether the vortex engulfment between adjacent jet ring-vortices occur by the time they impinge upon the convex cylinders.

For more detailed quantitative results, time-sequenced DPIV vorticity fields associated with EJ1-configured impingement upon the $D/d_h = 1.15$ and 2.3 cylinders are employed to reveal their different flow modes along the cylinder straight-edges, as depicted in Figs. 9 and 10. Here, the first time-sequenced DPIV vorticity image for each test cylinder shows either when discrete ring-vortices are about to impinge the test cylinders or vortex engulfment prior to impingement

Fig. 9 Time-sequenced DPIV vorticity fields associated with EJ1-configured impingement upon $D/d_h = 2.3$ cylinder along the straight-edges, depicting both Flow Mode 1 (i.e. upstream interaction) and Flow Mode 2 (i.e. continuous convections) when discrete ring-vortex impingement and vortex engulfment occur, respectively.

occurring, which happens at $t = 0.40$ s or 0.50 s, respectively. Since the largest $D/d_h = 4.6$ cylinder present similar flow modes as with the $D/d_h = 2.3$ cylinder, it will not be discussed here for the sake of brevity. For the intermediate $D/d_h = 2.3$ cylinder, Fig. 9(a) shows the occurrence of Flow Mode 1 in that the separated vortex-dipole tilts back towards the upstream direction, “leapfrogs” and interacts with an upstream vortex-dipole in a rapid manner prior to transiting into incoherence. In particular, the secondary vortex initiation and subsequent vortex-separation occur at approximately $z/d_h = 2$ and 2.4 locations, as shown in Figs. 9(a)(ii) and 9(a)(iii). Upstream interactions by the separated vortex-dipole occurs approximately in the region between $z/d_h = 2.2$ and 2.8 , as shown in Fig. 9(a)(iv). When vortex engulfment between adjacent jet ring-vortices prior to impingement occurs however, secondary vortex S_B induced by ring-vortex B starts to initiate at approximately $z/d_h = 2.2$ location, as shown in Fig. 9(b)(iii). Thereafter, the subsequently formed vortex-dipoles continue to convect along the straight-

Fig. 10 Time-sequenced DPIV vorticity fields associated with EJ1-configured impingement upon $D/d_h = 1.15$ cylinder along the straight-edge, depicting Flow Mode 1 (i.e. upstream interaction).

edge without any upstream interactions of separated vortex-dipoles, as depicted in Fig. 9(b)(iv). For the smallest $D/d_h = 1.15$ cylinder shown in Fig. 10, the jet impingement behaviour with either vortex engulfment or discrete ring-vortex impingement are relatively similar to the $D/d_h = 2.3$ cylinder when vortex engulfment occurs in terms of the key vortical flow changes and upstream interaction process of separated vortex-dipoles (i.e. Mode 1). Nevertheless, wall-separated vortex initiation and vortex-separation occur comparatively closer to the impingement point, which are located at approximately $z/d_h = 1.6$ and 1.8 , respectively, when discrete ring-vortex impingement occurs, and $z/d_h = 1.7$ and 1.95 , respectively, when vortex engulfment occurs.

In addition, it should be mentioned that the vortical structures travel further downstream along the straight-edges as the diameter-ratio increases, a behaviour that is opposite to that observed along the convex surfaces. Apart from the influences due to the diameter-ratio, vortex

engulfment behaviour between adjacent ring-vortices also result in the later manifestations of vortex-separation, such that the resulting vortex-dipoles are able to convect along the straight-edges towards further downstream locations. Despite the ring-vortex core size being reduced shortly after it impinges upon the test cylinder, it remains physically larger than that when a circular jet is utilized (New and Long, 2015). Interestingly, this also suggests that less disparity between the vortex core size and comparable flow developments along the convex surfaces and straight-edges will be produced under the present EJ1-configuration, which could be improved upon further to produce relatively more uniform flow distributions.

3.2 EJ2-cylinder impingement

Elliptic jet-cylinder impingements are sensitive towards not only the cylinder-to-jet diameter-ratio and separation distance, but also to the orientation of the jet relative to the cylindrical axis. As such, this section will shed more light upon these differences. Figures 11 to 13 show time-sequenced LIF visualization images associated with the same elliptic jet impinging upon the convex surfaces of the present three cylinders when its major-plane is aligned with the cylindrical axis (i.e. EJ2-configured). Once again, vortex engulfment behaviour just prior to the jet impingements plays an important role, regardless of the exact diameter-ratio. For the three test cylinders (i.e. $D/d_h = 1.15, 2.3$ and 4.6), ring-vortex initiation appears at approximately at $H/d_h = 1.7$ location, similar to that of a free elliptic jet along the minor-plane, which indicate the presence of convex cylinders does not influence ring-vortex initiation regardless of the exact orientation of the jet relative to the cylinder axis, as seen in Figs. 11(a), 12(a) and 13(a). As the ring-vortices travel towards the convex cylinders, the engulfment behaviour (i.e. upstream jet ring-vortex B being engulfed by its downstream counterpart A) can be clearly observed to occur more rapidly as the diameter-ratio decreases, as shown in Figs. 11(d-g), 12(d-g) and 13(d-c). Furthermore, the appearance of wall-separated vortex S_B

Fig. 11 Time-sequenced LIF flow images of EJ2-configured impingement upon the $D/d_h = 4.6$ cylinder along the convex surface.

Fig. 12 Time-sequenced LIF flow images of EJ2-configured impingement upon the $D/d_h = 2.3$ cylinder along the convex surface.

Fig. 13 Time-sequenced LIF flow images of EJ2-configured impingement upon the $D/d_h = 1.15$ cylinder along the convex surface.

initiation occurs at $t = 0.83$ s after ring-vortex initiation for the largest $D/d_h = 4.6$ cylinder, as shown in Fig. 11(f). In contrast, it occurs earlier at approximately $t = 0.73$ s and 0.57 s for $D/d_h = 2.3$ and 1.15 cylinders, respectively, as depicted in Figs. 12(g) and 13(e). Thereafter, the subsequently-formed vortex-dipoles separate from the cylinder convex surfaces and transit into incoherence for $D/d_h = 1.15$ test cylinder. On the other hand, they do not appear to detach from the convex cylinders for larger $D/d_h = 2.3$ and 4.6 cylinders. Instead, they tend to continue to convect along the convect surfaces. But due to fast dye dissipation, this will be further verified using time-sequenced DPIV vorticity fields shown in Fig. 14.

Again, the first time-sequenced DPIV vorticity image for each test cylinder shows when the ring-vortices are about to impinge the convex surface, which correspond well with the previous visualization images at $t = 0.40$ s. For the largest $D/d_h = 4.6$ cylinder, the wall-separated vortex S_B induced by jet ring-vortex B starts to initiate at approximately 57° along the convex surface,

Fig. 14 Time-sequenced DPIV vorticity fields associated with EJ2-configured impingement upon (a) $D/d_h=1.15$, (b) $D/d_h=2.3$ and (c) $D/d_h=4.6$ cylinder along the convex surfaces.

as shown in Fig. 14(a)(iii). Thereafter, the wall-separated vortex S_A starts to initiate. However, the above-mentioned vortex- dipoles (i.e. A and S_A , B and S_B) do not detach from the convex surface subsequently. Instead, they continue to convect along the convex surface before transiting into incoherence, as depicted in Fig. 14(a)(iv). When the diameter-ratio is decreased

to $D/d_h = 2.3$, only one vortex-dipole (i.e. A and S_A) that is being engulfed by the downstream neighbour, remains attached to the convex surface before convecting towards the cylinder lee-side. In contrast, the other vortex-dipole (i.e. B and S_B) separates from the convex surface and moves downstream in an almost streamwise direction, as shown in Fig. 14(b)(iv). Further reducing the diameter-ratio to $D/d_h = 1.15$ shows that the downstream jet ring-vortex (i.e. A) does not induce any wall-separated vortex (i.e. S_A) to form. Instead, it separates away from the convex surface and transits into incoherence eventually, as shown in Figs. 14(c)(iii) and 14(c)(iv). Similar to the $D/d_h = 2.3$ cylinder, the trajectory of the separated vortex-dipole (i.e. B and S_B) is almost along the streamwise direction with little veering away from the impingement axis.

The overall vortical behaviour of EJ2-cylinder impingements along the straight-edges are largely similar for the three test cylinders. Interactions between adjacent braid vortices, jet ring-vortices and rib structure occur for all three of them, which is in contrast to EJ1-cylinder impingements where only the largest $D/d_h = 4.6$ cylinder produces any significant flow interactions. These interactions induce a wall-separated vortex to form, where it subsequently interacts with upstream vortical structures. For the sake of brevity, only the flow field for the intermediate $D/d_h = 2.3$ cylinder will be presented through time-sequenced LIF images and DPIV vorticity fields, as shown in Fig. 15. Again, both LIF and DPIV results are in excellent agreement with each other, hence they depict the flow developments well. As shown in Figs. 15(a)(i-ii) and 15(b)(i-ii), flow interactions occur in the region between $z/d_h = 0.6$ to 1.2 , where the ring-vortex encounters the braid vortices and rib structure. As a result, their interactions produce a vortical structure (i.e. I) that induces the wall-separated vortex to initiate and form a vortex-dipole at approximately $z/d_h = 1.8$ location. Note that this location is closer to the impingement point than that associated with corresponding flat-plate impingement, as can be

Fig. 15 Time-sequenced LIF images and DPIV vorticity fields for EJ2-cylinder impingement upon the $D/d_h = 2.3$ cylinder along the straight-edge.

seen in Figs. 15(a)(iii) and 15(b)(iii). Later, Figs. 15(a)(iv) and 15(b)(iv) show that this vortex-dipole subsequently interacts with an upstream vortex structure at approximately $z/d_h = 2.1$ location.

3.3 POD analysis

Some unique flow structures and behaviour arising from the present EJ1- and EJ2-configuration impingements upon convex cylinders have been revealed by LIF visualizations and DPIV vorticity fields. Now, results from POD analysis will be presented for a closer look into their flow energy distributions and POD modes. Velocity fields associated with POD modes 1 and 3 for EJ1-cylinder impingement along the convex surfaces for all diameter-ratios were reconstructed and presented in Fig. 16, where non-dimensionalized u-velocity regions are highlighted. Note that higher order POD modes are not presented here not only because for the sake of brevity, but they are also either relatively similar to the lower order POD modes or

Fig.16 Reconstructed velocity vector fields of EJ1-configured impingement upon (a) $D/d_h=4.6$, (b) $D/d_h=2.3$ and (c) $D/d_h=1.15$ along the cylinder convex surface for POD (i) mode1 and (ii) mode3. The maps are highlighted by u velocity component.

show significantly more incoherent flow structures. POD mode 2 results are not included here, since together with POD mode 3 they represent a typical POD mode pair due to their similarities in terms of flow structures exhibited by the velocity vector fields with a spatial shift in the streamwise direction relative to each other. Similar pairs of POD modes have also been discovered by Konstantinidis et al. (2007), Ben Chiekh et al. (2013), Shim et al. (2014), Zang and New (2015). This will apply whenever POD pairs appear in results for other test cases.

For the largest $D/d_h = 4.6$ cylinder, POD mode 1 indicates a flow recirculation area located within the jet shear layer just prior to impingement, with about 10.6% of the total flow energy.

This is likely to be associated with the strong interactions between adjacent jet ring-vortices, rib structure and braid vortices present at the same location as seen in the time-sequenced vorticity results earlier. POD mode 3 demonstrates a train of coherent large-scale structures along the jet shear layer prior to impingement, which are associated with the formation and convection of jet ring-vortices. Moreover, much smaller structures are discerned along the convex surface and they are associated with the newly-formed smaller-scale vortical structure resulted by impingement and interaction among adjacent ring-vortices, braid vortices and rib structures. For smaller diameter-ratios $D/d_h = 1.15$ and 2.3 , Figs. 16(b-c) show grossly similar POD results in that POD mode 1 is related to jet shear layer and POD mode 3 is related to jet ring-vortices both prior to impingement and along the convex surfaces.

Fig. 17 presents the first four POD modes for EJ1-cylinder impingement as well, but along the straight-edges for diameter-ratios $D/d_h = 1.15$ and 2.3 . In particular, POD modes 1 and 2 are related to the jet ring-vortices along the shear layer, while POD modes 3 and 4 are related to vortex engulfment behaviour between adjacent jet ring-vortices prior to impingement. Note that the largest $D/d_h = 4.6$ cylinder produces similar POD analysis results with comparable flow energy content for each POD mode, as compared to the intermediate $D/d_h = 2.3$ cylinder. This is within expectation since they possess similar flow modes which has been discussed earlier. Hence, POD analysis results for $D/d_h = 4.6$ cylinder are not included here. On the other hand, POD mode 5 can better illustrate the differences in the flow behaviour with three various diameter-ratios. In particular, for the smallest $D/d_h = 1.15$ cylinder, POD mode 5 demonstrates more coherent structures along the cylinder straight-edge, but at much closer locations to the impingement point as compared to the large vortex pair for $D/d_h = 2.3$ and 4.6 cylinders, as shown in Fig. 17(a)(iii). This corresponds well with that the location for Flow Mode 1 (i.e. upstream interactions) is much closer to the impingement point than that of Flow Mode 2

Fig. 17 Reconstructed velocity vector fields of EJ1-configured impingement upon (a) $D/d_h = 2.3$ and (b) $D/d_h = 1.15$ along the straight-edges for POD (i) mode 1, (ii) mode 3 and (iii) mode 5. The maps are highlighted by u -velocity component.

(i.e. continuous convections) which only occurs with larger diameter-ratios $D/d_h = 2.3$ and 4.6 .

When EJ2-configured impingement upon the convex surfaces, the first two POD modes show shear layer separating from the impingement surface for all diameter-ratios, which will not be discussed here. For the largest $D/d_h = 4.6$ cylinder as shown in Fig. 18(a), POD modes 3 and 4 are related to the jet ring-vortices along its shear layer, while POD mode 5 shows a sizable vortex-pair that indicates intense separations of the resulting vortex-dipoles from the convex surface. In contrast, a similar vortex-pair is demonstrated by the lower POD mode 3 which proves the separation process is a more energetic and dominant flow structure with the smaller $D/d_h = 1.15$ and 2.3 cylinders. On the contrary, large-scale coherent structures indicating shear layer vortices in turn occur in POD modes 4 and 5, and they are observed to persist till further downstream locations with decreased diameter-ratio. Moreover, it is interesting to note that two trains of coherent structures start to convect almost along the streamwise direction instead of only one train, at the location of almost 107° from the impingement axis. This may be

Fig.18 Reconstructed velocity vector fields of EJ2-configured impingement upon (a) $D/d_h = 4.6$, (b) $D/d_h = 2.3$ and (c) $D/d_h = 1.15$ along the cylinder convex surface for POD (i) mode1 and (ii) mode3. The maps are highlighted by u velocity component.

associated with the downstream jet ring-vortices being engulfed by the upstream ones, with them deviating away from the cylinder convex surface with a larger separation angle between its trajectory and impingement surface, as compared to the upstream one, as shown in Fig. 18(c)(ii).

For EJ2-configured impingements along the straight-edges, the POD analysis results are comparable between the three cylinders due to similarities in their overall vortex dynamics. Moreover, their first three POD modes are also quite similar to those associated with EJ1-configured impingement upon the $D/d_h = 4.6$ cylinder. The primary differences in the shear

layer vortices are revealed by lower POD modes 1 and 2, where smaller-scale coherent structures along the straight-edges are absent. This phenomenon indicates that the vortex-dipoles produced along the cylinder straight-edges are not the dominant flow structures as compared to jet ring-vortices along the shear layer prior to impingement. This is also within expectation that the vortical structure (i.e. I) core size is drastically reduced along the straight-edges after impingement and interaction process due to vortex-stretching effects, as compared to what was observed when the elliptic major-plane impinges the convex surface.

3.4 Momentum thickness analysis

Figure 19 shows the momentum thickness profiles of the jet mixing layers for both EJ1 and EJ2 configured impingements associated with the three test cylinders. For the sake of consistency, the momentum thickness profiles are presented up to $4D_h$ from the nozzle exit just prior to the jet impingements, so as to discern any influences arising from the different jet orientations and cylinder diameter-ratios. **It should be highlighted that the momentum thickness increases very gradually between the nozzle exit and $y/d_h = 1$ locations regardless of the exact flow scenario. As such, the results are only presented from $y/d_h = 1$ to 4 (where the jet flows impinge upon the test cylinders) so that changes in the momentum thickness can be better discerned.** Results for freely-exhausting elliptic jet from the jet exit up to $4d_h$ location have been compared to and correspond well with those determined in an earlier study (New and Tsovolos, 2011), where relatively similar elliptic jets had been investigated. As compared to the freely-exhausting elliptic jet, it can be discerned that momentum thicknesses grow much thicker as the elliptic jet approaches the cylinders, regardless of orientation or cylinder diameter-ratio. In particular, the momentum thickness along the major-plane of EJ1 configuration undergo rapid increments when smaller diameter-ratio cylinders ($D/d_h = 2.3$ and 1.15) are used. This could be associated with the cross-stream and upstream movements of the

Fig. 19 Momentum thickness profiles associated with (a) EJ1-configured and (b) EJ2-configured impingements upon (i) $D/d_h = 4.6$, (b) $D/d_h = 2.3$ and (c) $D/d_h = 1.15$ cylinders

braid vortices for $D/d_h = 1.15$ and 2.3 cylinders observed earlier. In contrast, it is interesting to note that there is a slightly “kink” in the major-plane momentum thickness profile for the largest $D/d_h = 4.6$ cylinder at locations between $0.5 - 1d_h$ away from the impingement surface, which could be a result of the jet ring-vortices undergoing interactions with adjacent braid vortices and rib structures described earlier. Additionally, for this particular cylinder, the minor-plane momentum thicknesses begin to exceed those along the major-plane, which is not observed in the other two test cylinders.

For EJ2-configured impingements, the momentum thickness profiles associated with $D/d_h = 2.3$ and 4.6 cylinder impingements are relatively similar to those observed for EJ1 configured impingement upon $D/d_h = 4.6$ cylinder. Other than rapid increases in the momentum thickness along both major- and minor-planes, they also depict “kinks” at approximately 1 to $0.5 - 1D_h$ upstream of the impingement surface. The probable cause of this observation will be similar to what was postulated above. In contrast, the smallest $D/d_h = 1.15$ cylinder leads to most gradual increments in the momentum thickness growth here, which could be attributed to the vortex engulfment behaviour between adjacent jet ring-vortices observed earlier.

3.5 Mean wall shear stress analysis

Mean skin friction coefficient distributions associated with both EJ1- and EJ2- configuration impingements upon the three test cylinders along both their convex surfaces and straight-edges are estimated based on similar procedures used by the authors previously and presented in Fig. 20. Results for flat-plate impingements are also included in each plot for direct comparisons. Starting with skin friction coefficient distributions along the convex surfaces as shown in Figs. 20(a) and 20(c), it can be observed that the maximum skin friction coefficient location is located further along the convex surface as the diameter-ratio decreases for both EJ1- and EJ2- configurations. For EJ1-configuration specifically, these locations are estimated to be $\theta = 74.9^\circ$, 41.1° and 26.6° for $D/d_h = 1.15$, 2.3 and 4.6 cylinders, respectively, which correspond well with the locations where the jet vortical structures impinge upon their convex surfaces. Moreover, the maximum skin friction coefficient level becomes progressively higher with reductions in the cylinder diameter-ratio. In this case, maximum skin friction coefficient levels are approximately $C_f = 0.0128$, 0.0147 and 0.0182 for $D/d_h = 4.6$, 2.3 and 1.15 cylinders correspondingly. Note that only the smallest cylinder leads to a

Fig.20 Comparisons of mean skin friction coefficients associated with EJ1- and EJ2-cylinder impingements along the cylinder (a, c) convex surfaces and (b, d) straight-edges for all three test cylinders, as estimated from DPIV velocity measurements.

higher maximum skin friction coefficient level than that of flat-plate impingements.

Additionally, not only are the locations and levels associated with the maximum skin friction coefficients important, the rate of skin friction coefficient reduction after the maximum point is important as well, as it shed light upon the efficacy of any applications based on the present configurations. Figure 20(a) shows that the skin friction coefficient reduction rate of the

smallest $D/d_h = 1.15$ cylinder is higher than larger $D/d_h = 2.3$ and 4.6 cylinders. This could be attributed to earlier observations that the braid vortices either interact with adjacent jet ring-vortices and rib structures or convect along the cylinder convex surfaces independently for $D/d_h = 2.3$ and 4.6 cylinders, which may enable skin friction coefficient levels to persist more and lead to slower skin friction coefficient reduction rates. As for EJ2-configuration, the maximum skin friction coefficient locations are approximately at $\theta = 51.5^\circ$, 33.4° and 20° for $D/d_h = 1.15$, 2.3 and 4.6 cylinders respectively. Unlike the case for EJ1-configuration however, these locations correspond well with locations where the upstream ring-vortex is engulfed by the downstream one along the convex surfaces.

It is also worthwhile to point out that the maximum skin friction coefficients for the three cylinders are lower than that associated with flat-plate configuration by about 5-10%. As will be shown later, the same trend can be observed along the straight-edges. Despite these small differences, it should be noted that the largest $D/d_h = 4.6$ attained higher maximum skin friction coefficients over the other two smaller cylinders. Furthermore, the skin friction coefficient for $D/d_h = 2.3$ exceeds that of $D/d_h = 1.15$ from $\theta = 64^\circ$ to 120° location. This observation may be attributed to the upstream ring-vortex being engulfed by the downstream one, as well as the subsequently formed vortex-dipole remaining attached to the convex surface, which would produce relatively higher skin friction levels. Comparing between Figs. 20(a) and 20(c), it appears that making use of EJ2-configuration could possibly lead to less issues associated with skin friction.

Moving on to the situation along the straight-edges, for EJ1-configuration shown in Fig. 20(b), higher maximum skin friction coefficients are attained as compared to flat-plate impingements, especially for $D/d_h = 1.15$ cylinder. The maximum skin friction coefficients levels are $C_f =$

0.0234, 0.0197 and 0.0187 for $D/d_h = 1.15, 2.3$ and 4.6 cylinders respectively. Moreover, the overall skin friction coefficient reduction rates after achieving maximum levels here are generally faster than that associated with flat-plate impingements. In contrast, the maximum skin friction coefficients produced by EJ2-configuration as shown in Fig. 20(d) remain at practically the same levels as compared to flat-plate impingements, except for the smallest $D/d_h = 1.15$ cylinder. Furthermore, their skin friction coefficient reduction rates after attaining maximum levels are more comparable to the flat-plate impingement case as well.

4. Conclusions

In the present study, vortex structures and flow behaviour of an $AR = 3$ elliptic jet impinging upon convex cylinders with different diameter-ratios have been experimentally studied via LIF and DPIV techniques and compared to flat-plate impingements, where emphasis is placed upon the effects of the elliptic jet alignment with respect to the cylindrical axis. Both LIF visualizations and DPIV vorticity fields show that comparable flow developments along both cylinder convex surfaces and straight-edges are produced by EJ1-configuration, which potentially lead to the least non-uniform flow distribution among other jet configurations. On the contrary, drastic non-uniform flow distributions are produced when the elliptic jet minor plane impinges upon the convex surfaces (i.e. EJ2-configuration), which also produce significantly larger vortex-dipole size and higher vorticity distributions along the convex surfaces than along the straight-edges.

The differences in the flow dynamics for EJ1- and EJ2-configurations due to variations in the diameter-ratio (i.e. $D/d_h = 1.15, 2.3$ and 4.6) are primarily caused by unique vortical structures and flow behaviour of an elliptic jet (i.e. braid vortices and rib structures along the elliptic major-plane, as well as vortex engulfment behaviour along the minor-plane). The most

intriguing flow behaviour include the occurrence of two flow modes (i.e. upstream interactions and continuous convection) caused by vortex engulfment behaviour when EJ1-configuration is employed, which results in the flow structures along the straight-edges being more energetic and attaching more to cylinders with larger diameter-ratios (i.e. $D/d_h = 2.3$ and 4.6). Moreover, along the convex surfaces, a systematic shift in the braid vortices behaviour from interacting between adjacent ring-vortices and rib structure to them undergoing cross-stream and upstream movement, which in turn influences the mean skin friction coefficient distributions.

Lastly, the maximum skin friction coefficient levels for EJ1-configuration are higher along the cylinder straight-edges than those along the convex surfaces, while EJ2-configuration demonstrates the opposite trend. Moreover, the maximum skin friction coefficients for EJ2-configuration remain at practically the same level as compared to flat-plate impingements, as opposed to EJ1-configuration which demonstrate dissimilar changes in the maximum skin friction coefficient where only $D/d_h = 1.15$ cylinder show an increase as compared to flat-plate impingements. Other unique changes in skin friction coefficient distributions can be attributed to the unique vortical behaviour demonstrated by EJ1- and EJ2-configuration impingements such as vortex engulfment behaviour, different braid vortices behaviour, among others. In short, the present study demonstrated that unique flow structures and behaviour arising from the present configurations affect the overall flow developments significantly.

Acknowledgement

The authors gratefully acknowledge the support for the present study by Nanyang Technological University.

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