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Effects of notch geometry and sharpness on turbulent jets issuing from indeterminate-origin notched nozzles

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ABSTRACT

An experimental investigation using hot-wire anemometry to identify the effects of notch configuration and relative sharpness on notched indeterminate-origin turbulent jets at $Re = 20{,}500$ was carried out. The notches are characterized by their V- and A-shaped cuts, as well as their relative sharpness due to the design aspect ratio ($AR = 2$ and 4) of the notch. Regardless of exact notch geometry, high aspect-ratio nozzles are shown to produce significant flow differences between measurements taken along peak and trough planes, in contrast to low aspect-ratio nozzles. Half-jet width results demonstrate that as the aspect-ratio increases, smooth peaks result in a constant increase within the measurement range while sharp peaks produce an initial decrease till some downstream location before increasing thereafter. In contrast, smooth and sharp trough produces significant nonlinear increases in the half-jet widths with the aspect-ratio increment. Cross-over points linked to axis-switching behaviour are observed for all nozzles except $AR = 4$ A-notched nozzle, when half-jet widths along peak and trough planes for each nozzle are compared. Increasing the aspect ratio also results in a 50% reduction in the distance away from the nozzle origin where the cross-over point occurs for V-notched nozzles. On the other hand, similar increase in the aspect ratio produces no cross-over point for A-notched nozzles. These results indicate that suitably configured notched nozzles are able to impart significant control over circular jet flow behaviour by inducing and manipulating axis-switching behaviour typically found in noncircular jets.

1. Introduction

Altering jet geometries remains one of the most effective passive jet-mixing and flow control techniques that worked remarkably well by influencing the underlying vortex dynamics. Different jet geometries have been investigated and benchmarked against conventional circular jets in earlier studies, and they were generally observed to achieve better jet-mixing characteristics, the extents of which depend on the exact azimuthal geometry of the jet exits or nozzles. For instance, the entrainment and self-induction behaviour of elliptic jets have been extensively surveyed and documented by Gutmark and Ho [1], Ho and Gutmark [2], Quinn [3], Hussain and Husain [4] and Husain and Hussain [5,6], with results showing the resultant axis-switching phenomenon to be responsible for much of the mixing and entrainment enhancements. Due to the noncircular vortex filaments, dissimilar circumferential self-inductions cause different filament regions to undergo very different vortical motions, which in turn lead to axis-switching behaviour. On the other hand, jet geometries such as squares and rectangles not only exhibit axis-switching behaviour, but they also have the unique ability to induce three-dimensional flow structures along the corners which affect the flow field developments significantly, as shown by Krothapalli et al. [7], Quinn and Militzer [8], Grinstein et al. [9] and Grinstein [10]. For more details on noncircular jet mixing and control, readers are advised to refer to an in-depth review paper by Gutmark and Grinstein [11].

Other than changing the shape of the jet exit geometry, the axial locations of the jet nozzle lip along its circumference can also be varied for jet-mixing and control purposes. Jets with axial variations along the nozzle lips are also known as indeterminate-origin (IO) jets as the jet origins cannot be determined easily using conventional definitions, i.e. distance from the nozzle base to the nozzle exit lip. Depending on the exact design, the axial undulations along the nozzle lips may either vary smoothly or discontinuously at certain locations. Due to the complex nature of the resultant flows, investigations and subsequent understandings are based on relatively simple nozzle designs. For instance, IO jets with inclined and stepped nozzle exits and the effects of varying the incline angle and step length on the behaviour of the jet shear layers have been previously investigated by Kibens and Wlezien [12] and Wlezien and Kibens [13]. It was observed that shear layer instabilities which developed earlier along the shorter axial length portions of the IO nozzles were able to perturb and excite other regions of the shear layer to become unstable. Such jets were

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Nomenclature

AR	aspect ratio of half-ellipse defining the notches
D	nozzle diameter
D_1	major-diameter of half-ellipse defining the notches
D_2	minor-diameter of half-ellipse defining the notches
H	nozzle mean height
U_e	mean jet exit velocity
U_{cl}	mean jet centerline velocity
u	mean jet velocity
u'	mean jet velocity fluctuation
y	cross-stream distance
$y_{0.5}$	half-jet width
z	streamwise distance
Re	Reynolds number ($Re = UD/\nu$)
St	Strouhal number ($St = fD/U$)
δ_ω	jet shear layer vorticity thickness
ν	kinematic viscosity of air

found to effect energy redistribution within their shear layers and possess significantly different jet flow characteristics, as compared to conventional non-IO circular nozzles.

Other forms of indeterminate-origin jet configurations were also studied, following the above early investigations. For instance, the effects of varying the number and the heights of peaks and troughs of "crown-shaped" IO jets have been studied by Longmire et al. [14] and experimental observations showed that coherent streamwise vortices aiding jet mixing were formed along the peaks and troughs of the cuts. Moreover, some IO jet nozzle configurations could lead to jet bifurcation under strong forcing as shown by Longmire and Duong [15] for stepped and sawtooth nozzles, which results in significant diversion of the jet path from its original streamwise direction. Webster and Longmire [16,17] studied inclined IO jets and vortex rings and results showed that the pairing of the ring vortices depends on the incline angle of the nozzle. Small incline angles will lead to successful pairings whereas large incline angles will cause the vortex cores to breakdown before any successful pairing could occur. Other more complex forms of IO jets have also been studied by Shu et al. [18] in their investigation on a four-point tapered crown nozzle, which can be treated as an extension of the conventional crown nozzle. Clear evidence of the jet shear layer being successfully manipulated to produce additional but yet coherent streamwise vortices over conventional crown nozzles shows that it is possible to improve passive jet-mixing enhancements through these relative simple but effective designs.

New et al. [19] attempted to reconcile earlier findings such that a plausible flow model could be constructed for low Reynolds number IO nozzle jets with V-shaped cuts designed using half-ellipses as the primary design rule. The primary aim was to have a robust and systematic design rule which confers noncircular jet axis-switching behaviour upon circular nozzle jets. Flow visualization results revealed that the general vortex dynamics may be modelled after initially bent vortex filaments (caused by the nozzle outlines) undergoing vortical motions resembling axis-switching behaviour to form streamwise vortices at the peaks and troughs. In a follow-up study by New and Tsai [20] using significantly higher Reynolds number but similarly configured V-notched nozzle jets, axis-switching behaviour was also observed and thus appeared to be robust across a significant range of flow regimes. However, these earlier studies made use of only one half-ellipse aspect ratio and as a result, did not vary the nozzle relative sharpness. To address that, studies were recently carried out by New and Tsovolos [21,22] to investigate the influence of nozzle relative sharpness on not only V-notched nozzles based on same design rules, but A-notched nozzles as well, at low Reynolds numbers. The former showed that A-notched nozzles also undergo axis switching and that increasing nozzle relative sharpness conferred substantial flow intensifications. On the other hand, the latter study revealed key flow mechanisms responsible for the apparent difference in the vortex-bending behaviour between V-notched nozzles of different relative sharpness. However, it should be noted that these investigations were restricted to relatively low Reynolds numbers and hence, there is a need to ascertain whether flow behaviour observed recently at low Reynolds numbers are sufficiently robust to extend to higher Reynolds number turbulent flow regimes.

To shed some light on the matter, the present study carried out an experimental hot-wire anemometry investigation on two V- and two A-notched nozzles of different relative sharpnesses at a substantially higher Reynolds number than New and Tsovolos [21,22]. The effects of changing nozzle relative sharpness will be assessed by velocity measurements taken in the streamwise and cross-stream directions, as well as other derived flow information. In Section 2, the complete jet apparatus and overall equipment setup used, as well as the design rules employed in designing the IO nozzles are described. Results are presented in Section 3 along with their analysis, interpretation and implications before some conclusions are summarized in Section 4.

2. Experimental setup and procedures

2.1. Jet apparatus

All velocity and turbulence measurements were carried out in the Fluids Dynamics Lab, Temasek Laboratories at the National University of Singapore using hot-wire anemometry in an air-conditioned room with the working temperature set at 25 ± 0.5 °C. The general experimental setup was similar to that used in [20] and hence will only be briefly described here. Before jet air supply from an air compressor entered a separate jet apparatus, it was passed through an air filter and dehumidifier to prevent contamination by oil and water vapour. Fig. 1 shows how air entering the apparatus will encounter a settling plenum, perforated sheets, honeycomb screens, fine steel grids and eventually a 36:1 contraction chamber such that it would be properly conditioned before exhausting out of the jet apparatus via the test nozzles.

Flow velocity of the jet was prescribed at $U_e = 30$ m/s and with the $D = 10$ mm diameter of the jet nozzles used, the corresponding Reynolds number was estimated to be $Re = 20{,}500$ and close to that used by Longmire et al. [14] where $Re = 19{,}000$ jets were used. Measurement origin was set to be located at the mean nozzle height, where z is the downstream distance from the nozzle mean height and y is the cross-stream distance from the nozzle exit center. Hot-wire measurements were taken at regular downstream intervals as well as along the cross-stream planes. For the latter, the nozzles were rotated 90° where necessary to change the plane to be measured.

2.2. Jet nozzle designs

Two sets of IO nozzles, each with two differently configured nozzles (V- or A-notched), were used for the present study. For a more consistent investigation, the mean heights (H) of all nozzles were kept constant at 2D (20 mm), similar to that used in [19,20] and taken as the jet origins. It should be noted that the mean height is defined as the average of the peak and trough heights, similar to the definitions used by Longmire et al. [14], New et al. [19], New and Tsai [20] and New and Tsovolos [21,22]. It represents a more intuitive and simple definition to locate a common nozzle origin during the nozzle design stage. Unlike earlier studies where the peak and trough configurations were determined solely by their