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Near field vorticity distributions from a sharp-edged rectangular jet

Alexandros P. Vouros [a], Thrassos Panidis [a], Andrew Pollard [b,*], Rainer R. Schwab [b]

[a] Mechanical Engineering and Aeronautics Department, University of Patras, 26504 Patras, Greece
[b] Department of Mechanical and Materials Engineering, Queen's University, Kingston, K7L-3N6 Ontario, Canada

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ABSTRACT

Experimental results on the near field development of a free rectangular jet with aspect ratio 10 are presented. The jet issues from a sharp-edged orifice attached to a rectangular settling chamber at $\mathrm{Re}_h \sim 23{,}000$, based on slot width, h. Measurements on cross plane grids were obtained with a two-component hot wire anemometry probe, which provided information on the three dimensional characteristics of the flow field. Two key features of this type of jet are mean axial velocity profiles presenting two off axis peaks, commonly mentioned as saddleback profiles, and a predominant dumbbell shape as described by, for example, a contour of the axial mean velocity. The saddleback shape is found to be significantly influenced by the vorticity distribution in the transverse plane of the jet, while the dumbbell is traced to two terms in the axial mean vorticity transport equation that diffuse fluid from the centre of the jet towards its periphery. At the farthest location where measurements were taken, 30 slot widths from the jet exit, the flow field resembles that of an axisymmetric jet.

1. Introduction

Rectangular jets have been studied extensively as a fundamental problem in turbulence and as a generic flow configuration in engineering applications. In the past, studies focused on the effect of a wide variety of initial-boundary conditions, which affect the development and the characteristics of the mean and turbulent properties of the jet.

Launder and Rodi (1983) provided a comprehensive review of wall jets including those that are rectangular; while this review encompassed what was known at the time, their proposition that the axial vorticity equation was fundamental to the anisotropic spread rates observed in these wall jets continues to intrigue the current authors. In this paper for the special issue dedicated to Launder and Rodi, we consider the rectangular jet in the absence of a wall, but the use of mean vorticity transport and the relative importance of some of the terms in that equation remains an approach that heretofore has not been considered.

Among the characteristic features of rectangular jets, the formation of 'saddleback' mean axial velocity profiles, presenting two off axis peaks and the 'axis-switching' phenomenon, where the major and minor axes of the jet cross section exchange locations downstream due to different contraction or spreading, seem to be directly related to the vorticity transport, although the mechanisms involved are not yet fully understood.

Since the earlier work of Bradbury (1965) and Sforza and Herbst (1970), who first characterized the three main regions of the development of the flow – the potential core, the characteristic and the axisymmetric decay regions – and discussed the development of saddlback profiles of the mean axial velocity in the near field of the jet (say $x/h < 30$), several investigators conducted experiments using a wide range of Reynolds numbers, jet aspect ratios (AR) and nozzle configurations (duPlessis et al., 1974; Sfeir, 1976; Krothapalli et al., 1981; Marsters, 1981; Quinn, 1992). Based on previous experimental work that demonstrated that axial mean velocity profiles featured a saddleback shape for aspect ratios higher than five, Tsuchiya et al. (1986) presented profiles of the velocity and temperature fields, and discussed the source of their formation in relation to the mixing process in the two directions perpendicular to the streamwise axis. They discussed extensively the spreading characteristics of three jets issuing from different nozzles (smoothed, orifice and long pipe) and concluded that except for the different geometry, the jet Reynolds number and also the low aspect ratios can produce remarkable changes on jet's half-width and the downstream evolution of the turbulence intensity of the streamwise velocity. Quinn et al. (1985) and Quinn and Militzer (1988) presenting velocity and pressure measurements along with numerical simulations of the mean and turbulent statistics, also confirmed that saddle-back profiles are formed for aspect ratio greater than a value of about five. Pollard and Iwaniw (1985)

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* Corresponding author.
E-mail addresses: panidis@mech.upatras.gr (T. Panidis), pollard@me.queensu.ca (A. Pollard).

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and Schwab (1986) used rectangular jets with and without corner rounding and found saddleback profiles in both cases. Schwab (1986) was the first to obtain, but did not fully interpret, cross-plane data so as to assess the three-dimensional features of the flow development. Additional studies were presented by Quinn (1991, 1992) and Grandmaison et al. (1991) with the latter reporting on the characteristics of the mixing of passive scalars in rectangular jets with high and small aspect ratio, respectively, while Quinn (1995) and Lozanova and Stankov (1998) discussed the mean and turbulence properties, the entrainment and the mixing process of jets issuing from contoured and smooth contraction rectangular jets with several aspect ratios. It is important to note that Quinn (1992), in his study of effects of jet aspect ratio, the orifices were attached to a settling chamber that was square in cross section; thus, the flow entering the orifice from the chamber does so with streamline curvature that is different along the major and minor axes of the exit slot; thus, for small aspect ratios no saddle backed velocity profiles were noted, which implies minimum sensitivity to that difference in curvature, whereas these saddle shapes in the axial mean velocity increased significantly with increasing aspect ratio. The sensitivity to jet aspect ratio was amply displayed in the triple velocity correlations, Quinn (1992). During the last decade, Deo et al. (2007a) in the frame of a systematic investigation on jets (Mi et al., 2005; Deo et al., 2007b, 2008) showed that saddle-backed profiles maybe eliminated by increasing the radius of the smoothed part of the orifice at the exit.

The complex near-field flow region of rectangular jets also gives rise to axis-switching, which has been investigated through the use of vortex structure and dynamics. Zaman (1996) provides a thorough review of this particular aspect. He considered rectangular jets with AR = 3 including the effects of tabs. Very close to the nozzle ($x/D = 1$), Zaman identified regions of positive and negative axial vorticity, which when viewed looking downstream from the orifice indicated counter clockwise rotation in the right upper and left lower quadrant with corresponding clockwise rotation in the left upper and right lower quadrant; for future reference, here, similar data will be presented but viewed looking into the flow towards the orifice. Interestingly, and importantly, the contours of the axial mean velocity did not feature any significant non-uniformity, even with increased distance downstream of the nozzle exit.

Computationally, Wilson and Demuren (1998) used Large Eddy Simulation (LES), with a Smagorinsky sub-grid model. At low Re (=750), where LES was not invoked, axis switching "is based on self-induction of the vorticity field", whereas for Re = 75,000 they argue it is the anisotropy in the Reynolds stresses that dominates since at these higher Re, the broad spectrum of instabilities in the shear layers precludes self induction. Grinstein (1995) also used LES to investigate vortex ring evolution from low-aspect ratio rectangular jets. To the authors' knowledge, these calculations were the first to identify and rather convincingly explain the vortex formation and their spatial and temporal evolution. Referring specifically to his 4:1 jet the initial vortex from the nozzle was found to deform by self-induction, and in so doing, appears to create what in this current contribution will be referred to as "puffs" (see his image 4 of 9 in Fig. 4). Eventually the initial ring performed a re-connection downstream to produce ring-like vortices on either side of the jet in the spanwise direction. These ring-like vortices merged together with increased distance from the jet exit. Following this, Grinstein (2001) used LES with a forced inlet condition (a pulsation to induce vortex roll up, as done by McIlwain and Pollard, 2002). Grinstein considered rectangular jets with aspect ratios up to 4; however, in all cases presented, a key feature was the interconnecting braids (Grinstein used the term "rib") of what seems to be axial aligned vorticity that emanate from the corners of the jet. In fact, from his Fig. 14, these appear in pairs, one each side of the corners. It is conjectured here that some of the features in the current experimental data have their manifest in the vortex features identified by Grinstein (1995, 2001).

As an aside, McIlwain and Pollard (2002) used large eddy simulation and identified that braids, which connect zero'th mode primary vortices, were responsible for increased entrainment due to their number density and surface area exposed to the free stream confirming the experimental finding of Liepmann (1991), Liepmann and Gharib (1992) and Citriniti and George (2000).

Tipnis (2009) and Tipnis et al. (2013) considered the effects of upstream conditioning of the flow on the formation of streamwise vorticity. They used Laser Doppler Velocimetry (LDV) and Reynolds-averaged numerical modelling in order to capture axial vorticity that appears in favourable accord with data of Zaman (1996) even though earlier work argued (Wilson and Demuren, 1998) that isotropic models are inappropriate. The upstream contractions all smoothly lead into the rectangular nozzles, as opposed to the use of an orifice plate (see Quinn et al., 1985).

More recently, Yu and Girimaji (2005, 2006, 2008) and Chen and Yu (2014) considered rectangular jets through the application of the lattice Boltzmann method as an alternate vehicle for LES to simulate the flow from low aspect ratio rectangular jets. They noted the importance of the jet corner axial vorticity and the role it plays to deform the jet (axis switching); they also featured "puffs" and a general dumbbell cross-sectional shape (see Fig. 21 of Yu and Girimaji, 2005); however, as will be argued here, their explanation for the appearance of the saddle-backed velocity profiles is not convincing. Interestingly, Uchiyama et al. (2013) performed a DNS for a 15:1 aspect ratio jet utilizing a top-hat mean velocity inlet profile and found no evidence of either a *vena-contracta*, axis switching or saddleback velocity profiles.

The present work uses the data from Schwab (1986) who performed measurements to obtain mean and Reynolds stresses on the central axis of jets and on a variety of cross-plane layers with respect to the streamwise axis, up to $x/h = 30$, which is at the onset of axis switching. Those data are further analysed here by carefully interpolating these data to produce maps of streamwise vorticity and the differences in the symmetric and skew-symmetric rate of strain tensor (*i.e.* Q) as well as analyzing the relative importance of terms in the axial mean vorticity equation to monitor the initial formation and downstream evolution of saddle-backed velocity profiles.

The paper is laid out as follows. In the next section, the experimental conditions and methodologies are given as well as an overview of the interpolation schema used to interpolate the point-by-point cross-stream and axial velocity components. The next section presents some flow visualization, mean and turbulence velocity data. Attention is then turned to the axial mean vorticity equation and what can be inferred from a term-by-term analysis of the hot wire data. Finally, conclusions are drawn and recommendations for future work offered.

2. Experiment

The jet was produced by a sharp-edged rectangular orifice of dimensions $70 \times 7\ \text{mm}^2$ (equivalent hydraulic diameter $D_h = 12.73$ mm, Fig. 1) mounted on the downstream end of a 1.05 m long, square cross sectioned settling chamber 0.350 m to the side. A small blower was used to supply air through the settling chamber, while flow straightening devices, including a baffle, filter material, honeycomb and 4 screens, were used to reduce the turbulence levels and produce a smooth flow before discharge. The exit Reynolds number based on the slot height ($h = 7$ mm) was approximately $\mathrm{Re_h} = 23{,}000$ or approximately $\mathrm{Re_{Dh}} = 42{,}000$ based upon the hydraulic diameter, D_h. This $\mathrm{Re_{Dh}}$ is beyond the mixing