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The role of vorticity in the near field development of sharp-edged, rectangular, wall jets

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ABSTRACT

Experimental results on the near field development of a turbulent rectangular wall jet with aspect ratio 10 that issues from a sharp-edged orifice at $Re_h \sim 23{,}000$ are presented and discussed, in comparison with results obtained in a free jet with identical initial conditions. Hot wire X-probe measurements on cross plane grids provide information on the 3D characteristics of the flow field. This work, besides presenting the main features of the jet, focuses on the effect of vorticity on the development of specific flow field characteristics. Mean vorticity components were estimated by interpolation and derivation from the mean and turbulent velocity measurements and the symmetries of the flow field were imposed by suitable averaging. Several terms of the axial vorticity equation are presented and discussed to uncover some complex flow physics, related e.g. to axis switching and the formation of a dumbbell shape of the jet outline, in the early stages of development.

1. Introduction

Three-dimensional wall jets are often used in industrial applications. They feature anisotropic spread rates that in certain applications are useful for enhanced mixing. However, the flow physics underlying the anisotropic growth rates continue to be probed and discussed. Many investigations that feature turbulent flow often assume that when a flow originates from a source then the resulting development of the flow is independent of its origin; it is now widely accepted that this is not true (see Section 4.3 of Ball et al., 2012). In the case of a wall jet, two effects must be accounted for: the initial conditions and the proximity of the wall to the jet orifice. In this paper, the initial conditions are identical to those described by Schwab (1986) and Vouros et al. (2015) for a 10:1 aspect ratio rectangular jet and the wall is very slightly removed vertically from the nozzle exit at approximately 0.8 h, where h is the jet orifice lateral height.

Before focusing on the wall jet literature, it is useful to briefly orient the reader to features (and methods employed) unique to the free rectangular jet. In our previous work (Vouros et al., 2015), we employed the Kriging algorithm available in Tecplot^{TM}, and the available measurements of the three velocity components, obtained with X-probe hot wire anemometry, on cross plane grids in a free jet issuing from a 10:1 aspect ratio, sharp-edged, rectangular orifice, at $Re_h \sim 23{,}000$ (Schwab 1986; Pollard and Schwab, 1988). Features unique to the free jet flow from sharp-edged rectangular orifices with high aspect ratios, are the development of a *vena-contracta* in the plane of the major axis of the jet (the spanwise direction) and the formation of saddle-backed velocity profiles in the characteristic decay region (typically, $5 < x/h < 30$, where x is the streamwise coordinate direction and h is the orifice height). The off-centre velocity peaks have been found to vary in magnitude depending on the jet aspect ratio and inlet conditions. Vouros et al. (2015) noted that key features in the near field of this type of jet are:

(i) a contraction of the jet dimensions in the spanwise direction, along the larger axis of the exit slot, leading to axis switching downstream,
(ii) the mean axial velocity profiles present two off axis peaks, commonly referred to as saddleback profiles, and
(iii) a predominant dumbbell shape as described by, for example, a cross-stream contour of the axial mean velocity.

They provided maps of streamwise vorticity and the differences in the symmetric and skew-symmetric rate of strain tensor (i.e. Q) and further analysed 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 saddleback shape was found to be significantly influenced by the vorticity distribution in the cross-stream plane of the jet, while the

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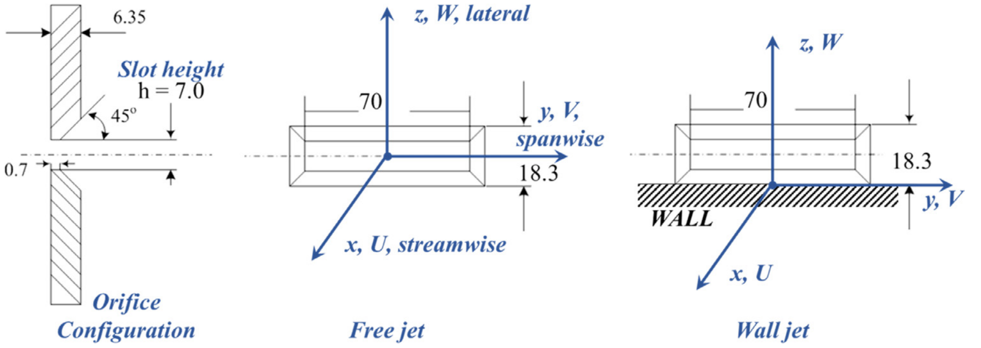

Fig. 1. Rectangular orifice configuration and coordinate systems for free and wall jets (dimensions in mm).

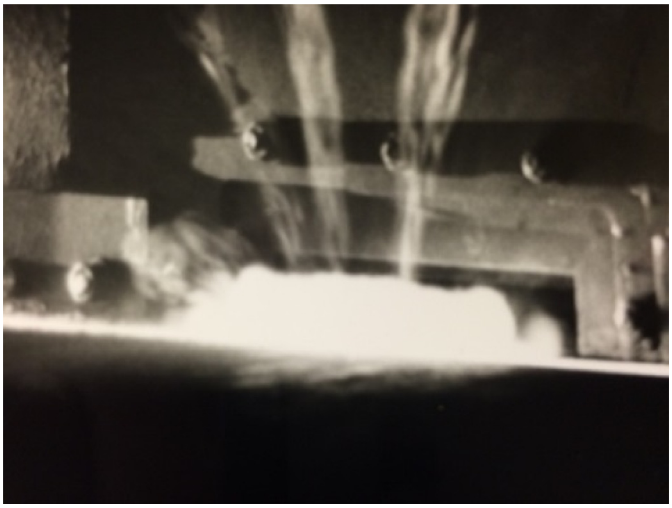

Fig. 2. Visualisation of wall jet flow at x/h = 2. Note smoke tuft on wall, right side of nozzle; and, undulation along top surface of jet. Vertical streaks of smoke indicate entrainment. From Schwab (1986).

dumbbell was traced to two terms in the axial mean vorticity transport equation that diffuse fluid from the centre of the jet towards its periphery. Several previous investigations have identified similar features as described in this work for free and wall jets. Despite these observations, there is still no consensus on the formation mechanisms of the jet as remarked e.g. by Yu and Girimaji (2005), for the saddle back profiles. Please note that in this paper, as with Vouros et al. (2015), the spanwise and lateral directions are consistent with and as first introduced by Sforza and Herbst (1970). Reference to other more recent publications often refer to the y direction, here, as the lateral direction.

In the case of wall jets, there have been many studies performed but most, if not all, have focussed on simpler geometries. For example, Sun (2002), who gives a comprehensive review of the wall jet literature up to that period, focussed on a plane two-dimensional wall jet prior to investigating a jet that issued from a long round pipe that was flush to a flat, horizontal wall. More recently, Namgyal and Hall (2016) followed on from Sun (2002) using a wall jet that originates from a circular contoured nozzle exit.

The anisotropic spread rate in three-dimensional wall jets feature spreading that is quicker in the spanwise (parallel to the wall) direction. The general shape of the nozzle used generally seems to not alter this feature, whether it be round, square or rectangular but Hall and Ewing (2007a) noted the dependence on initial conditions on coherent structures contained therein. Launder and Rodi (1983) proposed that the anisotropic spreading was due to vortex bending that drove fluid away from the jet centreline and also suggested that gradients in the Reynolds stress anisotropy in the cross-stream plane of the jet may also play a role. Matsuda et al. (1990) measured the vorticity in a wall normal longitudinal plane of a wall jet that issued from a round nozzle, and argued that the mechanism for the anisotropic spread rates were different to those proposed by Launder and Rodi (1983) since Launder and Rodi did not specifically consider large scale structures. Subsequently, Ewing and Pollard (1997) and Ewing et al. (1997) considered a flow similar to Matsuda et al. and found that the ring-like vortex structure deforms to generate large-scale structures, which it was hypothesised to be the “cause” for the anisotropy. Later, Sun (2002), Sun and Ewing (2002), and Hall and Ewing (2007a, b) further experimentally investigated these jets that issued from round and rectangular channels respectively and tended to reinforce the interpretation of Matsuda et al. More recently, Angelin-Chaab and Tachie (2011a, b) characterised round wall jets and applied the proper orthogonal decomposition (their 2011b paper) to “indicate that low-order modes contribute more to the turbulence statistics in the self-similar region than in the developing region.”

Craft and Launder (2001) used computational modelling of a round wall jet and suggested that the larger spanwise spreading of the wall jet is due to the creation of streamwise vorticity that is “entirely due to induced axial vorticity rather than to asymmetric diffusion and the driving vorticity source is created by the anisotropy of the Reynolds stresses in the plane perpendicular to the jet axis rather than to the bending of mean vortex lines”. However, as will be demonstrated our data do not support this view, because in the very near field, which is the region under consideration, the overwhelming effects of initial conditions dominate the flow thereby further reinforcing the need to view the wall jet first as a free jet. Hall and Ewing (2007a) remarked that the contours of the full flow field indicate that the turbulence mechanism that causes the spanwise growth of the three-dimensional wall jets is located in the spanwise outer shear layers and smaller near -wall structures. However, they provided no direct evidence of what may be physically occurring in those shear layers, such as the vorticity distributions or what components of the vorticity maybe responsible. Namgyal and Hall (2016) were the first to apply stereoscopic PIV to obtain the cross-stream distributions of all Reynolds stress components of a wall jet that issued from a contoured round nozzle. Their results “suggest that the anisotropy in the Reynolds normal stresses (term D) caused by the presence of the wall reinforces any vortex-line bending mechanism and contributes to the large lateral growth of the wall jet.” Here term D refers to the anisotropy in the gradients of the Reynolds normal stresses across the jet, see below. Further to this, Namgyal (2012) noted “The contours of instantaneous streamwise vorticity, shows a persistent pair of near-wall regions of counter-rotating vorticity similar to the mean streamwise vorticity which do not seem to depend on the outer vortex structures. This suggests that the streamwise vortex struc-

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