The 3D Velocity Field of an Impacting Turbulent Jet

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Abstract. The flow structure of a normally impacting jet is of interest for both its practical importance and because it represents an important test case for the development and validation of turbulent flow models. Experimental data, obtained using Stereo Digital Particle Image Velocimetry (S-DPIV), is presented for a submerged impacting water jet, operating in the turbulent regime (Re = 23400). Profiles of time-averaged velocity, fluctuating velocity and shear stress are presented for the impaction region out to a radial distance of 2.5 jet diameters. The DPIV results showed good agreement with the probe data found in the literature. The application of the DPIV technique overcame the directional ambiguity problems associated with the probe techniques and errors associated with their operation in regions of high turbulence intensity. The potential spatial resolution limitations of the DPIV technique are discussed.

1. Introduction

In fluid mechanics it is often the interaction between the fluid and a solid surface that provides the essential end product of the flow process. The impacting jet is a highly relevant flow in engineering terms, with many direct applications including heating, cooling and drying systems, vertical take-off and landing aircraft and ventilation during mining and tunnelling operations. A specific application is automotive engine cooling systems where the enhanced heat transfer rates of impacting jets can provide improved control of heat management in the engine.

A particular interest in the current study is the development of predictive models for the evaluation of the consequences of accidental releases of flammable gas. The dispersion field produced by an impeded jet is an important element of a hazard analysis performed as part of risk assessments of process plant and flammable gas transportation systems. In terms of the fundamental fluid mechanics of jets impinging normally on to a solid surface, the flow field formed in the region of the stagnation zone is demanding both in terms of experimental measurement and theoretical modelling.

The normally impinging jet has been the subject of much interest both for its practical importance and because it represents an important test case for the development and validation of mathematical models of turbulent flow. Work in the literature presents detailed experimental data for the velocity fields encountered in such flows [1,2], as well as the development of second-moment closure models [3,4] to predict the flow structure. In order to more accurately account for the influence of pressure reflections from the solid surface in damping velocity fluctuations normal to the wall, non-linear eddy viscosity turbulence closure approaches have also been presented5.
Studies of the concentration and velocity fields in the flow formed by a jet impinging normally on to a flat surface have also been reported by Fairweather and Hargrave [6,7,8]. They demonstrated the role of the entrainment field generated by the unimpeded jet in setting up a large scale recirculation region. In a study of the dispersion of a turbulent methane jet, Dianat et al.[9] presented predictions obtained using a second-moment turbulence closure, modified to include wall reflection effects. They demonstrated reasonable agreement with experimental data, however, in the outer regions of the radial wall jet the predictions from their approach were found to underestimate both mean and fluctuating concentrations. These discrepancies were attributed to differences between experimental and computational boundary conditions and, in particular, the fact that the downward firing jet studied experimentally may have given rise to a large recirculation zone. The existence of such a recirculation zone has important implications for ventilation, tunnelling and safety applications, since the re-entrainment of jet material could result in the build-up of unwanted flammable material or dust.

The majority of the earlier studies of impinging jets gathered data by means of probe techniques, for example, using either pitot-static tubes [10,11] or more recently hot-wire anemometry, [1,12]. The intrusive nature of these devices does, however, mean that they are prone to error. In addition, both probe techniques and laser Doppler anemometry (LDA) [9] are point measurement devices and necessarily restricted in terms of the extent of the data sets that can be gathered. Cooper et al. [1] also noted that the hot-wire technique may suffer from problems in separating the contributions from the velocity components in certain regions of the flow field. It is also well known that hot wires can generate erroneous data in regions of high turbulence [13,14], generally under-predicting the turbulence level.

In the light of the current extent of the knowledge of impacting jet structure, the present work was undertaken to apply the non-invasive field measurement technique of Digital Particle Image Velocimetry (DPIV) to provide detailed experimental data to improve understanding of what is a practically important flow. The aims of the present study were to resolve some of the uncertainties concerning the operation of the probe techniques and to provide high quality data to aid the formulation and validation of mathematical models of turbulent flows.

2. Experimental

The water jet studied experimentally issued from a circular cross-sectioned pipe with an internal diameter, \(d\), of 13.3 mm. The pipe was 80 \(d\) in length, and water was supplied by a pumped recirculation system, with flow rates metered using a turbine flow rate sensor. The average exit velocity from the pipe, \(V_b = 1.77 \text{ m.s}^{-1}\), gave rise to a fully developed turbulent flow with \(Re = 23400\). A schematic of the experimental arrangement is presented in Fig. 1 and an enlarged view of the impaction zone, with the co-ordinate system, is presented in Fig. 2. The fully submerged water jet was directed vertically down to impinge on the bottom surface of a 450 mm cubic water tank and the pipe exit was located 26.6 mm from the surface (\(h/d = 2\)). The pipe and tank were mounted on a hydraulic table with a horizontal traverse to allow two-dimensional positioning relative to the measurement location.

Three-dimensional velocity field measurements were made using a commercial Stereo Digital Particle Image Velocimetry (S-DPIV) provided by TSI inc. This technique provides rapid access to three-dimensional velocity fields by imaging the displacement of seeding particles in a flow field using a high-resolution digital cameras. For this study, the S-DPIV system was configured for cross-correlation analysis. The seeding particles added to the flow to act as tracers were 8-12 \(\mu m\) glass spheres with a relative density of 1.05 – 1.15. The flow system was run for 10 minutes before the start of each experiment to ensure a homogeneous seeding density, thereby minimising the velocity bias associated with variable particle number density within a measurement control volume.

The illumination source for the measurements was a pair of Nd:YAG lasers configured to generate 100 \(mJ\) pulses with a pulse width of 10 ns at a rate of 10 Hz. The beams from the two lasers were combined and focussed to the point of interest in the flow using a 1.5 \(m\) focal length spherical lens and formed into a sheet using a 250 \(mm\) focal length cylindrical lens. In the measurement region the sheet was uniform over an area of 25 \(mm\) square, and was approximately 1 \(mm\) thick. Imaging of the particles was accomplished using a pair of PIVCAM 10-30 digital cameras that provided images with \(1018 \times 1008\) pixels and 8 bits depth. The cameras were configured to view the illuminated region
at an angle of 30 degrees from the plane normal to the laser sheet. At each measurement location, 2000 S-DPIV image pairs were recorded at a rate of 10 Hz. For the current study, the separation between the laser pulses was varied from 50 μs to 2 ms, depending on the local flow velocity, in order to control the particle displacement between the two images.

The particle image size on the CCD was controlled to provide 2.4 pixel particle images to avoid errors from insufficient particle resolution and cross-correlation analysis was achieved using the processing algorithm Normalisation by Signal Strength (NSS) [15], since this technique provides the most accurate displacement assessment. The size of the imaged area was varied, depending on the region of the flow being investigated, but with an interrogation region size of 32 x 32 pixels and an imaged area of 6.6 mm x 6.5 mm, the vector resolution was 0.2 x 0.2 mm. Instantaneous velocity images were captured over a measurement grid extending from the jet centreline to a radial location of 2.5 diameters and a vertical distance of 2 diameters from the impingement surface. At each measurement location 2000 image pairs were recorded to allow the calculation of a statistically significant time-averaged and fluctuating velocity field, as well as local shear stresses.

3. Results and Discussion
The jet exit velocity profile is presented in Fig. 3. The flow shows a typical turbulent pipe flow profile with a peak centreline velocity of 2.12 m.s⁻¹ and a centreline turbulence intensity of 4%. The exit profile is consistent with the power-law equation expected for a fully developed turbulent pipe flow and is accurately described by \( u(r) = U(y/R)^{1/n} \), where \( u(r) \) is the time-averaged velocity, \( U \) is the time-averaged velocity at the centreline and \( n = -1.7 + 1.8 \log(Re_U) \) with \( Re_U \) the Reynolds number based on pipe diameter and \( U \). A visualisation of the time-averaged vector field in the vicinity of stagnation region is presented in Fig. 4. This figure was assembled from a total of 10 000 PIV images. The time-averaged radial velocity profiles at the stagnation line and through the wall jet at five distances from the stagnation point, \( r \), of 0.5, 1.0, 1.5, 2.0 and 2.5 \( d \) are given in Fig. 5. In this figure, \( U \) represents the time-averaged radial velocity, \( V_b \) the bulk time-averaged vertical velocity from the pipe and \( y \) the distance from the solid surface, with \( d \) being the jet pipe diameter. The development of the wall jet region is clearly illustrated in this figure, with the flow accelerating to a radial distance of \( r = 1.0 \, d \).

The time-averaged radial velocities within the wall jet peak at small distances from the surface, with maximum values \( (U_{\infty}) \) steadily decaying as the boundary layer mixes with ambient fluid. The location of the peak values also increases in distance from the surface as the boundary layer grows in thickness and the influence of the solid wall increases. In addition, the influence of the entrainment field of the unimpeded jet is clearly seen at the outer limits of the wall jet region where time-averaged radial velocities become negative. These velocities are very small compared with those encountered within the wall jet region itself and show peak values at approximately \( r = 1.0 \, d \), close to the free jet shear layer.

The time-averaged vertical velocity \( \langle \bar{V} \rangle \) is presented in Fig. 6. Along the stagnation line the data shows the expected deceleration of the flow as the surface is approached. At a position of \( r = 1.0 \, d \) the flow shows a negative vertical component close to the solid surface, showing that the near surface flow is beginning to expand upwards. In the outer shear layer at this location the residual effect of the expanding free jet flow is visible in the relatively high downward flow. With increasing radial distance, this vertical velocity component decreases and at \( r = 1.5 \, d \) the peak vertical component is the radial wall entrainment velocity in the outer layer. It is also clear that as the radial distance increases from \( r = 1.0 \, d \) to \( r = 2.5 \, d \), the vertically upward velocity slowly decreases as the depth of the expanding region grows. This observation is consistent with the expanding radial wall jet.

The large number of individual velocity vectors recorded at each measurement location not only allowed time-averaged radial \( \langle \bar{U} \rangle \) and vertical \( \langle \bar{V} \rangle \) velocities to be determined, but also permitted the derivation of root mean square (rms) fluctuating horizontal \( (u') \) and vertical \( (v') \) velocities, and the shear stress \( \langle \bar{uv} \rangle \).

Data for the rms of the U-component velocities is presented in figure 8. Along the stagnation line the turbulent velocities increase slowly from a value of \( u'/V_b = 0.028 \) at the exit to \( u'/V_b = 0.035 \) at a distance of \( y/d = 0.2 \, d \) away from the surface. Moving closer to the surface a significant increase in \( u' \) is observed as a result of the instability of the stagnation zone. At a radial distance of \( r = 0.5 \, d \) the
influence of the free jet shear layer on the turbulent velocities is apparent. With increasing radial
distance the formation of the wall jet is observed and a double-peaked profile develops in the $u'$ data.
This is a result of the two shear layers generated in the radial wall jet. The outer shear layer is formed
as the velocity decays from the peak close to the surface into the stagnant ambient fluid and the inner
shear layer forms due to viscous interactions with the solid surface. Turbulent fluctuations in the upper
shear layer and the outer edge surface boundary layer cause an increase in the $u'$ velocities. It is
interesting to note that the outer layer peak in the $u'$ coincides with the half-width of the time-averaged
velocity – see figure 6.

Data for rms. fluctuating vertical velocities (Fig. 8) are in qualitative agreement with the findings
of Cooper et al.\textsuperscript{1} Through the development region of the radial wall jet the peak in the $v'$ velocities
occurs at the same position as the $u'$ velocities, namely the jet half width. However, the $v'$ shows no
secondary peak on the inner shear layer. In a previous study\textsuperscript{1}, a peak in the $v'$ velocities was observed
in the region close to the solid surface. This peak was attributed to the single hot-wire becoming
sensitive to fluctuations parallel to the wall as the time-averaged velocity falls to zero. This effect is
not a factor with the current DPIV technique and the $v'$ velocities fall in to the surface as the vertical
fluctuations are damped by the solid surface. Beyond the limit of the wall jet, profiles of $u'$ and $v'$
asymptote to small, but non-zero, values. Shear stress data (Fig. 9) is similarly in accord with earlier
results (Poreh et al. \textsuperscript{12}), with values close to the surface being slightly negative, but then becoming
positive as the distance through the wall jet increases.

Comparison of the present data with earlier results, obtained using hot wire (Cooper et al. \textsuperscript{1}), is
shown in Fig. 10 and 11. These figures give profiles of normalised time-averaged velocity and
comparisons of time-averaged and fluctuating u-component velocities. The results having been non-
dimensionalised by the bulk flow velocity, $V_b$. Overall, the agreement with the data of Cooper et al. \textsuperscript{1}
is good. In Fig. 10, over a range of radial distances, the profiles and absolute magnitudes of time-
averaged velocity are reproduced in the current data. However, it is clear that the current data is not as
highly resolved as that achieved by these workers. This is mainly due to the physical scale of the
current experiment and the resolution limitation imposed by the current DPIV optical configuration
and analysis method. This limitation is more clearly seen in Fig. 11, which shows profiles of time-
averaged and fluctuating u-component velocity. Again the overall trends are in reasonable agreement,
but the lack of resolution means that the detail of the increase in turbulent velocities in the inner shear
layer is not resolved in the current data.

The time-averaged w-component velocity for the radial wall jet is effectively zero and for the
current data, within experimental error, this was found to be true. However, an interesting aspect of the
radial wall jet can be seen in the turbulence intensity measurements presented in Fig. 12. In this figure,
data for the U, V and W component turbulence intensities are compared with hot-wire data presented
by Poreh et al. \textsuperscript{12}. The agreement is reasonable, but the current data understates the turbulence
intensity compared with the hot-wire data at all locations. It can be seen that both the u-component and
the w-component (ie. the components parallel to the surface) show an increase near the surface,
whereas the v-component profile reduces significantly as the surface is approached. This is a result of
the ‘dampening’ of the vertical fluctuations due to the presence of the solid surface.

The data presented here is a preliminary study of the application of a whole field 3D measurement
technique for the acquisition of statistically significant data for time-averaged and fluctuating
velocities. However, it is clear that a significant increase in spatial resolution is required before the true
nature of the near surface flow field can be characterised. Improved resolution is possible for DPIV,
but at the sacrifice of interrogation region area. Current developments of the DPIV technique are
extending the resolution by extraction of sub-interrogation region information down to the level of
individual particle displacements. The advantage of the application of the DPIV technique is the ability
to extract whole field information, ie. velocity gradients, turbulent eddy length scales and vorticity.

4. Conclusions
An experimental study of a turbulent air jet that impinges orthogonally on to a flat surface has been
described. This study was undertaken to provide detailed experimental data for use in the formulation
and validation of mathematical models of turbulent flows, and to improve understanding of what is a
practically important flow configuration.
The major conclusions of this work are:

1. Useful data for time-averaged and fluctuating velocities, and shear stresses, can be obtained using the Digital Particle Image Velocimetry (DPIV) technique, provided that a sufficient number of instantaneous velocity vector images are employed to ensure that statistically meaningful time-averaged data are derived.

2. The present DPIV data are in good agreement with earlier results obtained in impinging jet. Some differences do occur, however, between the current data gathered using DPIV and earlier hot wire anemometer measurements, calling into question the application probe measurement techniques.

3. It has been demonstrated that, in comparison with hot-wire anemometry, the DPIV technique can be limited in terms of spatial resolution. However, the technique of DPIV does not suffer from directional ambiguity and the errors associated with the intrusive nature of probe techniques.

4. References

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Jet Diameter, \( d = 13.3 \text{mm} \)
Bulk flow velocity, \( V_b = 1.77 \text{ m/s} \)

**Figure 1.** Schematic of the submerged jet and associated flow system

**Figure 2.** A schematic of the impacting jet. \( \text{Re} = 23400 \)
Figure 3. The jet exit velocity profile.
Time-averaged and turbulent V-component velocities

Figure 4. Two-dimensional vector field of the fully-submerged impacting water jet, Re = 23400
Figure 5. Vertical profiles of time-averaged U-component velocity at six radial locations

Figure 6. Vertical profiles of time-averaged V-component velocity at six radial locations
Figure 7. Vertical profiles of rms U-component velocity at six radial locations

Figure 8. Vertical profiles of rms V-component velocity at six radial locations
Figure 9. Vertical profiles of time-averaged, normalised shear-stress at six radial locations

Figure 10. Comparison of mean velocity profiles at three radial locations
Figure 11. A Comparison of the U-component Mean and RMS velocities with the data of Cooper et al. [1]. Radial location = 1.5d

Figure 12. A Comparison of the u, v and w-component turbulence intensities with the data of Poreh et al. [12]. Radial location = 2.0d
(Open points: Poreh et al [12] and Closed points: current data)