Turbulence measurements in a short take-off vertical landing fountain

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Nomenclature

D	nozzle exit diameter
H	nozzle height above the ground plane
k	turbulent kinetic energy
S	spacing between nozzle centres
u'	turbulent fluctuating velocity in the fountain streamwise, z, direction
U	time-mean velocity in the fountain streamwise, z, direction
U_j	time-mean jet centreline velocity at nozzle exit
v'	turbulent fluctuating velocity in the x-direction
V	time-mean velocity in the x-direction
x	co-ordinate parallel to the ground plane in the plane of the jet centres
y	co-ordinate parallel to the ground plane in the plane of the nominal fountain axis
z	co-ordinate normal to the ground plane

Introduction

THE wall jets created by the impingement on the ground of the individual jet flows from a jet-lift, short take-off and vertical landing (STOVL) aircraft, with two nozzles, meet at a stagnation line and form an upwards-flowing 'fountain' that interacts with the airframe (Fig. 1).

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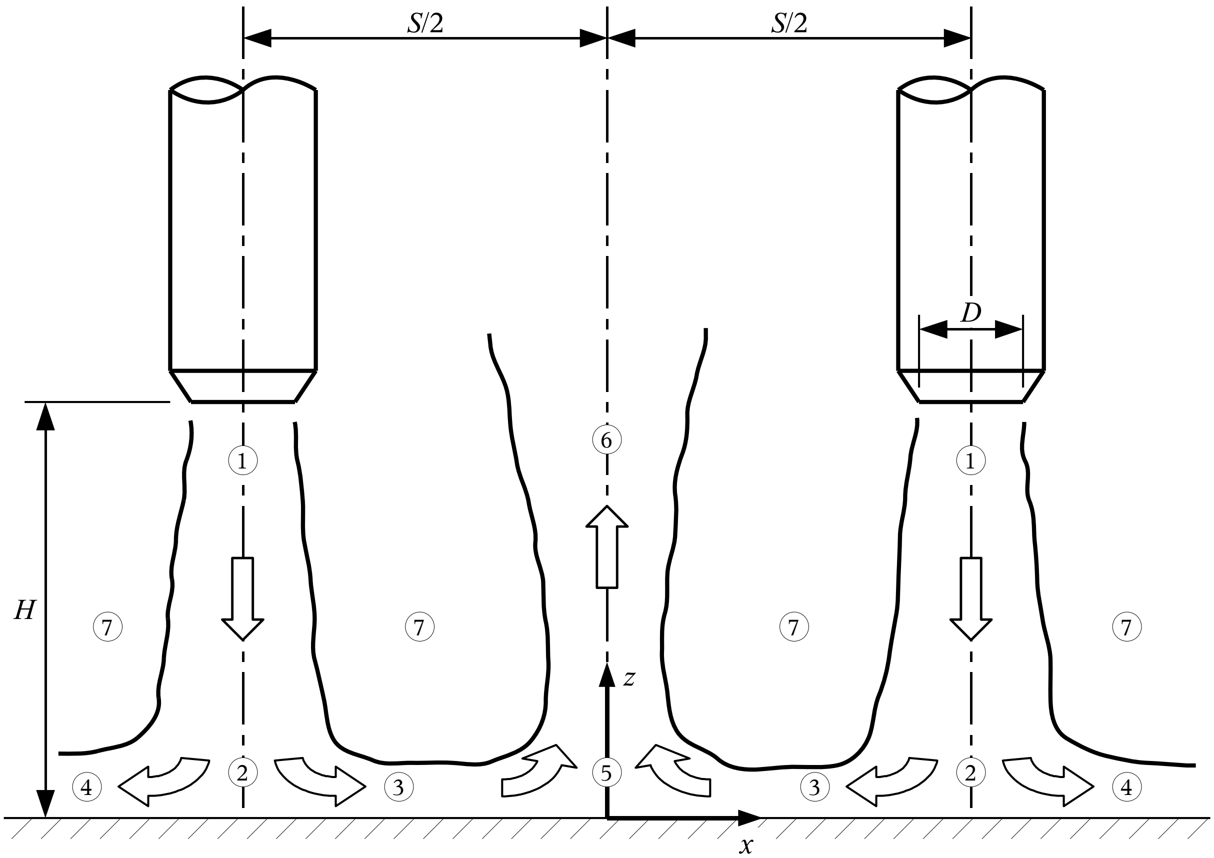

1. Lift jet flow
2. Jet impingement region
3. Inner wall jet flow
4. Outer wall jet flow
5. Fountain formation region
6. Fountain upwash flow
7. Entrainment region

Figure 1. Schematic of a twin impinging jet fountain flow.

Whilst it is evident that the fountain upwash flow is unsteady, only limited data on the transient characteristics of this flow region are available. Early experiments relied on intrusive measurement techniques to provide mean pressure data [1] with unsteady pressures on the ground plane being used to infer additional information [2]. Direct measurement of turbulence data has been made using hot-wire anemometry [3, 4], however, this technique is limited to low flow speeds and low turbulence intensities and is, therefore, likely to be inaccurate for compressible and highly unsteady flows; there is also the issue of probe interference. Techniques such as particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) offer the possibility of detailed non-intrusive measurements in the fountain region. Recently we have reported on the mean impinging jet and fountain velocity profiles obtained using PIV and LDV [5–7]. This paper extends the work further by presenting PIV-derived fountain turbulence characteristics.

Aims and objectives

The aim of this study was to describe and quantify some of the turbulence characteristics of the fountain upwash flow field. The objective was to gather PIV data through the fountain upwash in the vertical plane intersecting the nozzle centrelines (Fig. 1) for a nozzle pressure ratio (NPR, the ratio of nozzle exit stagnation pressure to ambient static pressure) of 1.05 and a nominal non-dimensional height above the ground plane, H/D, of 2.4 and a non-dimensional nozzle spacing, S/D, of seven.

Experimental set-up

The experiments were conducted in a dedicated impinging jet facility. The test rig (Fig. 2) and the PIV system are fully described in Reference [6]; for consistency we have adopted the same co-ordinate system and nomenclature.

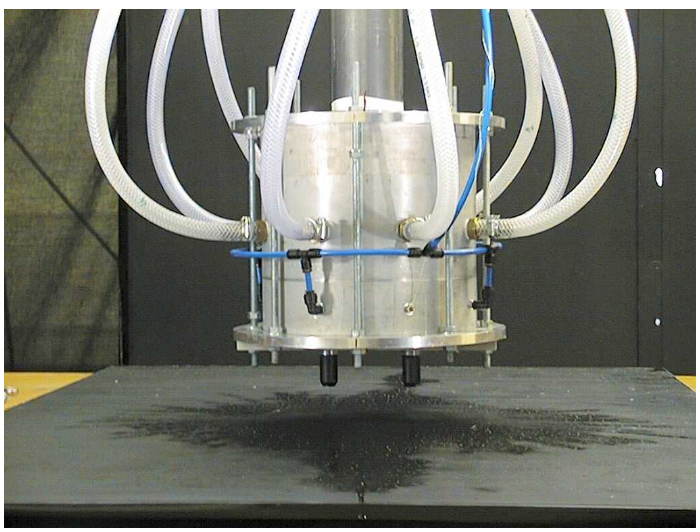

Figure 2. The settling chamber and impingement surface.

Results

Turbulent field

Contours of horizontal turbulent stress, $\overline{v'v'}$, non-dimensionalized with the jet exit velocity, U_j are shown in Fig. 3 and reveal that the wall jet interaction region is an area of large horizontal velocity fluctuations. It also contains high values of the velocity gradient, $\partial V/\partial x$. Maximum values of vertical turbulent stress, $\overline{u'u'}/U_j^2$, shown in Fig. 4, occur within a height range that corresponds approximately to the fountain formation region, within which high values of mean vertical velocity gradient, $\partial U/\partial x$, were recorded. Profiles of horizontal normal stresses, $\overline{v'v'}/U_j^2$, were found to attain self-similarity at a non-dimensional height above the ground plane of $z/D \approx 0.75$; profiles of vertical normal stresses, $\overline{u'u'}/U_j^2$, however, showed self-similar behaviour only above $z/D \approx 1.5$ [8].

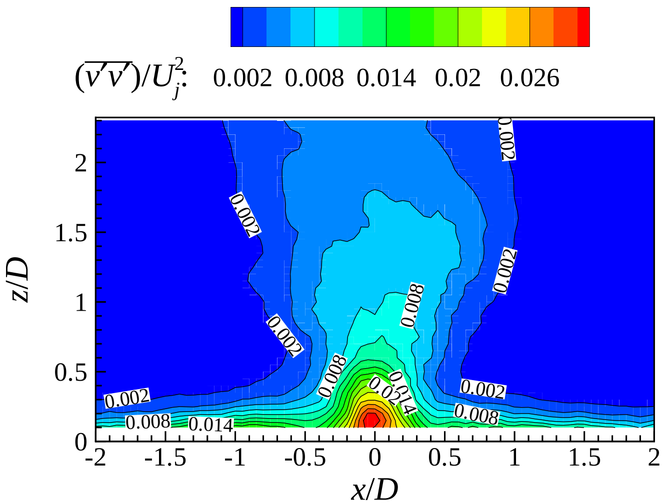

Figure 3. PIV-measured contours of horizontal normal stress in the fountain.

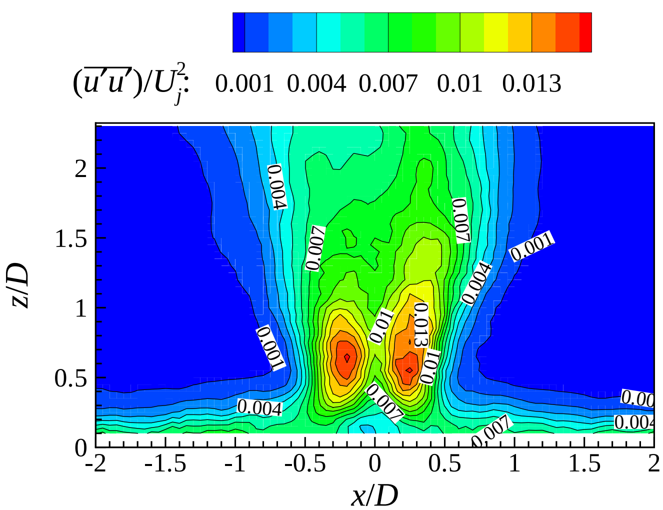

Figure 4. PIV-measured contours of vertical normal stress in the fountain.

Contours of $V_{\text{rms}}/U_{\text{rms}}$ shown in Fig. 5 reveal that in the wall jet interaction region the flow is highly anisotropic with values of $V_{\text{rms}}/U_{\text{rms}}$ reaching 2.9. Throughout the fountain decay region ($z/D > 0.5$) the flow is less anisotropic with $V_{\text{rms}}/U_{\text{rms}} \approx 0.8$.

Contours of shear stress, $\overline{u'v'}/U_j^2$, are presented in Fig. 6. They correlate well with the mean flow, with values in the region of zero in the centre of the fountain and in the flow surrounding the fountain. Shear stress is negative on the left-hand side of the fountain suggesting that an element of fluid in the upwash that suffers a positive vertical velocity fluctuation ($u' > 0$) tends to move away from the fountain's axis ($v' < 0$). Similarly, on the right-hand side, where shear stress is positive, positive vertical velocity fluctuations ($u' > 0$) correspond to positive horizontal fluctuations ($v' > 0$).

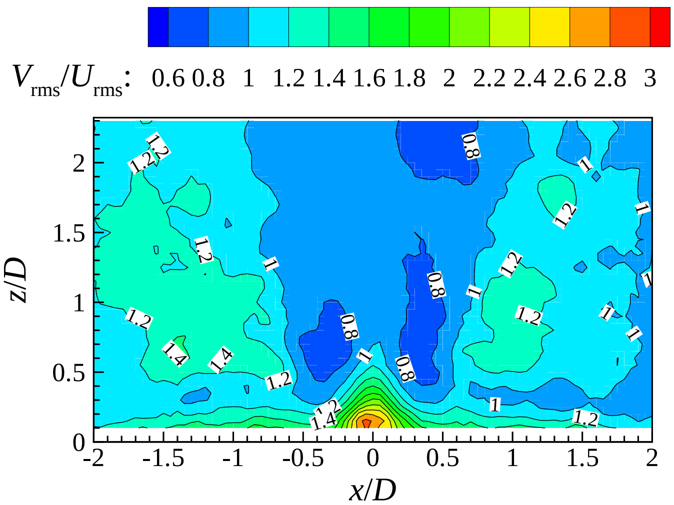

Figure 5. PIV-measured contours of turbulence anisotropy in the fountain.

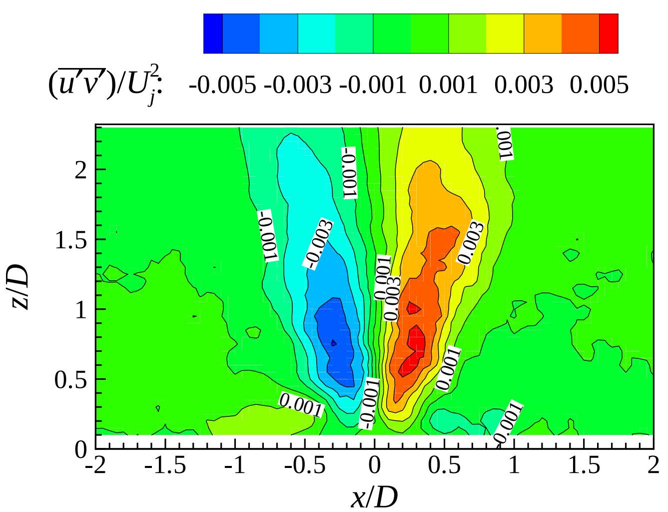

Figure 6. PIV-measured contours of shear stress in the fountain.

Turbulent kinetic energy

Turbulent kinetic energy, $k = 1/2(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$, is an important quantity for the understanding of the physical processes in turbulent fluctuations and in turbulence modelling. The transport equation for k expresses the balance between convection, production, diffusion and dissipation of turbulent kinetic energy and for the two-dimensional data presented here has the form [9],

$$U\frac{\partial k}{\partial z} + V\frac{\partial k}{\partial x} = P_k + D_k - \epsilon \tag{1}$$

The left-hand side of Equation 1 contains the convective terms and on the right-hand side P_k is the production term, D_k is the diffusive term (containing viscous and turbulent diffusion) and ϵ is the dissipative term. P_k can be decomposed in the following manner,

$$P_k = P_{uu} + P_{vv} + P_{uv} \tag{2}$$

with

$$P_{uu} + P_{vv} = -\overline{u'^2}\frac{\partial U}{\partial z} - \overline{v'^2}\frac{\partial V}{\partial x} \tag{3}$$

and

$$P_{uv} = -\overline{u'v'}\frac{\partial V}{\partial z} - \overline{u'v'}\frac{\partial U}{\partial x} \tag{4}$$

Equations 3 and 4 represent the production of turbulent kinetic energy by normal and shear stresses respectively (non-dimensionalized by nozzle exit diameter and jet exit velocity). The convection and production terms were obtained directly from the PIV data whilst the diffusion and dissipation terms were obtained by subtraction, since it was not possible to obtain measurements for these terms. In order to understand the production of kinetic energy in the fountain, each term was decomposed into velocity gradients and stresses. Contours of the production of turbulent kinetic energy by normal and shear stresses are shown in Figs. 7 and 8 respectively. In the region of wall jet interaction the production of turbulent kinetic energy by normal stresses is much larger than that by shear stresses. This results from the product of large values of $\partial V/\partial x$ and $\overline{v'v'}$, which outweigh the term $\overline{u'u'}\partial U/\partial x$. At $x/D = 0$, and as one moves upwards from the base of the upwash, the production of k by normal and shear stresses is approximately the same. Away from the centreline, however, shear stresses dominate the production of k.

The convective and diffusive plus dissipative terms in the transport equation of turbulent kinetic energy are presented in Figs. 9 and 10 respectively. Both terms have similar magnitudes throughout the flow-field except in the wall jet interaction region where diffusion and dissipation of k is the most negative, which balances the high production of k by normal stresses.

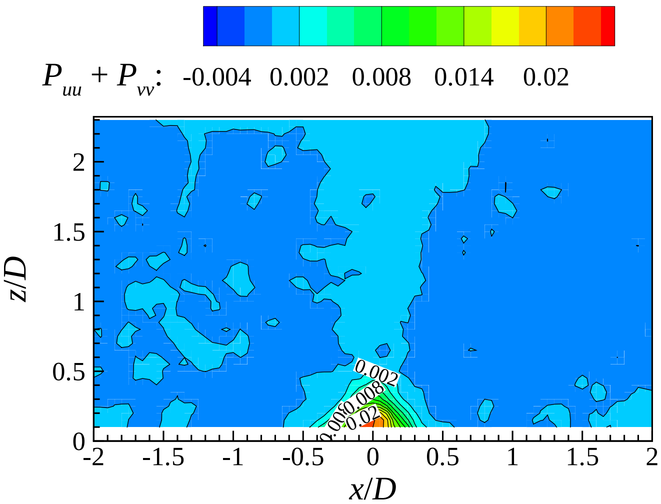

Figure 7. PIV-measured contours of turbulent kinetic energy production by normal stresses in the fountain.

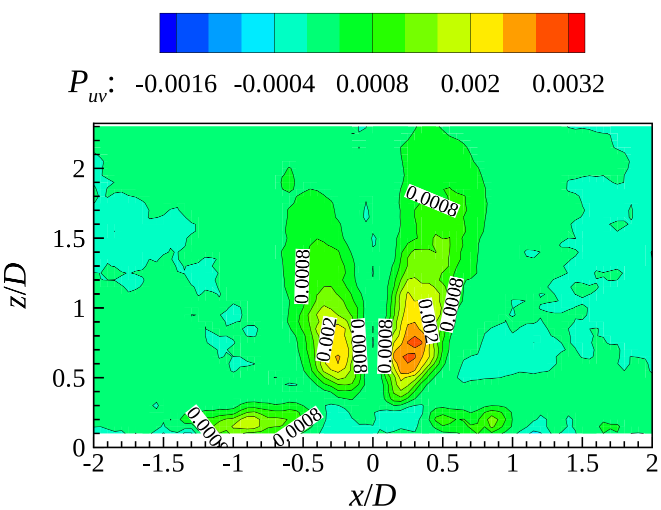

Figure 8. PIV-measured contours of turbulent kinetic energy production by shear stresses in the fountain.

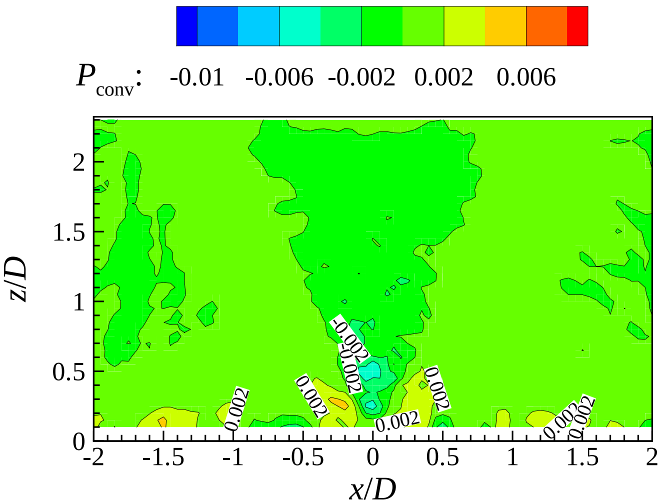

Figure 9. PIV-measured contours of turbulent kinetic energy convection in the fountain.

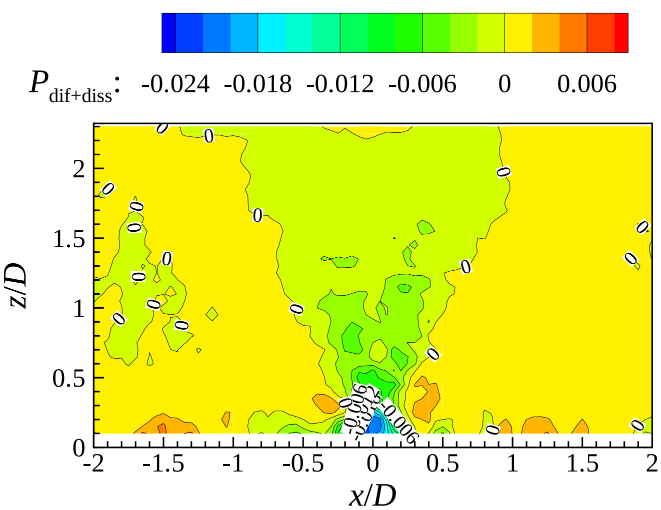

Figure 10. PIV-derived contours of turbulent kinetic energy diffusion plus dissipation in the fountain.

Conclusions

An experimental study was conducted to measure some of the turbulence characteristics of a twin-jet fountain upwash flow using non-intrusive particle image velocimetry. The results show that the point at which the wall jets meet is an area of large horizontal turbulent stress. The largest values of vertical turbulent stress were found in the fountain formation region. In the wall jet interaction region the flow was shown to be anisotropic with values of $V_{\mathrm{rms}}/U_{\mathrm{rms}}$ reaching 2.9. Turbulent kinetic energy production by normal stresses was concentrated in the wall jet interaction region whereas the fountain formation region was the source of turbulent kinetic energy production by shear stresses.

Acknowledgement

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