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LDA Experimental Data of Three-Poster Jet Impingement System

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During its near-ground hovering phase a Short Take-Off and Vertical Landing (STOVL) aircraft creates a complex three-dimensional flow field between jet streams, the airframe surface and the ground. A proper understanding and numerical prediction of this flow is important in the design of such aircraft. In this paper an experimental facility, used to gather validation data suitable for testing Computational Fluid Dynamics (CFD) model predictions of multi-jet ground impingement flows, is described. Water is used as the working medium and Laser Doppler Anemometry (LDA) measurements of three-poster impinging jet flow fields are reported. Emphasis is placed on the presentation of the mean and rmsvelocity contours in the fountain formation region between the jets. The effect of jet imbalance and splay-angle were studied. An overview were provided to guide users through the data and highlight several important flow features which have already emerged from the data and which are considered of importance to CFD model validation.

NOMENCLATURE

D_j	Nozzle exit diameter
H	Impingement height to ground plane
S	Jet spacing
V_j	Nozzle exit velocity
U	Longitudinal velocity
$u-\mathrm{rms}$	Longitudinal rmsvelocity fluctuation
V	Vertical velocity
$v-\mathrm{rms}$	Vertical rmsvelocity fluctuation
W	Transverse velocity
θ	Splay angle between jet nozzle centre lines

INTRODUCTION

Jets discharged transversely into a cross-flow appear as a flow element in many propulsion related systems. For external aerodynamic applications, the manoeuvring and lifting jets of STOVL aircraft (Figure 1), missiles and space vehicles require an understanding of the fluid mechanical interactions between closely spaced jets; impingement on a nearby solid surface (e.g. ground plane) is also of significance. For internal aerodynamic applications, several cooling scenarios (e.g. turbine blades, combustor liners, etc.) involve multiple jets, cross-flow and impingement. In recent years jet flow-field mathematical modelling has moved away from empirical models towards numerical models of a more fundamental nature, (e.g. References [1-3]). However, the continued improvement in CFD methods and their successful application to aircraft design requires, for verification, a body of high quality validation data gathered in a range of relevant test case flows. These test cases should focus attention on the fundamental flow components which are important in ground effect flowfields, e.g. multiple impinging jets, ground vortex flow, fountain formation, etc. Over the last decade, this viewpoint has motivated a shift in the emphasis of experimental studies on ground-effect flows, away from measurements intended to provide information on specific configurations of interest, towards more focused measurements aimed at improving our understanding of particular flow elements. These measurements are also served as benchmark test cases to determine whether particular numerical models can reproduce these flow elements adequately.

Bray [4] has previously reviewed the experimental research on jet flows. Although the effects of compressibility via jet pressure and temperature ratios

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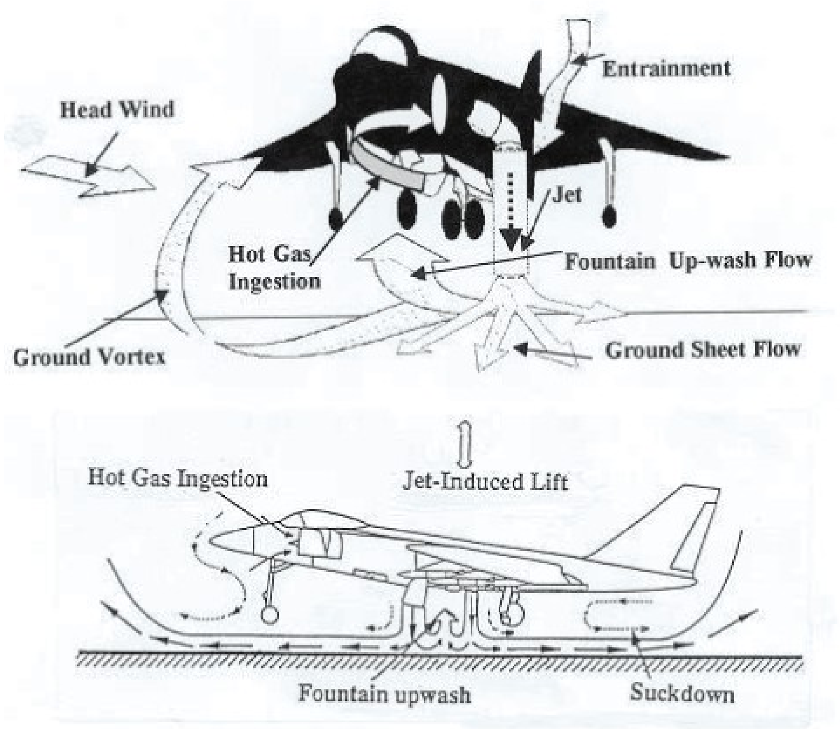

Figure 1. Major aerodynamic features associated with STOVL aircraft in ground effect

are undoubtedly relevant in practice, the difficulty of making detailed flow-field measurements in the ground impingement zone has meant that the available data in high pressure air experiments is usually restricted to ground plane pressure surveys (e.g. [4]), or wall-jet traverse information far removed from impingement [5]. Measurements of the turbulence field associated with ground-effect flows have usually been carried out in low-speed airflows (e.g. the ground vortex study of Ref. [6]) or, more commonly, in water flow experiments. Examples of the latter are the ground vortex study of Reference [1] and the fountain flow measurements of References [7-8]. The neglect of compressibility effects is not likely to be serious for ground vortex and fountain flows, since both measurements of Abbott and White [9] and predictions of McGuirk and Page [10] indicate that the fountain and ground vortex interactions lie in essentially low Mach number, subsonic zones. By choosing to study these flow features in incompressible experiments, emphasis has essentially been placed on the turbulence aspects so that data from such experiments form fundamental test cases for the validation of the turbulence model component of CFD models for ground-effect predictions.

Although the above comments have indicated that some suitable measurements for ground-effect validation studies have been made, the database is by no means large, and the effect of several parameters has yet to be established. If fountain flows are considered, for example, the data of Saripalli [7] formd the first detailed investigation, but are restricted to twin jets of wide spacing ($S/D_j = 9$ and 14) and do not consider the existence of a cross-flow. Barata et al [11] have included a cross-flow, but considered only the case of twin and three-poster parallel jets (i.e. all jet axes parallel and perpendicular to the cross-flow direction). Jet splay, i.e. angling of the jet axes in the plane connecting the jet centres is believed to influence fountain formation significantly. Behrouzi and McGuirk [12] have presented LDA results for generic lateral twin-jet impingement model with different jet splay angles, different twin-jet configurations [13-14] and also twin-jet-intake configurations [15].

The objective of the work reported here was to employ a specially designed experimental facility for the collection of flow field data for CFD validation of multi-jet ground impingement flows. Some validation work was reported in References [16-19]. In this paper quantitative experimental results for a three-poster-jet configuration are presented. Non-intrusive LDA techniques were used to obtain mean and fluctuating velocity fields. The influence of both jet imbalance and splay angle are studied.

EXPERIMENTAL FACILITY AND MEASUREMENT TECHNIQUES

The experiments were carried out in a specially designed and constructed water tunnel shown schematically in Figure 2. The rig is of a circulating design. The

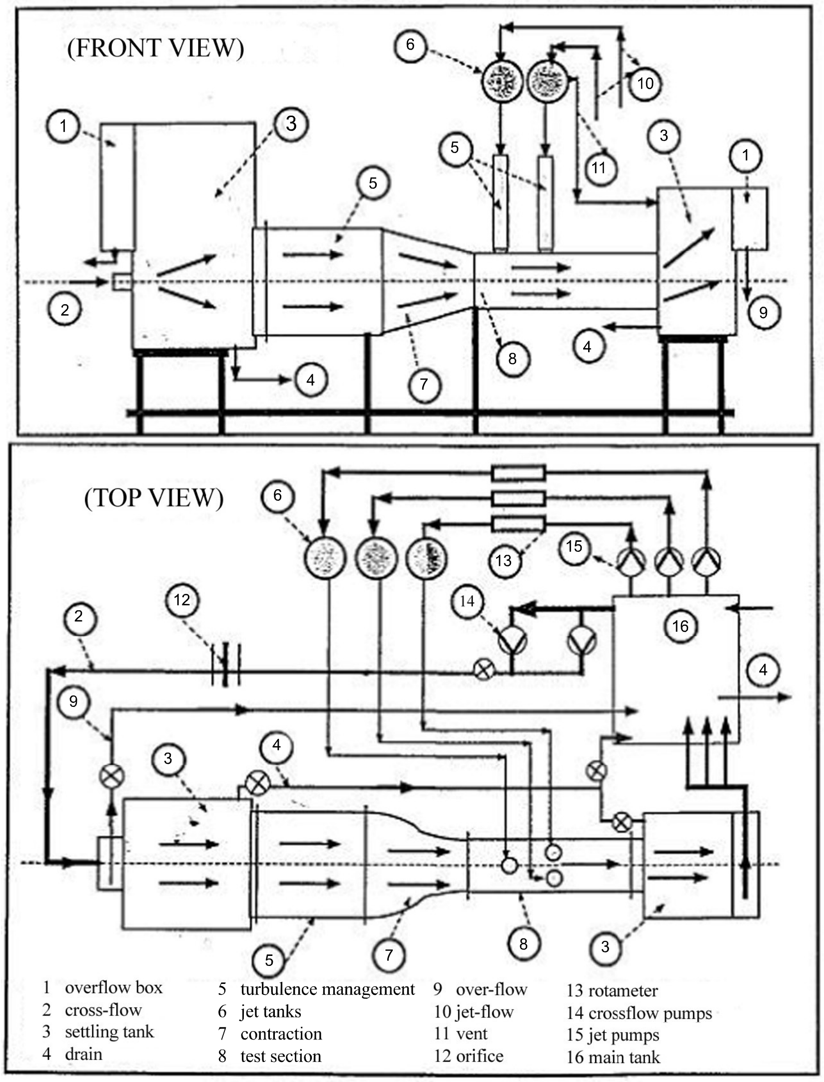

Figure 2. Schematic diagram of the STOVL experimental water tunnel

circuit consists of cross-flow and jet pumps that extract water from the main supply tank and pump it to a large settling chamber (for the cross-flow) or to overhead jet tanks which feed up to three separate jet units. The jet mass flow rates are monitored via rotameters. Turbulence management units are provided in both cross-flow and jet circuits, to provide controlled and well-defined conditions at all inlet boundaries to the test section (as required for boundary condition specification in CFD studies). The turbulence management systems represent a fairly standard combination of perforated plates, honeycomb and coarse and fine mesh screens. The jet unit design follows the suggestions of Saripalli [7]. The measured mean velocity was uniform over the central 85% of the jet diameter. The turbulence intensity at the jet exit was measured around 2%.

The water flows through the turbulence management and then the contraction section before entering the test section. The test section is made of Perspex with the jet units integral with the top plate. For all tests reported here a nozzle exit diameter (D_j) of 15mm was chosen. The test section dimensions are 1.125m long, 0.375m wide and 0.3m high (i.e. $75D_j$, $25D_j$ and $20D_j$ respectively). Cross and jet flows then discharge into the outlet settling tank and, through an overflow system, into the main supply tank. Valves were included in the circuit so that the rig could also be run without cross-flow. For the measurements reported here a three-poster-jet configuration was chosen. The line of centres of the rear twin-jets was perpendicular to the tunnel centre line. An impingement height (H/D_j) of 13 with a jet spacing (S/D_j) of 13 (longitudinal) and 6 (span-wise) were selected respectively (Figure 3).

In the co-ordinate system used below to report measurements (Figure 3), the origin of the longitudinal (x) co-ordinate is at the rear twin-jet symmetry plane (negative towards front jet). The vertical (y) co-ordinate has its origin in the rear twin-jet exit

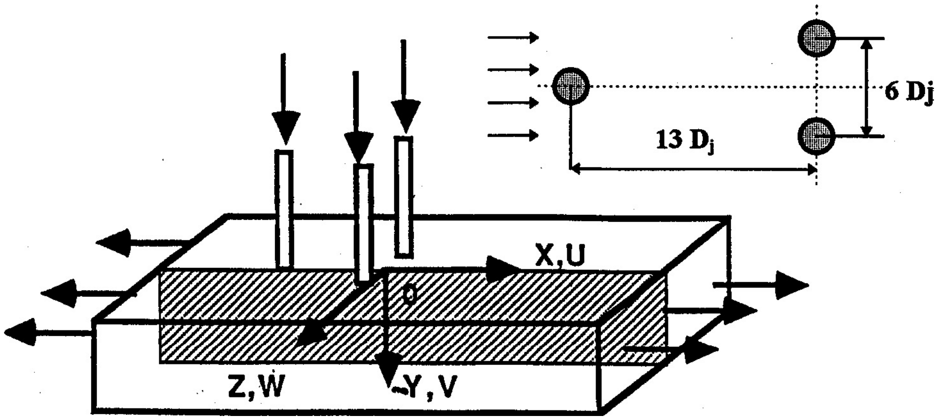

Figure 3. Co-ordinate system and x-y (front jet/ fountain) symmetry plane

plane and is measured positive upward. Finally, the transverse (z) co-ordinate has its origin in the test-section symmetry plane and is positive towards the front of the rig. Measurements were typically taken over a range $-14 < x/D_j < 2$, $-13 < y/D_j < 0.0$, and on the longitudinal plane $z/D_j = 0.0$ (i.e. the symmetry plane of the twin-jet-fountain system) and the transverse plane $x/D_j = 0.0$. Each longitudinal plane of measurements consisted of around 30 (longitudinal) by 8 (vertical) points. The present results were taken for a fixed rear twin-jet nozzle exit velocity of 2.5m/s, corresponding to a jet Reynolds number of 37,500 to ensure fully turbulent conditions.

The velocity field was measured using a single channel forward-scatter fringe-mode Laser Doppler Anemometer with a Helium-Neon laser operated at a nominal power of 10 mW. The advantage of using water as the working fluid was that a plentiful supply of naturally-occurring dust particles in the water formed the scattering centres so that no artificial seeding was necessary and strong signals at high data rates (up to 20kHz) were obtained even with the low laser power used. Sensitivity to the flow direction was provided by a DANTEC 55X29 Bragg cell with variable frequency shifting made possible by a DANTEC 55N101 frequency shifter. A 310mm focal length transmission lens was used with a beam spacing of 60mm. Off-axis light collection meant that the effective size of the measuring volume was 2.0mm long with 0.3mm diameter. The signals were processed using a TSI IFA 550 processor connected to a PC and controlled by a ZECH LDA data acquisition interface. No corrections were made for sampling bias. Any associated errors were minimised by using high data rates compared to typical velocity fluctuation rates, as suggested by Erdmann and Tropea [20]. The signal processor was operated in trigger mode so that data at fixed time intervals were acquired. The typical data rate used was 2kHz. To minimize statistical (random) errors, the number of individual velocity values used in the experiments to form averages was set to the large value of 40,000 for all data points (sampling time 20 sec.). This was not necessary in all regions of the flow, but was found essential for meaningful averages in the fountain zone. Finally, the tunnel was run for at least two hours before each test to establish steady conditions. The final setting of jet velocities was carried out using the LDA system to guarantee, for example, equal jet velocities for twin-jet systems and repeatable conditions.

EXPERIMENTAL RESULTS

All velocity and rmscomponents are normalised by the nozzle exit velocity V_j and all distances by the nozzle exit diameter D_j. Three test cases were investigated and the summary of results is presented here.

Test Case-1: Base-Case

The three jets exit velocities were fixed at 2.5 m/s for this case. Figures 4, 5a, 6a and 7a show mean and rmsvelocity fields for the base-case. The front jet behaves essentially the same as the twin-jet system at the same impingement height and spacing although the entrainment into the lee side of the jet is obviously slightly different since the velocity decay up to $y/D_j = -12$ is larger (velocity decreased to 39% of V_j rather than 45% V_j in twin-jet system). The strength of the central fountain (at $x/D_j = -7$) is also similar to twin-jet system ($\sim 16\% V_j$ up-wash), although in the three-poster case this now merges into the fountain between the twin rear jets, whose strength is even larger ($\sim 22\% V_j$ up-wash). If the central fountain has any inclination, it is forwards, towards the front jet, whereas the twin jet fountain is obviously tilted rearwards. The central fountain penetrates all the way to the roof of the water tunnel, but the rear fountain only rises to around $6D_j$ off the ground plane. The negative U-velocity region measured near the ground plane indicates that the central and twin-jet fountains have essentially merged into one.

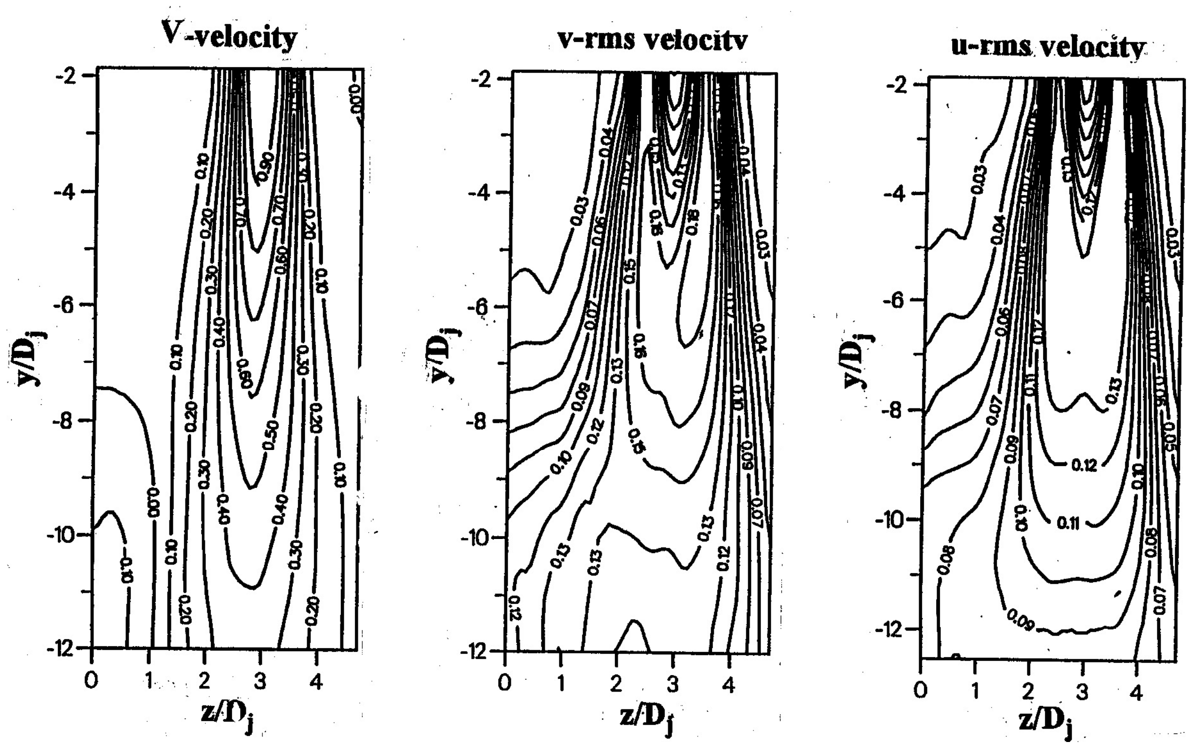

Figure 4. Measured mean vertical (V) velocity and rms(u,v) in the twin-jets symmetry plane ($x/D_j = 0.0$); test case-1; No cross flow

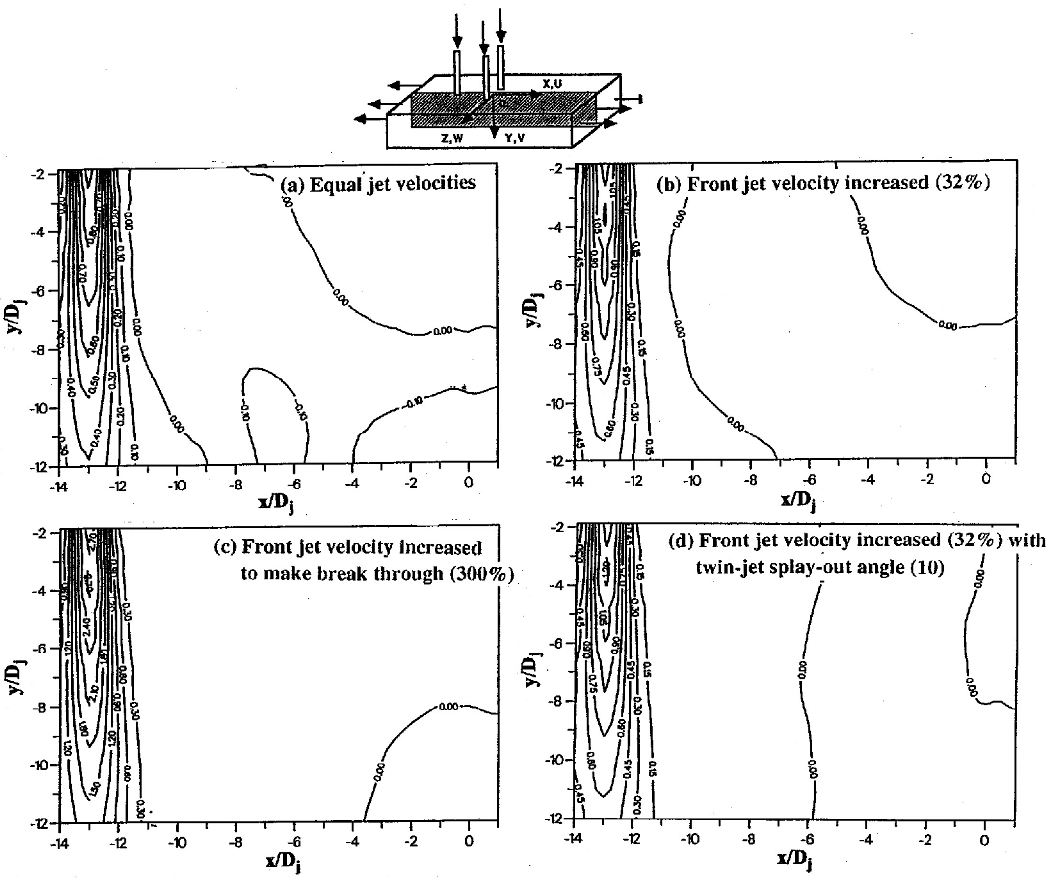

Figure 5. Effect of jet imbalance and splay-out angle on measured mean vertical velocity (V) in longitudinal symmetry plane ($z/D_j = 0.0$)

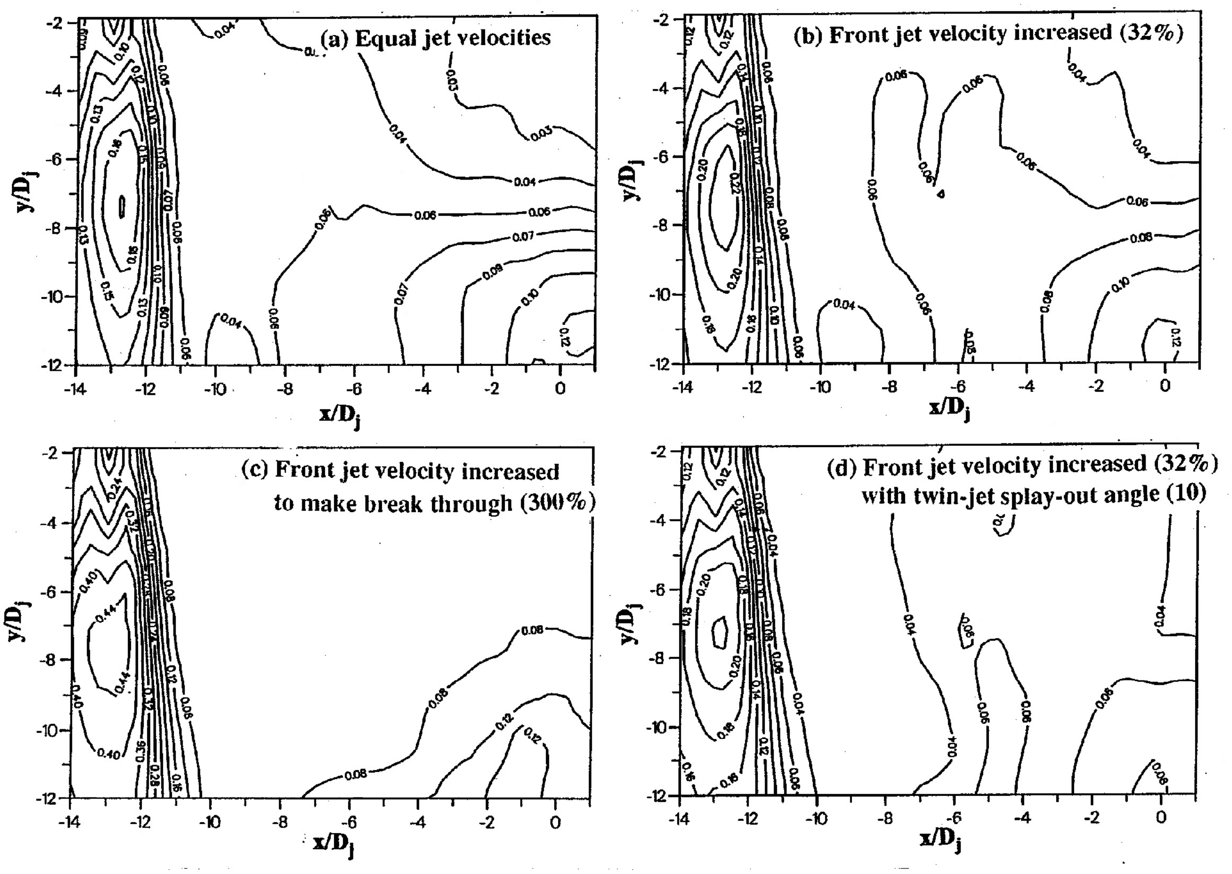

Figure 6. Effect of jet imbalance and splay-out angle on measured rmsof vertical velocity (V) in longitudinal symmetry plane ($z/D_j = 0.0$)

Strongly anisontropic turbulence fields are generated. Figures. 6 and 7 clearly display the complexity of the ground sheet flows. In the central fountain the u-rmsis larger than the v-rmsby a factor of 2. In the twin jet fountain region (Figure 4) the situation is reversed, with the v-rmslarger by some 50%.

Test Case-2: Effect of Jet Imbalance

This study was performed for the two different front jet velocities that follow:

a) Same condition as base-case, except the front/rear jet velocity ratio was chosen as 1.32 rather than 1. The objective of increasing the ratio of front jet to rear jet velocity is to simulate the thrust split typically found in three-poster type aircraft between the single front jet and each of the rear jets (a typical ratio of 70KN/40KN was assumed). For equal size nozzles, this produces a ratio of 1.323 between front and rear jet velocities.

b) Front jet velocity increased to achieve breakthrough (300%; jet velocity increased around base-case value by a factor of 3). Breakthrough was defined here as sufficient jet momentum to enable the rearward flowing ground sheet of the front jet (positive U-velocity in ground sheet) to penetrate past the rear jet entry plane ($x/D_j = 0$).

Figures 5(b,c), 6(b,c) and 7(b,c) contain examples of comparisons of these cases with the base-case. Increasing the strength of the front jet by 32% pushes the central fountain rearwards by some $2D_j$, but a large region of up-wash still exists on the symmetry plane. The negative measured U-velocities show that the rear jet ground sheet is still able to penetrate forwards against the strengthened momentum of the front jet. The u and v turbulence stresses display a similar pattern to the base case, with only a rearward displacement. When the front jet velocity is increased by a large amount (V_j − front/V_j − rear = 3.0) the character of the ground plane flow changes completely. Positive (i.e. downward) V-velocities are observed in the wake of the front jet practically over the whole downstream region measured. Negative (up-wash) velocities still exist, but Figure 5 indicates that these occur in conjunction with positive vertical velocities so any fountain regions are inclined strongly downstream. The turbulence quantities (Figures 6c and 7c) display

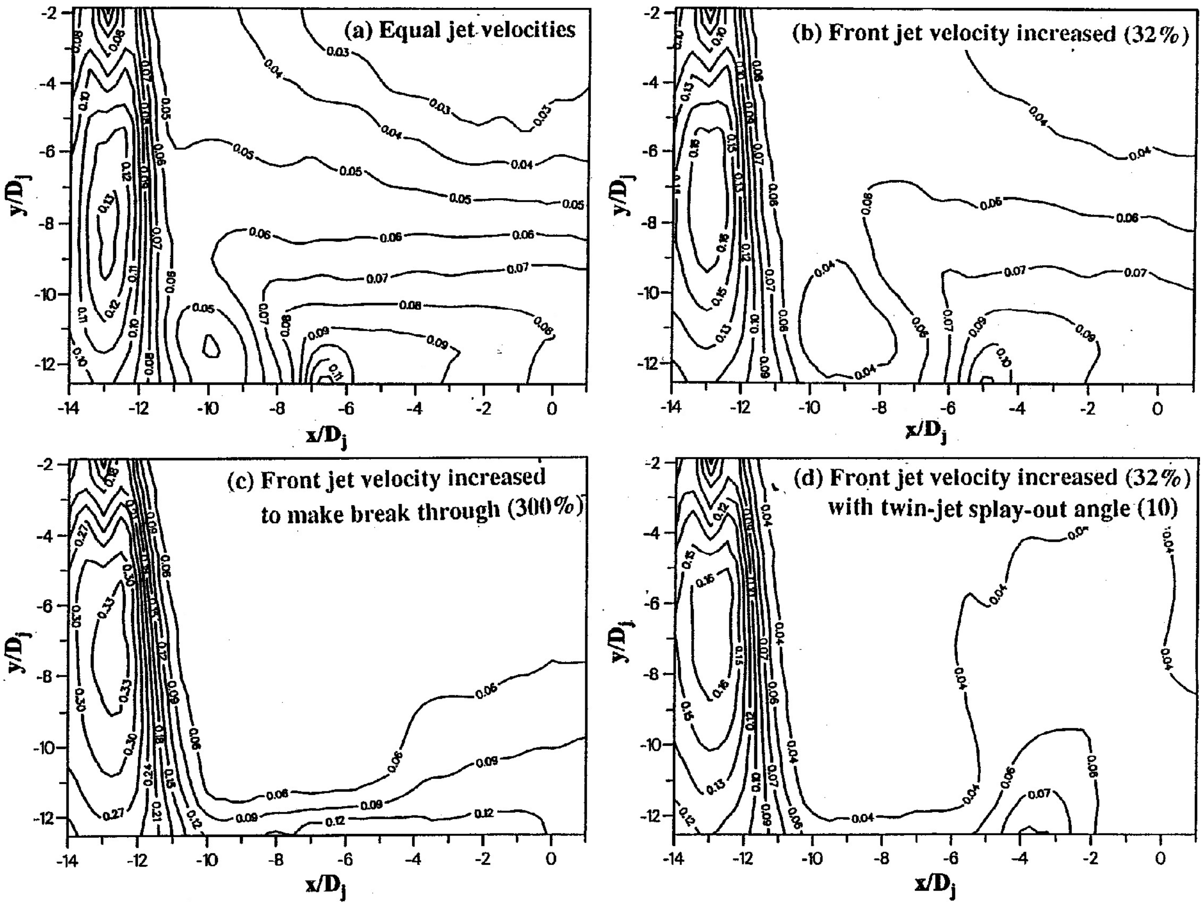

Figure 7. Effect of jet imbalance and splay-out angle on measured rmsof longitudinal velocity (U) in longitudinal symmetry plane ($z/D_j = 0.0$)

a much more isotropic behaviour now that the strong impingement processes of the ground sheet have been removed.

Test Case-3: Effect of Twin-Jet Splay Angle

This study was carried out using the zero splay results from the test case-2 (32% enhanced front jet velocity) rather than the base case (equal jet velocities) since this may be more relevant in practice. Figures 5d, 6d and 7d contain sample data plots, again restricted for brevity to the z(0) plane. Splay-out of 10^o was introduced into the rear jets. The effect on the fountain region is considerable. The fountain between the rear jets is weaker and smaller, with turbulence levels also decreasing. The presence of two peaks in the rms(Figure 6a) shows that a distinct central and rear jet fountain are still both present but are both be weaker. The location of the central fountain also moves $1D_j$ closer to the rear jets. Measurements also indicate that the absence of any negative U-velocities in the splay-out case has changed the inclination of the fountain, which is now clearly tilted rearwards.

The level of normal stress anisotropy is an important feature for turbulence modelling of the CFD predictions. The vertical rmsvelocity fluctuation levels displayed in Figure 6 may be contrasted with the longitudinal rmsvelocity fluctuation measurements shown in Figure 7. In the jet shear layers the (v-rms) normal stress is the largest, with peak values greater than the u-rmspeak by a factor of 1.4. This is what is to be expected (although slightly greater) for free mixing layer turbulence. At the base of the fountain v-rms/u-rmsalso assumes values of 1.4, in spite of the fact that the fountain origin is near the ground plane, where v-rmslevels might be expected to be preferentially suppressed.

CONCLUSIONS

An experimental facility particularly suited to the study of mean flow and turbulence characteristics of multi-jet impingement ground-effect flows was employed. LDA measurement was obtained in this facility for a three-poster impinging jet flowfield. Measurements were obtained and have been reported here for, in particular, the effect of jet imbalance and splay angle on the fountain formation process. The fountain region was noted to be a zone of large local turbulence intensities (greater than 50%), and also a region where normal stress production was dominant, due to the impingement of opposing ground sheet flows. These experimental data are believed to be of sufficient accuracy and detail to serve well as a benchmark test case for CFD validation activities (such as those reported in References [16-19]).

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