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EXPERIMENTAL INVESTIGATIONS INTO TWIN IMPINGING JETS IN CROSS-FLOWS

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Abstract

Parameters which affect the flow-field surrounding twin jets impinging in a cross-flow have been investigated experimentally. These parameters include jet-to-cross-flow velocity ratio, nozzle height above ground, nozzle pressure ratio, ground-plane conditions (fixed or moving), nozzle vector angle and skew angle. The experimentation has been based upon measurements of the ground-plane static pressure distributions with additional data provided through the use of smoke flow visualisation. The nature of the ground vortex has been found to be particularly affected by those factors which also influence fountain flow characteristics. These include nozzle height, nozzle spacing distance and toe-in or splay angle. All of the other parametric effects have also been addressed quantitatively.

Nomenclature

Abbreviations

ASTOVL	Advanced Short Take-Off and Vertical Landing
BAe MAL	British Aerospace Military Aircraft Ltd
HGI	Hot Gas Ingestion
RMCS	Royal Military College of Science
RVL	Rolling Vertical Landing

Symbols

C_p	Pressure coefficient = $(p - p_\infty)/(0.5\rho_\infty V_\infty^2)$
d_n	Nozzle exit diameter
h	Nozzle height above ground-plane
pr_n	Jet pressure ratio = p_0/p_∞
V_e	Effective velocity ratio = $(0.5\rho_\infty V_\infty^2/0.5\rho_1 w_1^2)^{0.5}$
V_g	Ground-plane velocity
V_∞	Cross-flow velocity
w	Jet velocity
x_d	Twin nozzle centre-line spacing distance at exit
y	Horizontal distance measured upstream from nozzle centre-line
ρ	Density
θ	Jet injection (vector) angle

Subscripts

c	Maximum
g	Ground-plane
n	Nozzle
p	Penetration position
s	Separation position
v	Vortex core position
∞	Ambient (cross-flow)
0	Nozzle stagnation conditions
1	Jet exit conditions

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Introduction

When a single jet impinges onto a surface normal (or nearly normal) to its axis, a wall jet forms, which spreads out radially from the impingement point. In the presence of a cross-flow (parallel to the wall) this wall jet eventually separates and rolls up into a so-called ground vortex, arranged as a horse-shoe around the impingement point.

A form of ground vortex also occurs in cases involving twin impinging jets in a cross-flow. An additional flow-field feature under such conditions is that of the upwash fountain (see Fig 1). The flow-field also contains two other noticeable vortical features, as observed by MacLean et al [1]. Firstly, a forward reinforcement of the ground vortex is usually present, in the form of a "spike" (referred to by MacLean at al as a forward vortex pair). Secondly, vortices are caused by entrainment between the jets and the upwash fountain, with the size and location of each vortex changing rapidly. All three types of vortical structures are shown in Figs 2 and 3, from MacLean et al's four-poster experimental work.

All of the flow-field features described above are of particular interest in the development of Advanced Short Take Off and Vertical Landing (ASTOVL) aircraft, where they can affect both airframe airloads and engine intake flows.

The fountain flow can be useful since it creates a significant upload on the airframe and thus greatly opposes the suckdown effects caused by entrainment into the free jets and wall jets. Frequently, lift improvement devices (LIDs) or cushion augmentation devices (CADs) are incorporated into the design of the lower fuselage to increase the fountain lift.

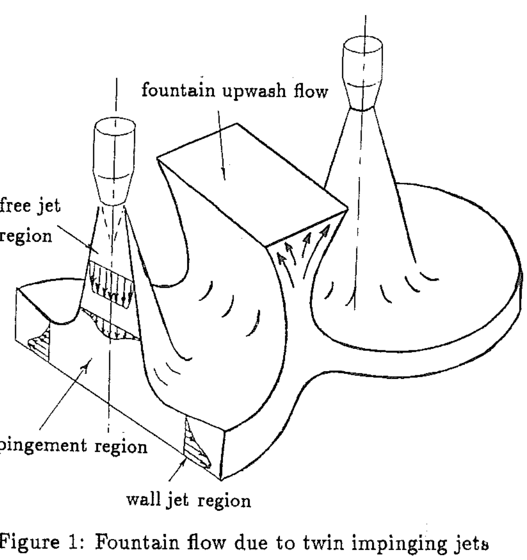

Figure 1: Fountain flow due to twin impinging jets

Unfortunately, the fountain flow can also be extremely harmful to aircraft operations since it is the primary cause of near-field hot gas ingestion (HGI) and the resultant engine thrust losses. These can again be controlled in many instances, however, by appropriate fuselage design procedures; the use of dams and strakes is again of use in this respect.

The ground vortex and the forward penetrating spike formed in cases where a relative cross-flow is present are also of crtical importance regarding far-field HGI effects. These cross-flows can either be caused by ambient winds or by relative aircraft motion over the ground, as in the case of a rolling vertical landing (RVL). Far-field ingestion through such means is critically important to ASTOVL aircraft development [2] since it is far more difficult to control through standard fuselage design techniques.

The ground vortex due to a single jet has already been studied extensively, e.g. Refs [3] to [12]. Little work has previously been presented on the flow-fields due to twin impinging jets in a cross-flow, however. Due to its importance in the field of V/STOL aerodynamics, a need therefore exists for experimentally modelling such flow-fields. In particular, there is a need for addressing and quantifying those parameters which might be important as scaling parameters for the resultant ground vortex and forward penetrating spike.

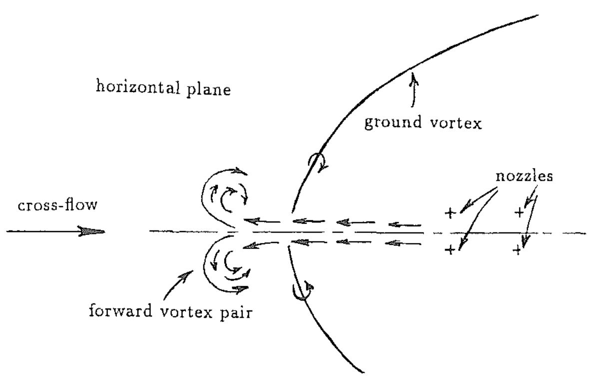

Figure 2: Plan view of multiple nozzle ground vortex and forward vortex pair (Ref 1)

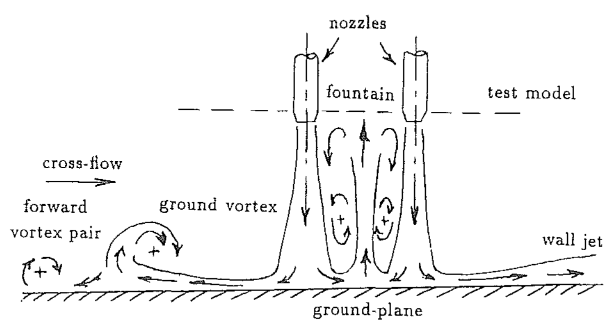

Figure 3: Side view of multiple nozzle vortical structures (Ref 1)

Experimentation

Two different types of experimental methods are conventionally used for studying these types of flow-fields.

Most previous investigations have been based on flow visualisation, usually involving either smoke/dust introduction (e.g. Refs [3, 6]) or oil accumulation methods (e.g. Ref [4]). Such methods can be used to provide both plan-views and side-views of the ground vortex, thus indicating both the shape and overall dimensions (forward extent and height, respectively) of the ground vortex. Different characteristic vortex positions will, however, be indicated by the two types of methods. The plan-view of the smoke-filled flow-field indicates the position of maximum forward penetration while, with the oil accumulation technique, the indicated position relates to where the ground sheet separates from the ground-plane.

Other investigations have been based upon ground-plane static pressure measurements. For single nozzle flow-fields, the time-averaged static pressure distribution along the ground in the plane of symmetry has been found to consistently produce three characteristic and quantifiable key points, representing ground vortex positions. Moving into the cross-flow from the impingement region, there is a sharp decrease of C_p to negative values and then an increase to some maximum positive value followed by a gradual fall-off to ambient conditions. Previous investigations (including Refs [4, 8, 9, 10, 13, 14]) have shown that the minimum C_p position (y_v) is coincident with the location of the ground vortex core, the zero C_p (y_s) point represents wall jet separation while maximum C_p (y_p) defines maximum vortex penetration.

Similar C_p distributions are measured along the plane of symmetry in the case of twin nozzle flow-fields, though the minimum C_p position is much less distinguishable. Comparisons with flow visualisation data (e.g. Refs [15, 16]) have again shown that the maximum forward penetration of the vortex is well represented by the maximum C_p point.

Investigations have been undertaken at RMCS using both the ground-plane static pressure distribution and smoke flow visualisation experimental techniques, using two separate sets of apparatus. These are known as the primary and secondary rigs respectively.

Primary rig

A schematic of the primary rig, as used for the majority of the experimentation, is shown in Fig 4. The RMCS open-jet wind-tunnel (OJWT), having a 1.1 by 1.5m elliptical nozzle, supplies the cross-flow with a maximum wind speed of 42m/s. In the working section is a removable moving belt or "rolling road" (1.1 by 1.7m).

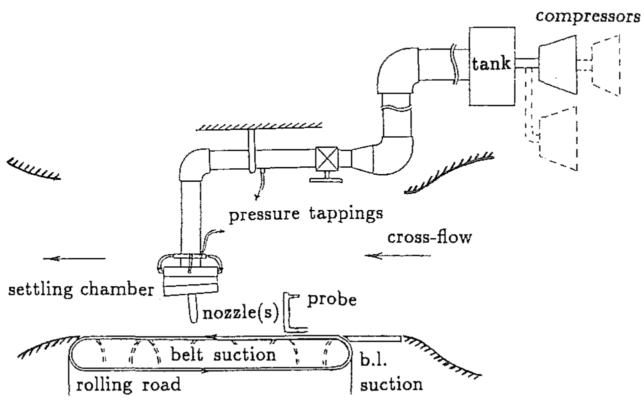

Figure 4: Schematic of primary experimental rig

Compressed air for the jets is provided by two "Howden" screw-type compressors; these can be run either in series (giving a maximum flow rate of 0.9kg/s at 7bar) or in parallel (1.8kg/s at 4bar). The air is dried and then dumped into a $34m^3$ storage tank. The ambient-temperature air is then supplied through a 5in diameter pipeline which is reduced to 2.5in before reaching the wind-tunnel working section. In the tunnel the pipe is connected to a settling chamber (approx. 34cm wide, 14cm deep and 15cm high, externally) to the lower surface of which single or twin nozzles can be fitted. By incorporating different designs of lower plate, nozzle vector (fore and aft) angle and splay or toe-in angle can be varied.

The nozzles used for most of these tests were of a conical, convergent design, having a 0.5in (12.7mm) exit diameter (d_n), a 0.125in long contraction of 10^o semi-angle and a parallel section upstream of this. The total nozzle length was 5in (127mm) below the settling chamber. Nozzle pressure ratio was determined from the measurement of settling chamber static pressure (provided by four tappings around the perimeter which were manifolded together).

Secondary rig

This uses an open-jet wind-tunnel (3ft long circular working section of 30in diameter) for provision of the cross-flow (maximum wind speed 45m/s).

Compressed air was supplied by a portable compressor, of 100l capacity and 10.8bar working pressure. Cylindrical pipes of 10mm internal diameter provided the jet flow, as opposed to the conical nozzles used in the primary rig experimentation. The jet velocities were at low subsonic values for all test cases; pressure ratio effects were therefore not studied with this facility. The air was made visible by the direct introduction of smoke through a venturi arrangement.

Ground vortex test data were recorded with a video camera. Vortex penetration positions were then obtained for different test conditions by averaging the results from several video stills.

Results and discussion

Shape of the ground vortex

Flow visualisation with the secondary rig indicated a different ground vortex locus for a twin parallel nozzle arrangement compared with the classical elliptical ground vortex shape obtained with a single nozzle [17]. A noticeable "spike" was clearly observed, protruding in front of the ground vortex and thus considerably increasing vortex penetration. MacLean et al have described this flow feature as a forward vortex pair [1] and noted its extreme unsteadiness.

Extensive investigations into the ground vortex shapes due to both parallel and non-parallel (splayed-out and toed-in) nozzles, and how they are affected by parameters such as jet to cross-flow velocity ratio, nozzle height above ground and nozzle spacing distance, were more recently carried out by Matson at RMCS [18], also using the secondary rig.

A prominent spike could not be detected under all test conditions. In some cases, the footprint area was quite small and the vortex shape was more elliptical in nature, as for the standard single nozzle cases. This occurred when simple geometry dictated that the jet boundaries (taking free jet spreading into account) had merged before reaching the ground-plane so that no fountain flow existed. This was therefore more likely under high h/d_n conditions (when considering parallel or toed-in nozzles) and small nozzle spacing distances. The spike was also sometimes extremely weak in nature, almost to the point of disappearing altogether, under opposing sets of conditions. This occurred when there were large flow paths between the jets along the impingement plane, e.g. with wide nozzle spacings. The disappearance of the spike at wide nozzle spacings has also been reported previously by Barata [19]. Similar effects were also found in the case of splayed nozzles at high nozzle heights. In all such circumstances, the velocity decay of the wall jets is significantly increased due to the increased flow path distances, resulting in weaker fountain flows being formed. The spike itself, and the resultant forward penetration of the ground vortex, was consistently shown to be maximum in conditions where the jet boundaries were only just on the point of merging at the ground-plane. All of the above suggests that the presence of the spike can be directly attributed to a reinforcement effect, originating from the fountain flow.

Some vortex shapes, as obtained from the flow visualisation work, are shown in Fig 5. These apply to twin parallel nozzles at spacing distances of between $1.5d_n$ and $9d_n$. Two different heights ($h/d_n = 4$ and 8) and velocity ratios ($w_{c1}/V_\infty = 7.9$ and 15.75) have been tested. The data show all of the trends discussed above.

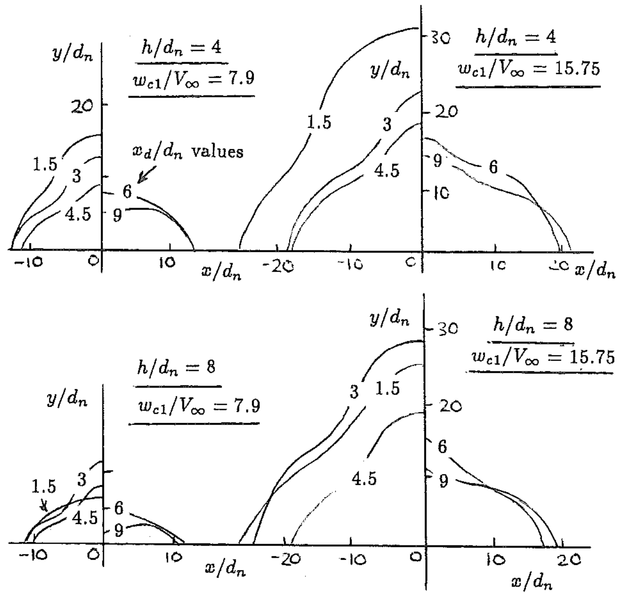

Figure 5: Twin parallel nozzle vortex shapes

Nozzle spacing distance - effect upon vortex penetration

Some typical results from the flow visualisation work are shown in Fig 6 (nozzle toe-in angle = 20^o, $h/d_n = 4$). This clearly shows how dramatically vortex penetration varies with spacing distance. Very small vortex penetrations are produced in cases where there is a significant amount of jet merging prior to impingement (i.e. at small nozzle spacings), due to the large momentum losses involved. Peak penetration occurs when the jet boundaries are just on the point of merging at the ground-plane.

Nozzle spacing effects are obviously greatly reduced in such cases where no merging of the jet boundaries occurs. This relates to such cases which concern parallel or splayed-out nozzle configurations at reasonably low heights. Under these circumstances, an increase in spacing distance would always result in a decrease in vortex penetration, due to a lengthening of the wall jet flow paths after impingement. Such an effect is shown in Fig 7 (parallel nozzle configuration, $h/d_n = 4$).

Nozzle height - effect upon vortex penetration

Vortex penetration is greatly affected by the height of the nozzles above the ground, mainly for the reasons outlined above (i.e. due to the resultant changes in the wall jet flow paths or the degree of jet merging). Such effects swamp out any others that might be present due to nozzle height variations: for instance, a small height effect has been observed in the case of a single nozzle, apparently due to a change in the efficiency of the turning process in the impingement region [5, 14, 16].

The height effect for twin parallel nozzles at a spacing distance of $3d_n$ is shown in Fig 8. Here, the penetration increases with increasing height since the net effect of the spreading free jet boundaries results in smaller wall jet flow paths after impingement, as discussed above. For the range of heights shown, the jets remain unmerged prior to impingement so that a fountain flow, and vortex spike, exists throughout. Free jet deflection only becomes noticeable in the case of the lowest V_e^{-1}, where the size of the ground vortex (and therefore its blocking effect) is at a minimum [4].

Nozzle height effects are even greater when jet merging characteristics are affected. This is clearly illustrated in Fig 9, based on a spacing distance of $3d_n$ and a toe-in angle of 20^o per nozzle. This shows that vortex penetration is dramatically reduced at $h/d_n = 8$, due to the greatly increased extent of jet merging.

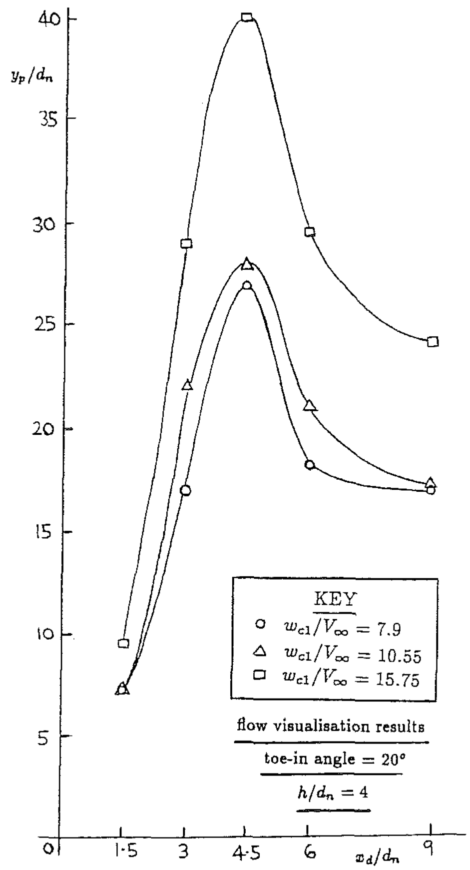

Figure 6: Typical effect of twin nozzle spacing distance

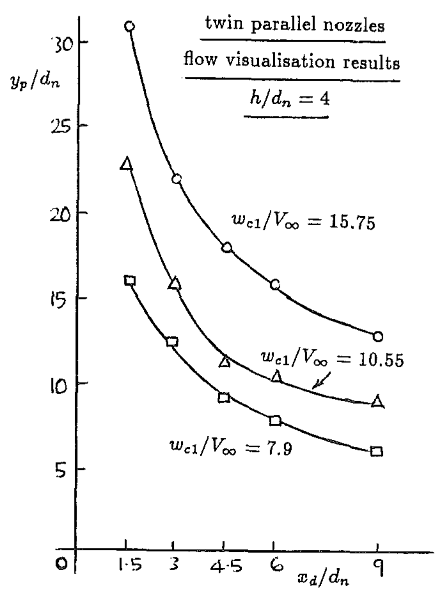

Figure 7: Typical effect of twin nozzle spacing distance - no jet merging effects

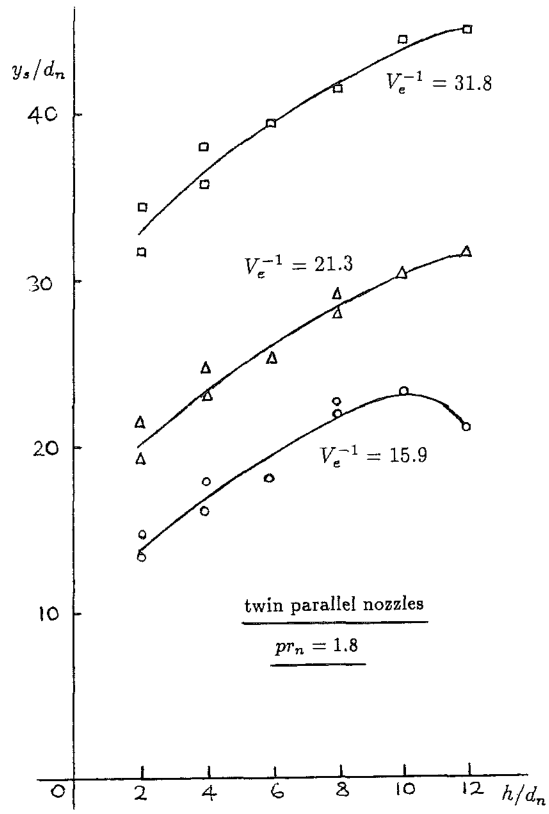

Figure 8: Typical effect of twin nozzle height

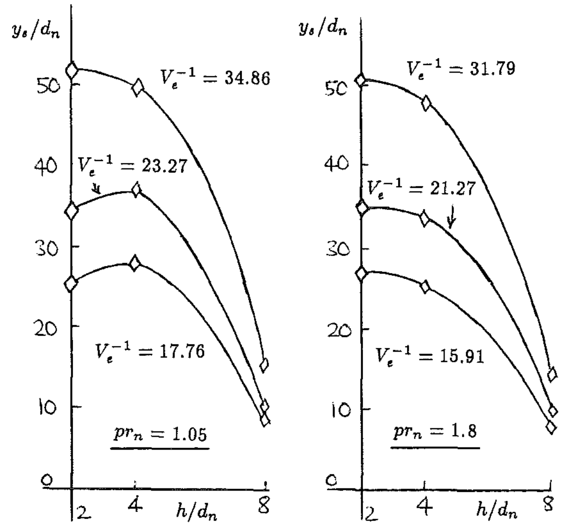

Figure 9: Nozzle height effect for 20° toed-in nozzles

Ground vortex self-similarity laws

Consistent self-similarity laws, relating the measured y_s and y_p positions (zero and maximum C_p positions respectively) in the plane of symmetry, exist for twin nozzle flow-fields (see Fig 10). Regardless of the type of configuration or operating conditions, the data can be well represented by $y_s = 0.805y_p$.

This is identical to the relationship obtained from the single nozzle test data [13, 14, 16, 20]. It is a useful finding, since only one of the characteristic positions needs to be determined: the other can be deduced from the fixed relationship. It is for this reason that the y_s position has been used in all the parametric investigations, as it is easier to measure with accuracy. For the same reasons, conclusions based upon comparisons between y_s data can also be applied to vortex penetration data.

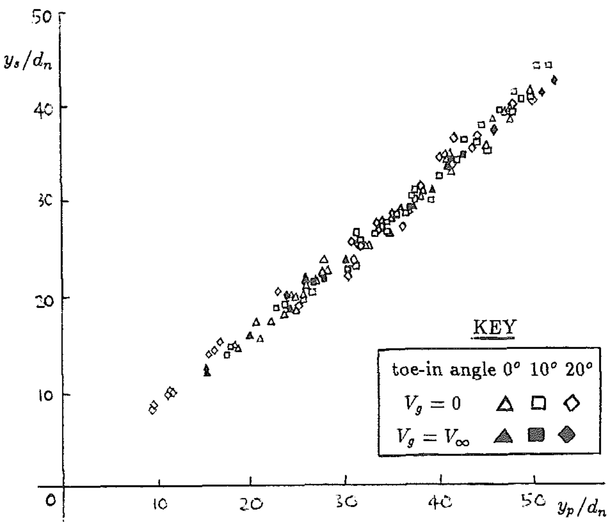

Figure 10: Twin nozzle ground vortex self-similarity law

Velocity ratio effects

The ground vortex is found to grow and move away from the impingement region with increasing jet-to-cross-flow velocity ratio, as expected. The precise relationship, however, depends on the other parameters being investigated and also on the precise definition of velocity ratio. An improved collapse of data is obtained when an *effective* velocity ratio is used so that density differences are taken into account (as originally proposed by Abbott [3]). This improves data correlation in the case of heated jets (as in Abbott's work) or jets subject to appreciable compressibility effects. In cases involving ambient-temperature jets at low pressure ratios (such as the present series of secondary rig tests), the simpler velocity ratio definition of w_{c1}/V_∞ is still appropriate.

Nozzle pressure ratio effects

At constant effective velocity ratio there is a marked and consistent nozzle pressure ratio effect. In fact, the same trends have been observed for all types of both single and twin nozzle configurations [14]. Fig 11 shows these trends for cases involving single and twin parallel nozzles at $h/d_n = 4$, though more single nozzle data are presented. Vortex penetration peaks are observed to be present at nozzle pressure ratios of around 1.8 and 3.0.

The reduction in penetration once underexpanded ($pr_n > 1.893$) is probably directly attributable to total pressure losses in the resultant shock waves. In particular, a large penetration reduction would be expected once highly underexpanded ($pr_n > 3.85$) due to the formation of strong normal shock discs.

The peak at $pr_n = 3.0$ can also be explained, as follows. Abbott and White [22] have extensively studied the characteristics of twin underexpanded impinging jets and shown that terminal shock waves are produced through interaction with the ground-plane (see Fig 12). The wavelength of the shock cells was found to vary with pr_n so that the position of a terminal shock relative to its adjacent shock cell also changed with pr_n. Marked changes in impingement pressure were thus found; in particular, a pr_n of 2.9 resulted in a very strong fountain flow. The previously described inter-dependency between the fountain flow and the vortex spike therefore suggests that a large vortex penetration would also result at the same pr_n.

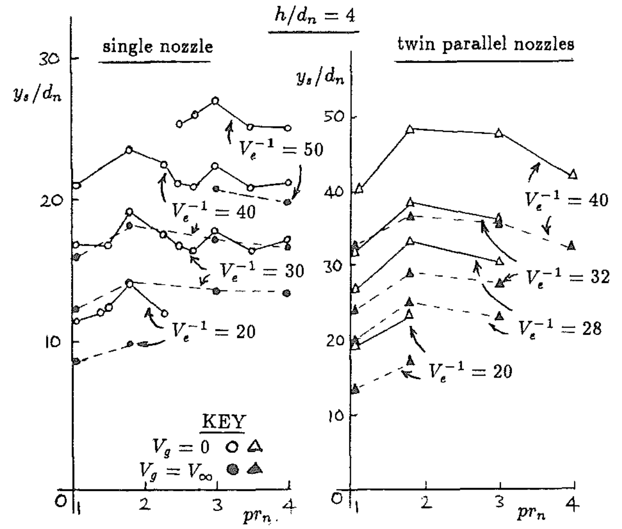

Figure 11: Nozzle pressure ratio effect for twin nozzle ground vortex

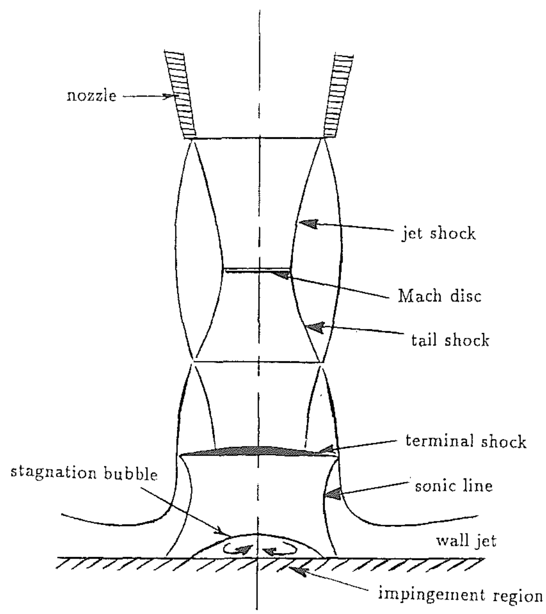

Figure 12: Characteristics of a highly underexpanded impinging jet

Moving ground-plane effects

A particularly noteworthy feature of the present authors' work has been the study of the ground vortex formed on both fixed and stationary ground-planes. The former provides an accurate simulation of the ground vortex formed when hovering in a cross-wind, while the latter simulates rolling/creeping STOL operations. The moving ground-plane condition consistently gives a marked reduction in vortex penetration, due to a combination of increased wall jet shear stresses and reduced cross-flow momentum deficit. In the case of the single nozzle ground vortex, the resultant penetration reduction has been shown to be 22.8% [14].

The experimental data for each twin nozzle configuration can also be correlated into straight line relationships passing close to the origin (see Fig 13). For the twin parallel nozzle arrangement, the effect is similar to that obtained for the single nozzle (24.2% reduction): for both configurations, there is little scatter of data.

In the case of toed-in nozzles, however, the scatter is increased while there is evidence to suggest that the overall moving ground-plane effect is slightly reduced, especially at a toe-in angle of 20°. These results suggest that a rolling/creeping landing can only be accurately simulated with moving ground-plane or moving model.

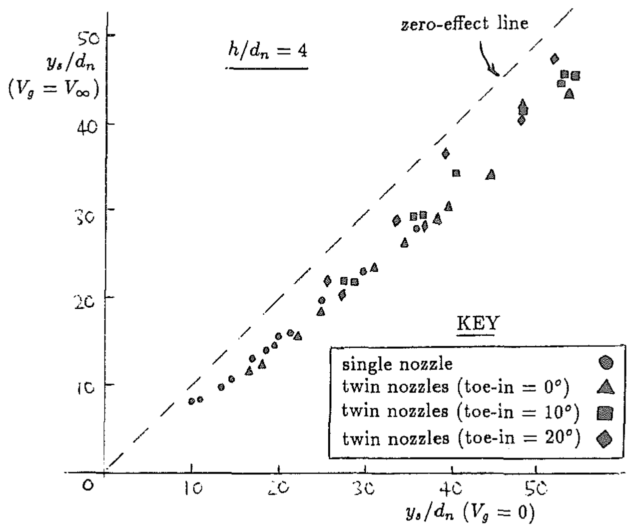

Figure 13: Moving ground-plane effect

Vector angle effects

Forward (positive) and rearward (negative) vectoring of the nozzles produces the expected increases and decreases in vortex penetration, even after taking the associated geometric changes in jet impingement position into account. Fig 14 shows the vector angle results for twin parallel nozzles, as obtained from both the flow visualisation and static pressure traverse tests. The data for each vector angle can be represented by a straight line passing through the origin, with little resultant scatter. The gradients of these lines are 1.14, 0.793 and 0.585 for vector angles of −5°, +5° and +10° respectively (i.e. penetration changes of +14%, -20.7% and -41.5%). These effects are broadly similar to those obtained for the single nozzle tests [14].

The effects vary slightly, however, when considering non-parallel nozzle configurations (not shown on Fig 14). This can be partly attributed to the changes in jet merging characteristics, due to the increased free jet lengths which result from toe-in angle variation.

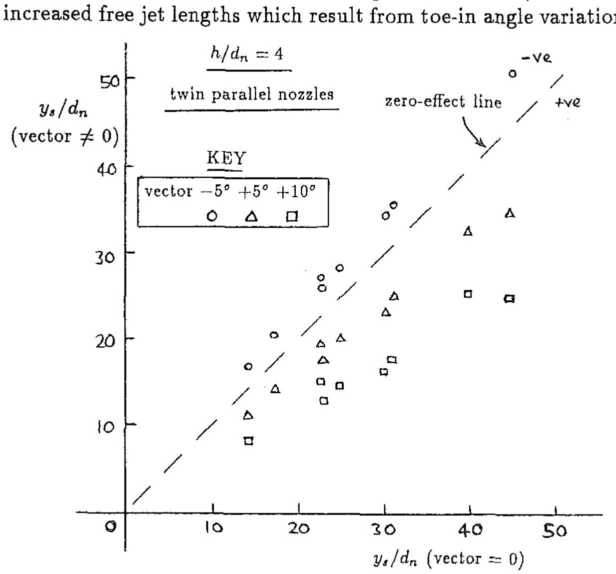

Figure 14: Twin nozzle vector angle effects

Skew angle effects

These have only been looked at for parallel twin nozzles, using both the ground-plane static pressure measurement and flow visualisation methods [15]. In all of the cases tested, there is a small, but consistent, effect (see Fig 15). The position of the residual vortex spike appears to rotate in the same direction as the applied skew angle, but to a consistently greater degree. This may be due to the forward vortex pair being deflected by the cross-flow. This also results in the peak vortex penetration occurring at an increasing distance away from the y-axis. It is emphasised, however, that the overall effects over the tested skew angle range are reasonably small compared with the observed fluctuations due to flow-field unsteadiness (as discussed below).

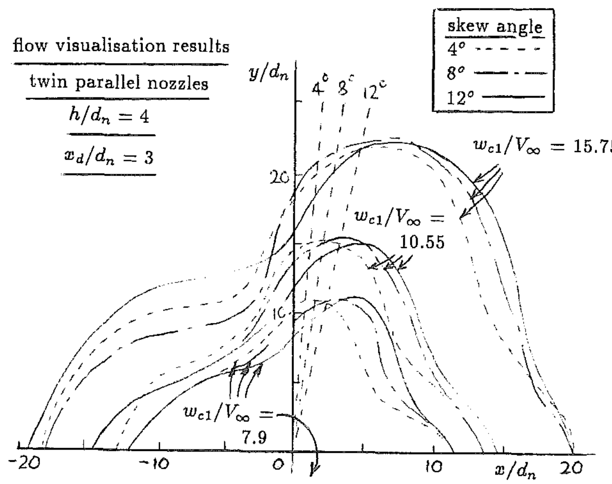

Figure 15: Skew angle effect on twin nozzle vortex profile

Flow-field unsteadiness

It was noted throughout the testing that twin nozzles produced a much more unsteady flow-field than a single nozzle. A limited number of investigations into these unsteadiness phenomena have therefore been carried out at RMCS [21]. All of this work has taken place in the large OJWT described above, with a wooden ground-board fitted on top of the rolling road. Ground-plane static pressures were measured using a miniature diffused silicon diaphragm differential transducer, flush-mounted into the board. The output signals from the transducer were amplified and put through a low-pass filter prior to being digitised and logged at a standard sampling rate of 1kHz. The following characteristics have been noted to date.

- The fountain is characterised by a low frequency broadband hump.
- The range of frequencies is wider than for a single jet, while the fluctuation levels are significantly higher.
- The spike is seen to "flip" from one side of the flow-field centre-line to the other.

More details of this experimentation are contained in Ref [21].

Comparisons with single nozzle penetration data

Fig 16 shows a comparison between the vortex penetrations for a single nozzle, twin parallel nozzles and twin toed-in nozzles (10°

and 20°) under identical operating conditions. The conditions have been chosen so that the penetration differences are maximised (i.e. at the maximum h/d_n of 8). Under these conditions, the jets from the twin parallel nozzle arrangement will be completely unmerged at ground-plane impingement. The 10° toed-in jet centre-lines will be almost merging while the 20° jets will have undergone considerable mixing by this stage.

It is clear that there are considerable differences in penetration under such circumstances. Of particular interest is the comparison between the single nozzle and 20° toed-in nozzle data; the penetrations in the latter cases are considerably smaller. This highlights the dominant rôle played by the jet merging characteristics in determining the shape and size of the resultant ground vortex.

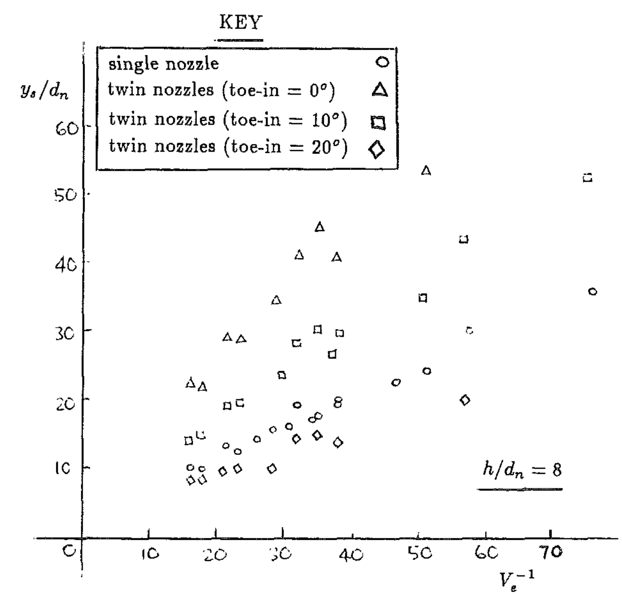

Figure 16: Comparison between vortex penetrations for different types of nozzle configurations

Conclusions

The flow-field due to twin impinging jets in a cross-flow has been studied in detail. Most investigations have been based on measurements of the ground-plane static pressure distribution; this has been found to accurately characterise the position of the forward extent of the resultant ground vortex. Supplementary data have been obtained using smoke flow visualisation with a different rig.

An exhaustive set of results has been obtained, thus enabling most of the existing parametric trends to be isolated and identified.

- The shape of the twin nozzle ground vortex can be noticeably different to the single nozzle type. The latter is regularly elliptical while there is usually a distinct protruding spike present in the former (provided that the jets do not merge before impingement). The spike appears to be due to a horizontal reinforcement of the vortex by the fountain flow; it is a highly unsteady flow-field feature.
- Parameters which affect the fountain flow therefore also greatly affect the penetration of the twin nozzle ground vortex. These include nozzle spacing distance, nozzle height above the ground and toe-in (or splay) angle. Maximum penetration occurs in cases where the jet boundaries are just merging at the ground-plane.
- Vortex penetration increases with effective jet to cross-flow velocity ratio; this is a dominant scaling factor.
- The definition of effective velocity ratio needs care, especially when considering underexpanded jets.
- The definition of nozzle exit velocity also requires careful consideration; a definition based upon the velocity existing in an equivalent fully-expanded convergent-divergent nozzle is recommended.
- Nozzle pressure ratio needs to be correctly modelled, though its precise effect is linked to the definition of effective velocity ratio that is used. Pressure ratio effects are mainly due to complex interactions between the shock cell structures and the terminal shocks produced by the ground-plane. For highly underexpanded nozzles, large total pressure losses take place across the Mach discs; this translates into significant ground vortex penetration reductions.
- A moving ground-plane (or moving model) must be used to simulate a rolling type of vertical landing. A significant reduction in vortex penetration occurs when using a moving ground-plane relative to a fixed ground-plane.
- Vector angle effects have been consistently found to be in line with expectations. A forward vectoring of the nozzles, i.e. into the cross-flow, results in an increase in vortex penetration, etc.
- Skew angle effects have been found such that the ground vortex rotates in the same direction as the applied skew, though to a consistently greater degree.

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