SCALING OF ASTOVL JET FLOW-FIELDS

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Abstract

This paper discusses some of the factors involved in the scaling of jet flowfields relevant to STOVL aircraft, especially in ground effect. The ground vortex formed by impinging jets in cross-flow is seen to scale predominantly, but not solely, with jet-to-crossflow velocity ratio. The definition of jet velocity needs care for underexpanded cases and a fully-expanded equivalent velocity is recommended here. Even using this definition, however, it is seen that the ground vortex also scales with nozzle pressure ratio, independently of velocity ratio. There is an effect of nozzle height on the ground vortex and this is discussed in the light of detailed wall jet measurements. The correct scaling of aircraft motion near the ground is shown to need a moving ground; removal of the cross-flow boundary layer is unlikely to be adequate on its own. Ground vortex unsteadiness has been investigated and seems to scale with vortex size. The characteristic "puffing" frequency of the vortex is shown to scale with cross-flow velocity ratio. The paper then discusses scaling of multiple jet flow-fields and shows that jet merging can have a strong influence on the flow-field. Finally, the need to represent intake flows on STOVL aircraft is discussed.

Notation

C_p	Pressure coefficient = $(p - p_\infty)/\frac{1}{2}\rho V_\infty^2$
D_n	Diameter of nozzle
f	Frequency
H_n,h	Height of nozzle above ground
NPR	Nozzle pressure ratio = p_o/p_∞
p_o	Nozzle stagnation pressure
p_∞	Ambient static pressure
r	Radial position along ground from nozzle centre-line
St_j	Strouhal number based on jet velocity = fD_n/V_j
St_∞	Strouhal number based on cross-flow velocity = fD_n/V_∞
V_e	Effective velocity ratio (see Eqn 1)
V_E	As V_e but with thrust-based w_{c1}
V_g	Velocity of moving ground plane
V_j	Jet velocity
V_∞	Free-stream cross-flow velocity
w_{c1}	Peak velocity at nozzle exit
x	Lateral position from flow-field plane of symmetry
x/c	Chord-wise position on wing
x_d	Twin nozzle spacing (between centre-lines)
y	Upstream position from nozzle centre-line in flow-field plane of symmetry
y_p	Ground vortex peak pressure position (Fig 3)
y_s	Ground vortex zero pressure position (Fig 3)
y_v	Ground vortex minimum pressure position (see Fig 3)
$Y_{½}$	Height in wall jet to half peak velocity
ΔC_p	Peak-to-peak static pressure fluctuation
ρ_1	Jet density at nozzle exit
ρ_∞	Freestream cross-flow density

Introduction

The design of STOVL (Short Take-Off and Vertical Landing) jet-lift aircraft is dominated by problems associated with jets in ground effect and cross-flow.[1] These problems include hot gas ingestion, suck down and jet-induced airloads. The fluid flow features which cause these problems include: jet impingement on the ground, entrainment into free and wall jets, fountain flows between multiple impinging jets and wall jet separation in cross-flow (leading to the formation of a ground vortex). Many of these flows are seen to be highly unsteady.[2] In the past scale model tests on STOVL aircraft in ground effect have been found to scale poorly to full-size, especially where hot gas ingestion is involved.[3] There is also considerable scatter in existing small-scale experiments. We have been engaged for several years on extensive experimental and computational studies of many aspects of these flows.

This paper will discuss factors which have been identified as influencing the scaling of flow-fields which involve impinging jets in cross-flow. The mean flow scaling of the ground vortex formed by a single impinging jet in cross-flow will be discussed first. Associated with this is a discussion of some of the flow physics which have been elucidated for a single impinging jet. Scaling of the unsteady characteristics of the ground vortex will then be described. Attention will then be turned to multiple jet flow-fields, including co-annular jets, before a brief discussion of jet/airframe interactions. Firstly, however, there is a brief outline of the experimental facilities used at Shrivenham for these studies of STOVL jet flow-fields.

Experimental Facilities

Over the last nine years or so, a series of experiments has been conducted by the author and his co-workers at Shrivenham.[1, 2, 4-7] All the high nozzle pressure ratio tests use Shrivenham's high pressure air supply. This is provided by two Howden screw-type compressors which can either be run in series to give 0.9kgs^{-1} at nozzle pressure ratios up to 7:1, or in parallel to give 1.8kgs^{-1} at pressure ratios up to 4:1. This is sufficient to run one 25mm diameter nozzle continuously at NPR=7, or two such nozzles at NPR=4. The results presented here, however, were mostly taken with 12.7mm diameter, conical nozzles of length 10D$_n$. In each case the compressed air is first dried and then passed to a 34m^3 receiver. This contains a heat sink so that the test air is then supplied at ambient temperature.

This compressed air supply is available to a number of facilities, including the Shrivenham 1.52m x 1.14m open-jet wind tunnel (OJWT). This wind tunnel (Fig 1) can be fitted with either fixed or moving ground simulations. The rolling road ground simulation consists of a 1.7m x 1.1m belt driven over a flat bed. This bed is provided with differential suction to control local belt flapping. This has proved particularly useful for ground vortex work, when it was necessary to increase belt suction under the forward part of the ground vortex to overcome the "lift" generated there but reduce it under the impingement point. Upstream of the rolling road is a boundary layer suction system to remove the tunnel contraction floor boundary layer. Measurements using this high-pressure facility have consisted of pitot traverses in the free and wall jets for fixed ground cases and static pressure probe traverses close to the ground for the moving ground cases. These latter have largely been confined to the flow-field plane of symmetry. Additionally, flow-visualisation has been employed. This has been limited to surface oil flow under high pressure ratio impinging jets, Schlieren for high speed jets, or the use of a separate, dedicated smoke flow visualisation rig at very low jet speeds. These, nevertheless, have provided useful insights into many flow characteristics, especially for the more complex three-dimensional cases.

Detailed, free jet and impinging jet measurements have been taken using the above compressed air facility at NPR = 1.05, with a fixed ground plane and without cross-flow.[7] This gives a nozzle exit velocity of about 90ms^{-1}. For these tests the small nozzle settling chamber is fitted with baffles and filter material. An accurate probe traverse system (end-to-end traverses to within ±75 μm) has been used for taking hot-wire measurements. The hot-wire system used is the Dantec 55P63 cross-wire probe or the Dantec 55P61 single-wire probe, together with a Dantec Constant Temperature Anemometer. The raw output voltage is digitised using 16 bit A/D converters, which are capable of holding a total of 32768 samples with sample interval times down to 20μs. The sample time is typically fixed at 15 seconds at a sample frequency of 1.0kHz, with the interval between readings of the individual wires of the cross-wire probe being 20μs.

Ground Vortex Scaling

Mean Conditions

When a free jet impinges on the ground, it forms a radial wall jet. In the presence of a cross-flow, which may be due to an ambient wind or to aircraft motion, the wall jet will separate from the ground and roll up into a so-called "ground vortex" (Fig 2). As discussed by Blake and Stewart[8], amongst others, this is not a vortex in terms of increasing local velocities closer to the core, but rather it is a turbulent separation bubble with a rotational characteristic.

The position of a ground vortex can be characterised by ground plane pressure distributions (Fig 3), which we have found[4,6] to be self-similar (Fig 4). We have measured static pressure distributions just above the ground using a traversing static pressure probe for a wide range of conditions.[4,5,6] The position of the ground vortex, characterised by any of the points shown on Fig 3, can then be plotted against various parameters of practical interest including: jet-to-cross-flow velocity ratio; nozzle pressure ratio nozzle height above the ground; cross-flow boundary layer thickness; and nozzle vector angle. These conditions have been investigated for both single and twin (side-by-side) nozzles with both fixed and moving ground planes. This latter is important in determining the difference in scaling between an aircraft hovering in a headwind and one moving through still air (close to the ground).

Contrary to some previous assumptions (see, for example, Blake and Stewart[8] who review much of the previous low-jet-velocity work in this area) we have shown[4-6] that cross-flow velocity ratio (or momentum ratio) is *not* the sole scaling parameter and that no single curve of ground vortex position versus velocity ratio can be drawn for all conditions of practical interest. This accounts for some of the scatter in existing data (Fig 5). When data for underexpanded jets are included the definitions of nozzle equivalent exit velocity and effective velocity ratio affect the degree of data collapse. Our preferred definitions are:

$$V_e = \sqrt{\tfrac{1}{2}\,\rho_\infty\, V_\infty^2 / (\tfrac{1}{2}\,\rho_1\, w_{c1}^2\,)} \qquad (1)$$

with w_{c1} defined as the velocity which would exist at the exit of a correctly-expanded convergent-divergent nozzle operated at the same nozzle pressure ratio as the convergent nozzle. We showed early in our investigations [17] that plotting vortex penetration against V_e^{-1} reduced the data scatter compared with plotting against W_j/V_∞ with W_j being a thrust-based jet velocity.

Using the definition of V_e^{-1} given by Eqn (1), we have kept velocity ratio constant and varied NPR. It can be seen (Fig 6) that there *is* an effect of pressure ratio, independent of velocity ratio. This result is significant, particularly in the light of Blake and Stewart's quite recent statement that "there has been no systematic study of nozzle pressure ratio". Our results clearly indicate that NPR is a scaling factor as well as velocity ratio. The trends in Fig 6 are not only self-consistent but are also consistent with the changes in shock structure observed for an underexpanded impinging jet[18].

A key question in the scaling of the ground vortex flowfield for aircraft hot gas ingestion considerations has been whether "pressure scaling" or "buoyancy scaling" should be used[3,19]. Curtis and Bradley[3] conclude that, although absolute levels of ingestion are not greatly different between the two scaling criteria, buoyancy scaling "is more correct" and that "this method of scaling is appropriate for use in achieving a low ingestion configuration". Penrose[19] on the other hand, whilst agreeing with Curtis and Bradley[3] on absolute levels of ingestion, expresses concern at the use of low jet velocities to simulate high NPR cases. This stems from his own company's experiments on hot gas ingestion which showed higher levels at higher NPR if the airframe being tested was particularly susceptible to ingestion. A further contribution to this debate has been made by McGuirk[20] who stated that buoyancy has no effect on the ground vortex. This was based on an experiment which he conducted: using a Reynolds-Averaged Navier Stokes code he "switched off gravity" and found no difference in the results. It should be emphasised, however, that this numerical experiment can only consider time-averaged behaviour; the physical experiments are concerned with a highly unsteady flowfield (see below).

The cross-flow boundary layer does not seem to be a significant parameter, except for very thick boundary layers[4]. Of more significance is the use of a moving ground plane to simulate a rolling vertical landing as opposed to hover in a headwind. In our experiments we found a significant reduction (22.8%) in ground vortex penetration compared to the fixed ground cases (Fig 7). This is due to a *combination* of reduced cross-flow momentum deficit and increased wall jet shear stress when the rolling road is used. It is not true that only the lack of a boundary layer contributes to this effect, as Blake and Stewart[8] suggest. This is particularly important when considering wind-tunnel testing of models in ground effect in large tunnels - control of the tunnel floor boundary layer will not provide sufficient representation of aircraft motion close to the ground.

Scaling of Wall Jets

Varying the height of the nozzle above the ground produces some unexpected effects for impinging jets in cross-flow (Fig 8). There is a general trend for the ground vortex to move *away* from the nozzle centre-line as height is initially increased, followed by a reduction in vortex penetration at high nozzle heights. This reduction at high heights seems to be due to increasing jet deflection in the cross-flow: at low nozzle heights the jet is shielded by the vortex. The initial vortex movement with increasing height is, however, somewhat surprising.

Similar trends are seen in the data of Stott[14]. The differences between these two sets of data, in particular the differing heights for peak vortex penetration, are probably due to rig interference in the cross-flow. Our rig consisted of a nozzle projecting $10D_n$ below a small, bluff plenum chamber, whereas Stott's rig had a nozzle projecting only $5D_n$ below a large, faired body. Such a body can act to "trap" the ground vortex at low heights, as described by Blake and Stewart[8].

We have conducted detailed experiments (and CFD simulations) on a single impinging jet (without cross-flow) at varying heights and pressure ratios[7]. These have revealed an effect of both parameters on wall jet momentum flux and have led to a new correlation for wall jet growth. As with previous studies[21,22] wall jet growth was measured using the height to half peak velocity, $Y_{1/2}$, and the correlation was of the form

$$Y_{½}/D_n = K(r/D_n)^a \qquad (2)$$

In our case, however, K was taken as a function of H_n/D_n and NPR. We found the effect of H_n/D_n to be greatest at low nozzle heights and quite small beyond a certain value. This was accounted for by using a two-part correlation, thus:

$$\text{for} \quad 0.0 \le \frac{H_n}{D_n} \le (5.575\ NPR - 6.9)$$

$$\frac{Y_{½}}{D_n} = \left(0.00118\ \frac{H_n}{D_n} - 0.0063\ NPR + 0.1173\right)\left(\frac{r}{D_n}\right)^{0.97} \qquad (3)$$

and

$$\text{for} \quad \frac{H_n}{D_n} > (5.575\ NPR - 6.9)$$

$$\frac{Y_{½}}{D_n} = \left(0.00005\ \frac{H_n}{D_n} + 0.1095\right)\left(\frac{r}{D_n}\right)^{0.97} \qquad (4)$$

This correlation is compared with our experimental data and two previous correlations, for varying nozzle height in Fig 9. The effect of increasing NPR is to cause a reduction of wall jet thickness.

Integration of our measured wall jet velocity profiles reveals that momentum flux increases with increasing nozzle height; it also increases (but less linearly) with increasing NPR over the range 2 to 4. These measurements are generally consistent with our observations of ground vortex parametric trends. It has been suggested that the height effect is caused by "more efficient turning" due to lower impingement velocities at higher nozzle heights.[11] To investigate this proposition we have measured peak turbulence intensity just before and just after impingement.[7] This has shown that the turbulence level just before impingement increases with increasing nozzle height but the turbulence in the initial region of the wall jet remains constant. The ratio of wall jet to free jet turbulence thus falls with increasing nozzle height, which could be taken as an indication of increasing "turning efficiency". More details of the effect of nozzle height on wall jet turbulence are given in Ref (7).

Unsteady Characteristics

Unsteadiness is a significant factor in these flow-fields, affecting hot gas ingestion and airframe and store airloads. We have characterised this unsteadiness and attempted to identify sources and scaling factors[2,24]. Our measurements were confined to a fixed ground plane using a pressure transducer located at various positions along the plane of symmetry of the flowfield produced by an impinging jet in cross-flow. Measurements were concentrated in the region of the ground vortex. The only previous time-dependent measurements in this region were those of Cimbala et al.[16,23] Using hot-wire anemometry and flow visualisation they concluded that the ground vortex is characterised by a low-frequency, broadband, "puffing" motion and that this characteristic frequency does not appear elsewhere in the flow (in the cross-flow turbulence, in the jet shear layer or in the vortex street behind the nozzle). Cimbala et al.[16,23] concluded that ground vortex unsteadiness was due to an inherent instability.

We have analysed the published data of Cimbala et al.[16,23] to try to determine scaling factors for ground vortex unsteadiness. The authors felt that the puffing frequency predominantly scaled with cross-flow velocity, with very little influence of jet velocity. Our analysis shows, however, that the varying jet velocity tests covered a velocity ratio range which was less than two-thirds of that covered in the varying cross-flow velocity tests. When Cimbala's puffing frequency is plotted against velocity ratio (Fig 10), it can be seen that the two sets of data follow very similar trends. The overall trend is, however, clarified if frequency is non-dimensionalised as a Strouhal number based on jet velocity (Fig 11). By contrast, using a Strouhal number based on cross-flow velocity does little to collapse the data (Fig 12). This contrasts with the interpretation of Cimbala et al. [23] who conclude that "the frequency of the puffing oscillation is highly dependent on freestream velocity ... and is nearly independent of jet velocity".

Our own tests have covered a much wider range of nozzle pressure ratios than those of Cimbala et al.[16,23] and have concentrated on quantifying the nature of the ground vortex unsteadiness[2,24]. Our measured surface static pressures have been spectrum-analysed and generally reveal a low-frequency broadband hump similar to that seen in the hot-wire measurements of Cimbala et al.[16,23] We have also looked at the *magnitude* of the pressure fluctuations, to investigate the scaling of this quantity. Two measures have been considered: peak-to-peak pressure fluctuation, expressed as a coefficient, ΔC_p; and standard deviation of the pressure signal, σ. We have found that pressure fluctuation level generally decays in the wall jet, moving away from the impingement point, but with local peaks in the vicinity of the ground vortex[2]. Consequently, when ΔC_p is plotted against streamwise position for all our test cases there is a wide spread of data with levels of ΔC_p depending on axial position, nozzle pressure ratio and cross-flow velocity. The use of σ does nothing to reduce this scatter. The position of the ground vortex is predominantly determined by the velocity ratio, V_e^{-1} and so this has been used to normalise the non-dimensional streamwise position. As shown in Fig 13, this has partially collapsed the data, revealing a trend for ΔC_p to reduce with increasing normalised distance until about $y/D_n = V_e^{-1}$. Our feeling is that pressure fluctuations scale predominantly with vortex size. An improved experimental procedure is needed, however, to clarify this.

Multiple Jet Flow-fields

In this section we discuss a few observations relevant to multiple-jet STOVL flowfields. We have studied twin (side-by-side) impinging jets in cross-flow both from the point of view of mean flow conditions and unsteady characteristics. Many of the findings are similar to those for the equivalent single jet cases. An important characteristic of multiple impinging jet flowfields is the reinforcement flow which occurs where two wall jets collide. Factors influencing this for a wide variety of geometries have been investigated by Miller [21,25]. In cross-flow we have shown that there is a strong influence of nozzle height on forward penetration of the ground vortex/reinforcement flow (Fig 14). This seems to be associated with jet merging (Fig 15), a conclusion which is reinforced by our results for toed-in twin nozzles (Fig 16) and twin nozzles at varying spacing (Fig 17). Thus, we might expect the details of these twin jet flowfields to be dependent on nozzle design, since this can dramatically affect free jet spreading.

We are currently investigating co-annular jets, including cases with a low-pressure ratio core and a higher pressure ratio outer flow. Initial results here suggest that, whilst inner-to-outer jet velocity ratio is important, so too is the ratio of NPRs. For an inverted-profile co-annular jet we have measured an effect of outer nozzle NPR on inner nozzle conditions. This is likely to change with impinging jet height. To what extent the two nozzle conditions affect the wall jet flow is currently being investigated; previous work on annular jets, however, has shown that the ground vortex is smaller than for an equivalent circular jet.[26]

Jet/Airframe Interactions

To produce the correct mean flow conditions under a scale model STOVL aircraft the scaling conditions identified in the previous sections need to be observed. These mean flow conditions may, however, be influenced by the flow induced by the engine air intakes and in most sub-scale wind tunnel tests on STOVL aircraft configurations the intakes are normally blanked off. This is a practical solution to the problem of simulating both jet and intake flows on small-scale models but it may neglect certain mutual interference effects. To investigate this possibility we are currently testing a generic STOVL aircraft with powered jets and intakes.[27]

With side-mounted intakes the effect of fairing them is to deflect more freestream flow past the wing, thereby changing its lift (reducing it for a high wing). There will also be an influence of the jet on the wing pressure distribution and on the intake flow (which is normally simulated separately), particularly during transition and with forward-mounted nozzles when entrainment into the jet will tend to produce a download on the wings and intakes (Figs 18 & 19). Further testing with powered intakes and jets will reveal whether there are any systematic mutual interference effects and hence show whether accurate scaling of complete aircraft flowfields requires intake simulation.

Conclusions

This paper has presented a discussion of factors which influence the scaling of jet flow-fields relevant to STOVL aircraft in ground effect, based largely on the results of the author's research group within Cranfield University. With reference to flow-field scaling the main findings are as follows.

1) Ground vortex position is heavily, but not solely, dependent on effective velocity ratio.
2) This velocity ratio should be defined in terms of dynamic pressures (Eqn 1) with nozzle exit velocity being taken as a fully-expanded equivalent velocity for underexpanded nozzles.
3) Nozzle pressure ratio should also be correctly represented since it is seen to affect ground vortex position independently of velocity ratio.
4) Aircraft motion over the ground should be simulated using a moving ground plane. Control of the wind tunnel floor boundary layer is unlikely to give an accurate representation of ground vortex location (and hence size).
5) Nozzle height is seen to have an effect on ground vortex location (independently of model interference effects) and this has been shown to be due to the influence of free jet development on wall jet growth.
6) The ground vortex is seen to be highly unsteady. There is often an identifiable dominant frequency to this unsteadiness and this frequency is seen to scale with effective velocity ratio. The magnitude of this unsteadiness seems to scale, roughly, with vortex size.
7) Twin jet flowfields are strongly influenced by jet interaction. With side-by-side jets the position at which they merge is important, which in turn implies that jet exhaust angles must be correctly represented and that spreading rates may be important.
8) Current work within the author's research group is investigating co-annular jets and mutual interference between jets and intakes on STOVL aircraft.

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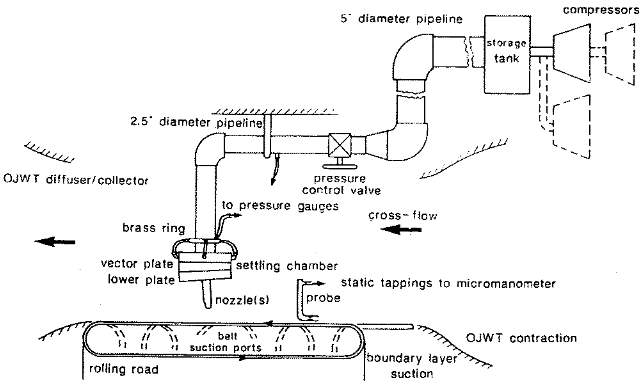
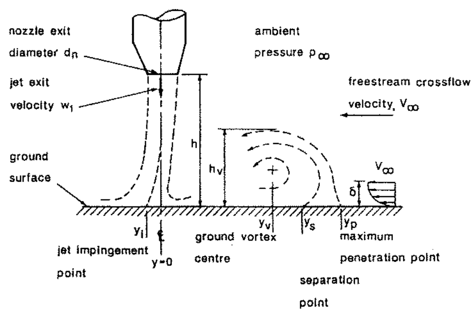
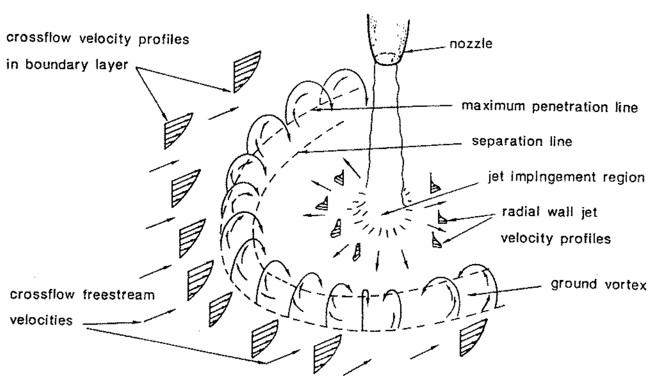


Fig 1 Schematic view of impinging jet rig in Shrivenham Open-jet Wind Tunnel



(a) Section through flow-field plane of symmetry



(b) 3-D view of ground vortex on fixed ground

Fig 2 Ground vortex formed by single impinging jet in cross-flow

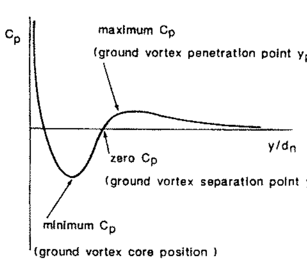


Fig 3 Ground vortex pressure distribution and characteristic points

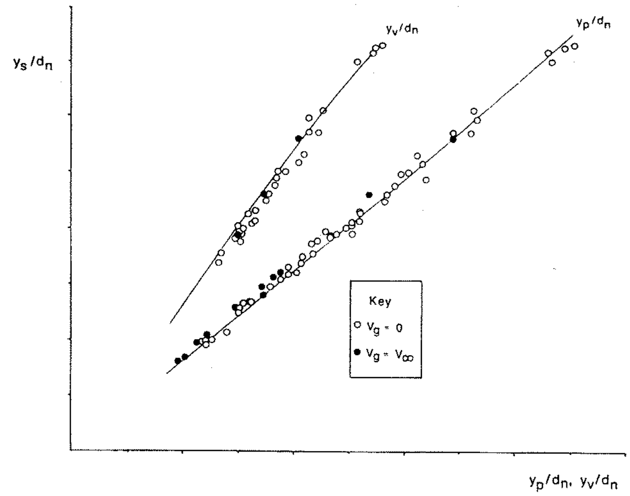


Fig 4 Ground vortex self-similarity

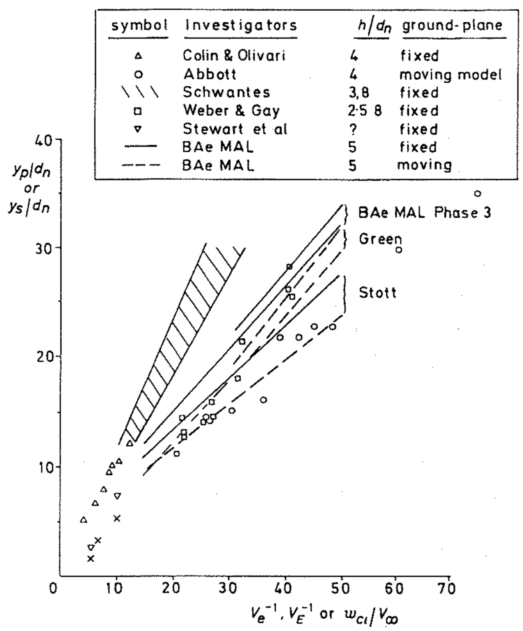


Fig 5 Ground vortex penetration - comparison of previous investigations

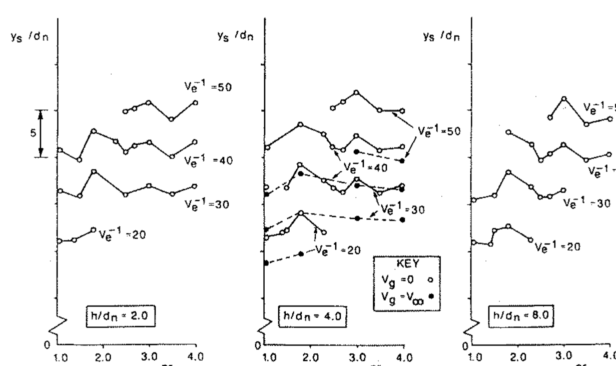


Fig 6 Effect of NPR on vortex separation position

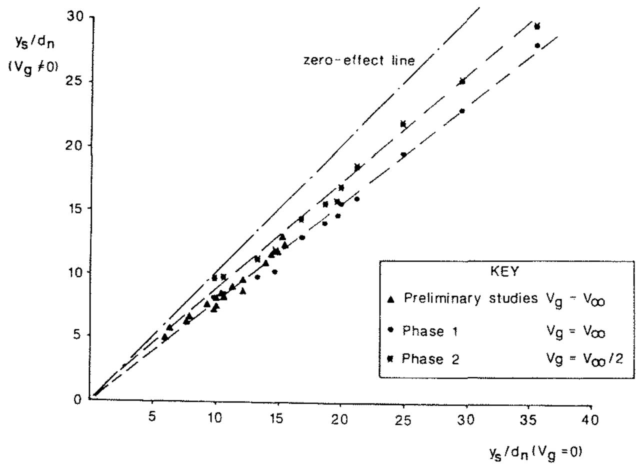


Fig 7 Effect of rolling-road on ground vortex separation distance

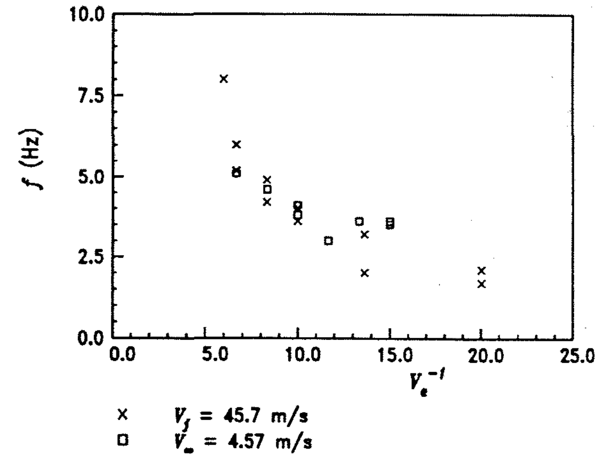


Fig 10 Scaling of ground vortex puffing frequency with effective velocity ratio

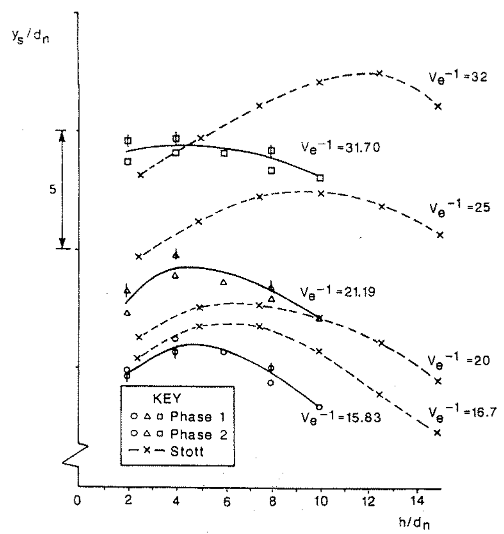


Fig 8 Effect of single nozzle height on ground vortex separation distance (NPR = 1.8)

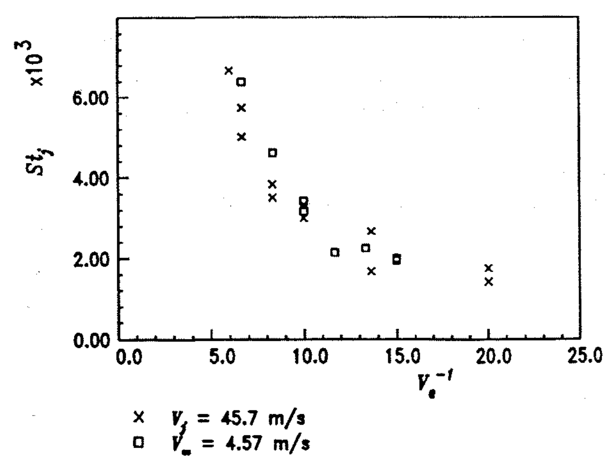


Fig 11 Scaling of ground vortex puffing frequency with effective velocity ratio and jet velocity

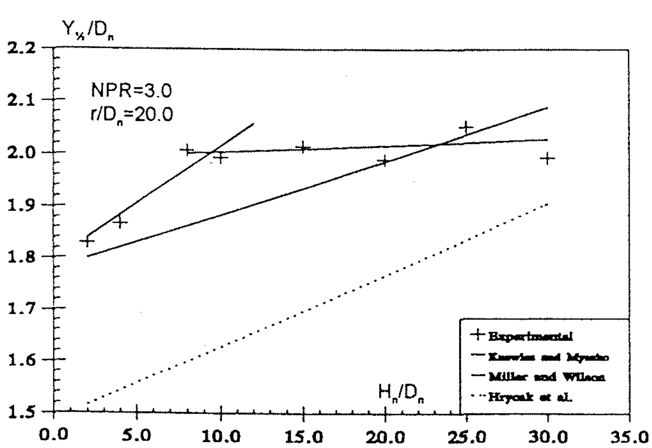


Fig 9 Correlation of wall jet half-thickness with nozzle height

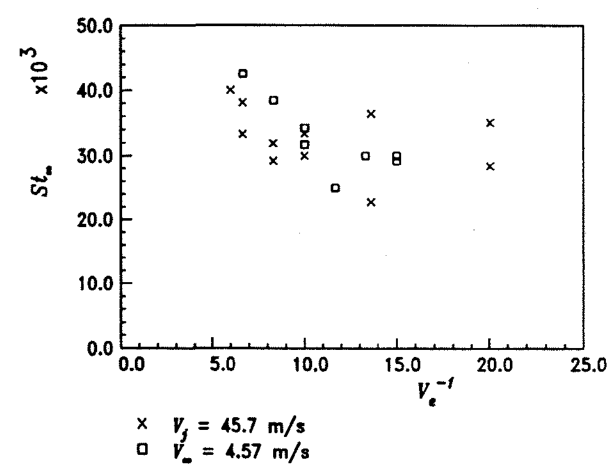


Fig 12 Scaling of ground vortex puffing frequency with effective velocity ratio and cross-flow velocity

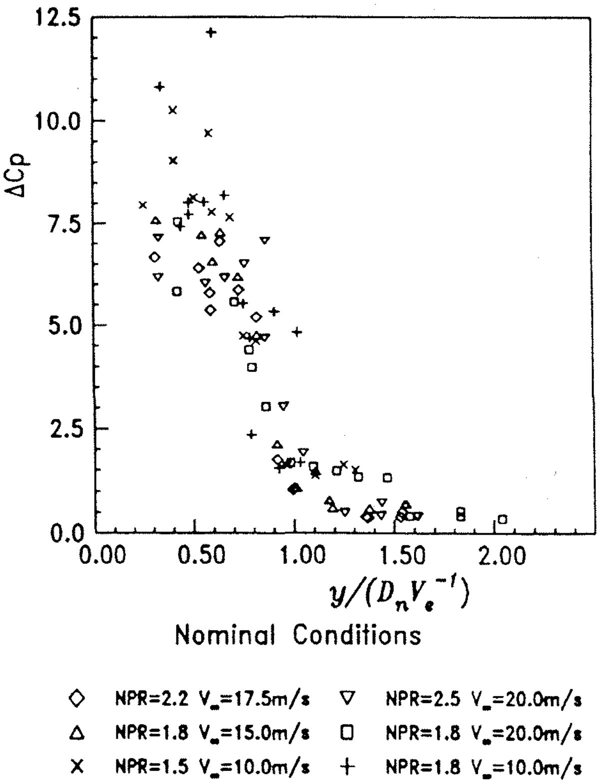


Fig 13 Scaling of ground vortex peak-to-peak pressure fluctuations with V_e

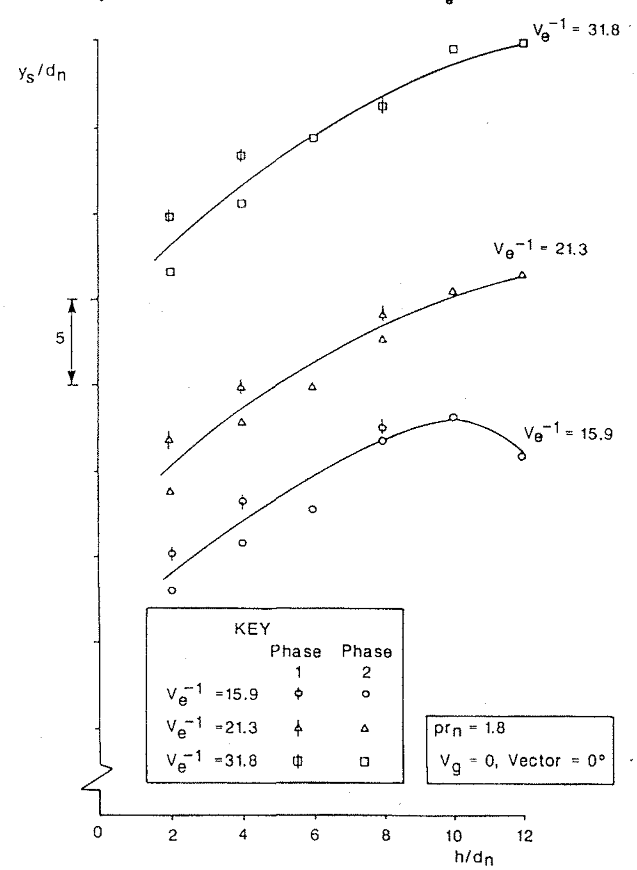


Fig 14 Effect of twin nozzle height on ground vortex separation distance

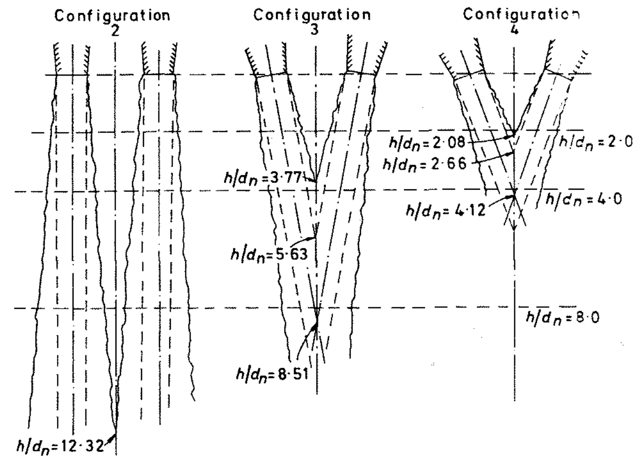


Fig 15 Twin jet merging

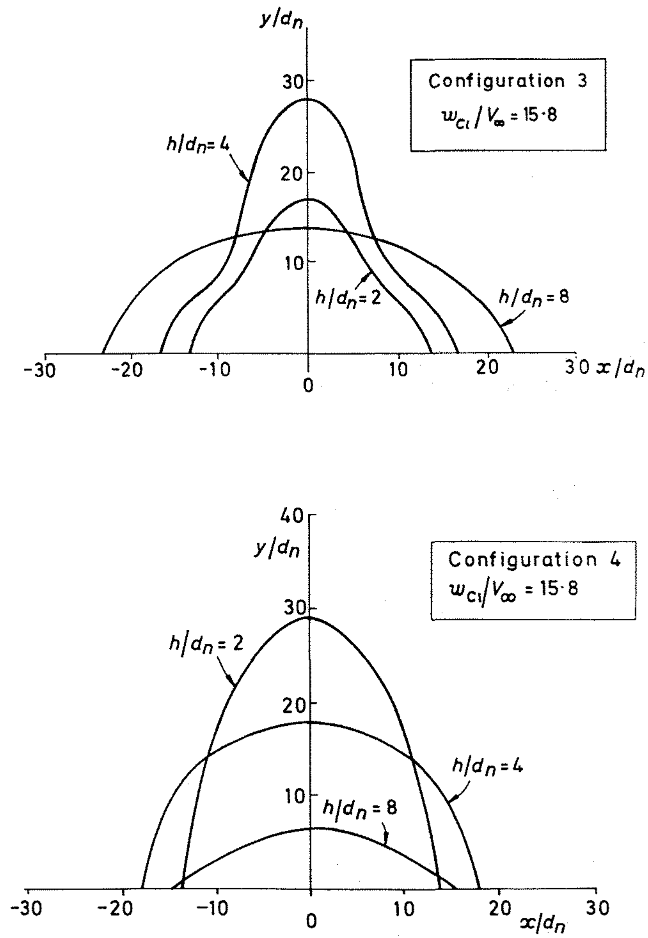
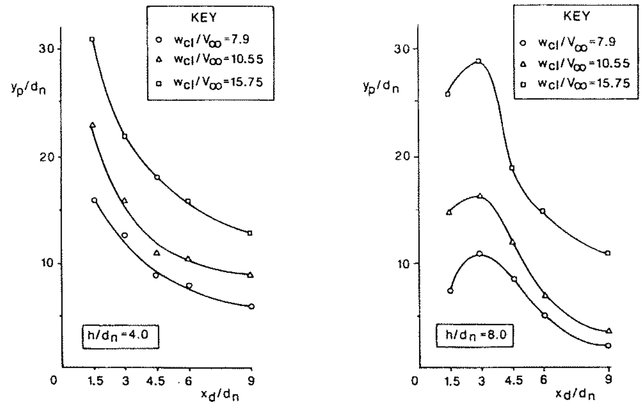


Fig 16 Ground vortex locus for twin toed-in nozzles



(a) Twin parallel nozzles

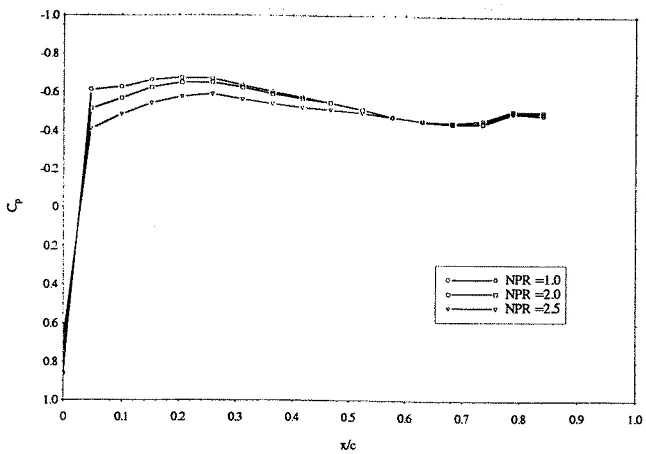
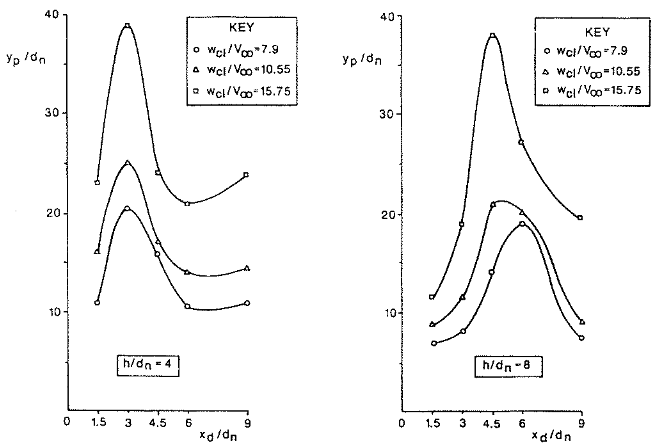


Fig 19 Wing upper surface pressure distributions for jet-off and two jet-on conditions



(b) Twin toed-in nozzles

Fig 17 Effect of twin nozzle spacing on ground vortex peak penetration

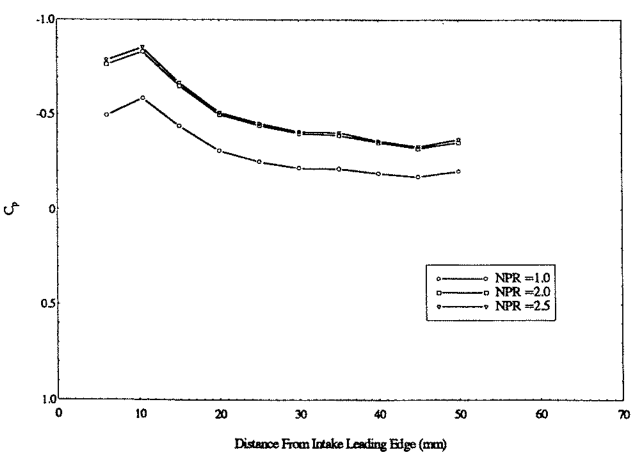


Fig 18 Intake lower surface pressure distributions for jet-off and two jet-on conditions