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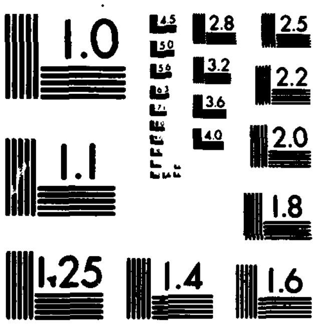

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ON THE INTERACTION OF WALL JETS AND FOUNTAIN FORMATION

K. T. Yen
Aircraft and Crew Systems Technology Directorate
NAVAL AIR DEVELOPMENT CENTER
Warminster, Pennsylvania 18974

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results in some recent works regarding the upwash angle are discussed, and it is shown that the fountain should leave the ground surface in direction perpendicular to it, and approach the upwash angle asymptotically.

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LIST OF SYMBOLS

d	Jet exit diameter
D	Distance between the impingement points of two jets
k	Strength ratio of two jets
M	Momentum flux
p	Static pressure
r	Radial distance from impingement point
R	Integration Circuit (Figure 1)
r_5	Half velocity radius of free jet
s	Shape factor of wall jet velocity profile
t	Momentum flux parameter
u	Velocity
w_c	Centerline velocity of free jet
x, y	Cartesian Coordinates
α	Angle (Figure 2)
δ	Wall jet thickness (Figure 3)
δ_t	Wall jet thickness (Figure 3)
θ	Angle (Figure 2)
λ	Ratio of shape factors ($= s_2/s_1$)
ν	Kinematic viscosity
ξ, η	Coordinates of G (Figure 2)
ρ	Density
φ	Upwash angle
ω	Angle (Figure 2)

Subscripts

0	Impact point 0
1	Jet A
2	Jet B
G	Stagnation line
m	Maximum value in wall jet

A B S T R A C T

An analysis of the fountain formation produced by the vertical impingement of two jets on a flat-ground surface is presented. A method has been developed for the determination of the upwash angle of the fountain in the plans of symmetry and the ground stagnation line. Comparison of the calculated results from the present analysis with test data obtained by the Grumman Aerospace Corporation shows generally good agreement. The different methods of approach and results in some recent works regarding the upwash angle are discussed, and it is shown that the fountain should leave the ground surface in direction perpendicular to it, and approach the upwash angle asymptotically.

INTRODUCTION

It has been established that the ground impingement of lift jets of a V/STOL aircraft in hovering flight can produce a fountain which will interact with the flow field around the aircraft and may also impact on the aircraft. The phenomena of multi-jet interaction and fountain formation have been treated by many workers including Kotansky, Durando, Bristow and Saunders (reference 1) and Wohllebe and Siclari (reference 2). Some differences appear to exist in the works regarding some aspects of the fountain formation, and the determination of the ground stagnation lines. The purpose of this work is to re-examine these problems and analyze some dynamic features of the phenomena. Sample calculations have been made to illustrate their characteristics.

MOMENTUM FLUX AND UPWASH ANGLE OF THE FOUNTAIN

A sketch of the impact of two wall jets A and B and the fountain C is shown in figure 1. The points A and B are taken to be the impingement points of the free jets at the flat surface. The point O is the "impact point," and OG is a segment of the ground stagnation line as shown in figure 2.

It is well known that in analyzing the wall jets the viscous effects must be taken into account. There are reasons to believe, however, that the impact of wall jets and fountain formation is essentially an inviscid phenomenon, and many aspects of the phenomenon can be judiciously studied accordingly. Results from such studies can be verified either experimentally or analytically by using the Navier-Stokes equations. At the present time, however, solution of the Navier-Stokes equations for general three-dimensional high-Reynolds number, turbulent flows is still not yet feasible.

Consider first the determination of the upwash angle Φ in the plane of symmetry x y , figure 1. In the section AOBC, let the total momentum flux in the x direction of the jet A to O be M_{10}, and that of the jet B be $-M_{20}$. These flux values are those of the wall jets. After the impact and merging of the jets, a single jet or fountain C is formed with an upwash angle ϕ with respect to the x axis. Let the momentum flux of the jet C be M. By the principle of conservation of momentum in the x direction over the circuit R_1 shown in figure 1,

$$M_{10} - M_{20} = M \cos\phi \tag{1}$$

Take $M = M_{10} + M_{20}$ disregarding the frictional losses. Equation (1) becomes:

$$\cos\phi = \frac{M_{10} - M_{20}}{M_{10} + M_{20}} \tag{2}$$

In reference 1, the following empirical formula for ϕ was given:

$$\tan\phi = \frac{1.56\ (M_{10}\ M_{20})^{\frac{1}{2}}}{M_{10} - M_{20}} \tag{3}$$

which is equivalent to

$$\cos\phi = \frac{M_{10} - M_{20}}{(M_{10}^{\ 2} + 0.4366 M_{10} M_{20} + M_{20})^{\frac{1}{2}}} \tag{3}$$

Equations (2) and (3) differ only in the coefficient of $M_{10}\ M_{20}$. However, equation (3) does not necessarily yield more accurate results for the upwash angle ϕ (see figure 5).

THE GROUND STAGNATION LINE

Consider now the determination of the impact point 0 and the ground stagnation line (figures 1 and 2). Assuming the flow in the impact region to be inviscid the point 0 can be considered as a stagnation point. From the Bernoulli equation:

$$p_{10} + \tfrac{1}{2}\ \rho u_{10}^{2} = p_{20} + \tfrac{1}{2}\ \rho u_{20}^{2} \tag{4}$$

Taking the static pressures p_{10} and p_{20} to be equal, the condition for determining the location of 0 is:

$$u_{10}^{2} = u_{20}^{2} \tag{5}$$

For compressible flows, the condition will be $\rho_{10}u_{10}^{2} = \rho_{20}u_{20}^{2}$.

Since the effects of viscosity and turbulence are known to be significant for wall jets (see reference 3), the use of the Bernoulli equation may open to objection. Consequently, it is more reasonable to use a momentum analysis for determining the ground stagnation line. Consider an elementary volume dsdn with height dy (see figure 1) surrounding the point G as shown in figure 2. The streamlines of the jets are taken to be radial. Flow visualization studies in e.g., reference 1, show the assumption as valid. Taking the static pressures as equal, the momentum balance normal to the direction S yields the following relation:

$$u_{1G}^{2} \sin^{2} \omega_{1} = u_{2G}^{2} \sin^{2} \omega_{2} \tag{6}$$

Evidently, the above expression reduces to equation (5) in the plane of symmetry. Thus, the jet C leaves the ground vertically as shown in figure 1, consistent with the consideration of momentum balance over the circuit R_2 with a small height dy. The inclination of the jet will approach the upwash angle ϕ asymptotically at a large distance from the impact point 0.

The angle ω_1 and ω_2 are related to θ , the inclination of ds with respect to the x-axis, by

$$\omega_1 = \theta - \alpha_1, \omega_2 = \alpha_2 - \theta$$

where α 's are the angles between the radii AG and BG and the x-axis (figure 2). The location of OG can be calculated using equation (6) written in the following form:

$$\tan \theta = \frac{\xi\left(u_{1G} \sqrt{\xi^2 + (r_2 + \eta)^2} + u_{2G} \sqrt{\xi^2 + (r_1 - \eta)^2}\right)}{u_{1G} (r_1 - \eta) \sqrt{\xi^2 + (r_2 - \eta)^2} - u_{2G} (r_2 + \eta) \sqrt{\xi^2 + (r_1 - \eta)^2}} \qquad (7)$$

where ξ and η are the coordinates of G in a coordinate system with 0 as the origin (figure 2). The calculation should start from 0 in a step-by-step manner.

In order to compute the upwash angle ϕ and the ground stagnation line using equations (2) and (7), it is necessary to determine the momentum flux and velocity field of wall jet.

WALL JETS

A theoretical analysis of turbulent wall jet spreading over a plane surface has been given by Glauert in reference 3. Experiments carried out by Bakke (reference 4), Donaldson and Snedeker (reference 5) and others (see reference 6) have substantiated Glauert's results. The velocity distribution is of the general form shown in figure 3 with the shape parameters u_m and δ, where u_m is the maximum velocity and δ is the value of height y at which $u = u_m/2$. It is known that:

$$u_m \sim r^a, \quad \delta \sim r^b, \tag{8}$$

where r is measured from the jet impingement point, and a and b are constants but dependent on the jet Reynolds number $RN = u_m \delta_t / \nu$ where δ_t is the distance between the points $u = u_m$ and $u = u_m/2$ (figure 3). A typical set of values due to Bakke is a = -1.12 and b = 0.94 for the jet RN of 3500.

Donalson and Snedeker (reference 5) found from their measurements that within a range of radial stations the momentum coefficient $u_m^2 \delta r$ is very nearly independent of r. Thus:

$$u_m^2 \delta r = t^2 w_c^2 r_5^2, \tag{9}$$

where w_c is the centerline velocity and r_5 the half-velocity radius of the free jet in the plane of impingement. The parameter t has been found to be nearly independent of r, but is a function of the impingement angle and the azimuthal position of the radius r.

SIMPLIFIED ANALYSIS OF THE GROUND STAGNATION LINE

In the following simplified analysis of the ground stagnation line, the velocities u_{10} and u_{20} in equation (7) will be assumed to be the velocity u_m of the wall jets A and B. From equation (9) and by taking $-a = b = 1$, an approximate expression for the velocity ratio

$$\frac{u_{1G}}{u_{2G}} = \frac{r_2}{k\, r_1} \tag{10}$$

is found. The parameter k is a strength ratio of the jets, i.e.,

$$k = \frac{t_2\, w_{c2}\, r_{52}}{t_1\, w_{c1}\, r_{51}} \tag{11}$$

where the subscripts 1 and 2 refer to jets A and B, respectively. The second relation for the determination of r_1 and r_2 is $r_1 + r_2 = D$, where D is the distance between the two impingement points. Equation (7) for the ground stagnation line can be written in the following form:

$$\tan\theta = \frac{\xi\left\{\frac{1}{k}\left[\xi^2 + \left(\frac{k}{1+k} + \eta\right)^2\right] + \xi^2 + \left(\frac{1}{1+k} - \eta\right)^2\right\}}{\frac{1}{k}\left(\frac{1}{1+k} - \eta\right)\left[\xi^2 + \left(\frac{k}{1+k} + \eta\right)^2\right] - \left(\frac{k}{1+k} + \eta\right)\left[\xi^2 + \left(\frac{1}{1+k} - \eta\right)\right]^2} \tag{12}$$

In the above expression, all lengths are made dimensionless in terms of D.

Figure 4 shows the calculated ground stagnation lines based on equation (12) for several strength ratio k. The Grumman test data (reference 7) are also shown. Although in obtaining equation (12) many approximations have been adopted, and, in addition, the strength ratio k is not the same as the jet diameter ratio d_2/d_1 used in Grumman's work, the calculated results and the test data are in fair agreement. The agreement appears improved if in equation (7) the velocity u_m is assumed to vary with $r^{-1.162}$. A calculated ground stagnation line from reference 1 is also reproduced in figure 4 for comparison. The results in figure 4 are for vertical impingement of the jets.

THE UPWASH ANGLE AND THE FLOW NEAR THE STAGNATION REGION

If the same approximations used in obtaining equation (12) are applied to equation (2), the result is

$$\cos \phi = \frac{1 - \lambda k}{1 + \lambda k} \tag{13}$$

where $\lambda = s_2/s_1$ and s_1 and s_2 are the shape factors for the momentum flux of the jets A and B (e.g., the momentum flux of jet A is $\rho s_1 u_{m1}^2 \delta_1 r_1$). Equation (13) can be written in the following form

$$\cos \phi = \frac{r_1 - \lambda r_2}{r_1 + \lambda r_2} \tag{14}$$

which agree with the formula given in reference 7, provided λ is taken to be equal to unity. Figure 5 shows the plot of ϕ vs. k ($\lambda = 1$). The measured values for several k's from reference 7 appear to be in fair agreement with the predicted values.

In reference 1, the total momentum flux balance (instead of the momentum flux density near the wall) is used as the condition for determining the ground stagnation line. It seems to follow from such a condition that the upwash angle will always be 90° irrespective of the strength ratio of the two jets. However, as mentioned already, an empirical formula, equation (3), was used in calculating the upwash angle in reference 1. Figure 5 shows that the empirical formula is not necessarily more accurate than equation (2) or (13).

The expression (2) for the upwash angle ϕ can be written as

$$\cos \phi = \frac{s_1 \delta_1 - s_2 \delta_2}{s_1 \delta_1 + s_2 \delta_2} = \frac{\delta_1 - \lambda \delta_2}{\delta_1 + \lambda \delta_2} \tag{15}$$

Thus, the upwash angle will be larger than 90° as long as $\delta_1 < \lambda \delta_2$. This is consistent with the free-streamline potential flow theory. Since the free-streamline velocities of both jets are the same, the momentum flux of the thicker jet will always be larger than that of the thinner jet, and the fountain will incline towards the thinner jet as shown in figure 1.

In the absence of detailed knowledge about the flow conditions near the stagnation region, many assumptions and approximations have been used in the present analysis. Comparison of the calculated results from the analysis with some test data has shown the agreement to be much better than expected. This does not prove that all the assumptions and approximations are valid under all conceivable circumstances. In particular, the use of the maximum wall jet velocity u_m in the expressions for the upwash angle and ground stagnation line was regarded as a tentative step. In fact, an estimate of the locations y_{m1} and y_{m2} of the velocities u_{10} and u_{20} based on empirical jet formulas from reference 8 yielded $y_{m1} = 1.225\ y_{m2}$ for $k = 0.75$. Thus, the condition for determining the location of the stagnation point 0 (figure 1) $u_{10}^2 = u_{20}^2$ may appear to be questionable. As a numerical example, take $k = 0.75$ and $r_1 + r_2 = 6.0$. If the difference in y_{m1} and y_{m2} is ignored, the location of the stagnation point is found to be at $r_1 = 3.39$ and $r_2 = 2.61$. If the level of momentum balance is assumed to be at y_{m2}, the results are $r_1 = 3.327$ and $r_2 = 2.673$. Test data given in reference 7 for $d_2/d_1 = 0.75$ are $r_1 = 3.33$ and $r_2 = 2.67$, suggesting that the difference in y_{m1} and y_{m2} is not a significant factor.

Surface pressure measurements made by Grumman showed the existence of negative pressure coefficients in the stagnation region for jet diameter ratio d_2/d_1 smaller than a value of 0.515. Thus, a more complete study of the flow in this region is needed.

CONCLUDING REMARKS

An analysis of some dynamic features of the jet fountain problem has been carried out in the present study. Analytical expressions for the upwash angle and the stagnation line have been derived by considering the momentum flux balance of the jets. The merged jet or fountain is shown to leave the ground vertically and approach asymptotically to the direction of the upwash angle. In reference 7, the upwash angle is taken to be the jet inclination as it leaves the ground. On the other hand, in reference 1, the condition of total momentum flux balance is used for the determination of the ground stagnation line. It appears that this condition leads to an upwash angle of 90° irrespective of the strength ratio of the jets. Evidently, additional studies, both experimental and theoretical, are needed to solve this problem.

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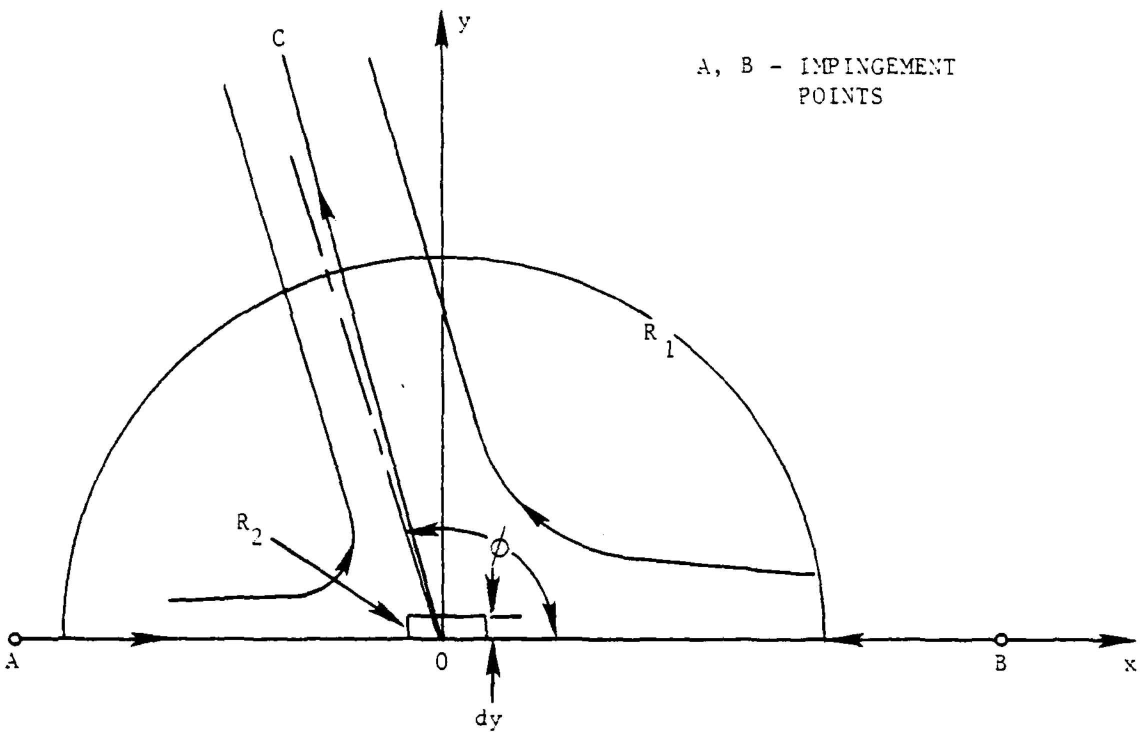

FIGURE 1 - Impact Of Wall Jets

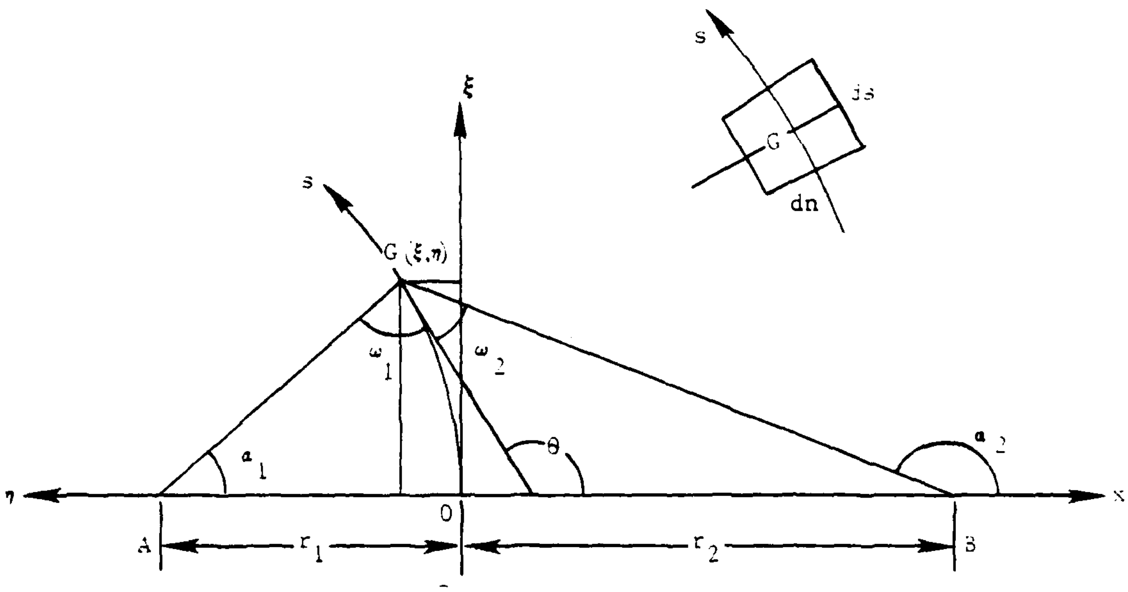

FIGURE 2 - Stagnation Line

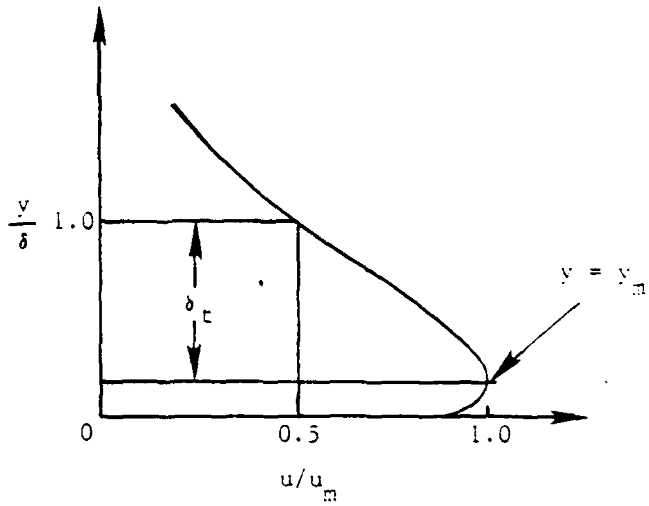

FIGURE 3 - Velocity Profile Of A Wall Jet

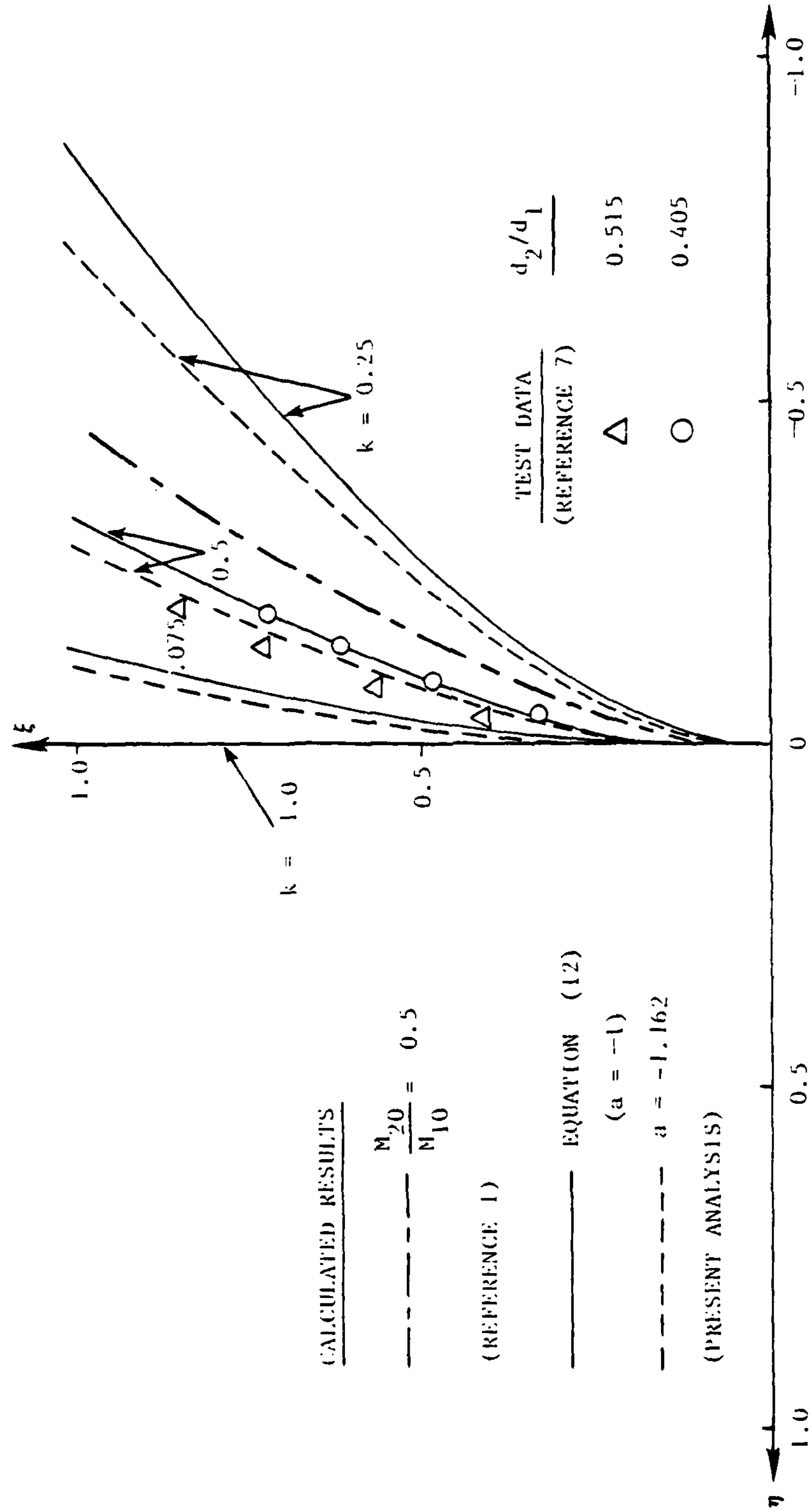

FIGURE 4 - Ground Stagnation Lines Vs. Strength Ratio of Two Jets

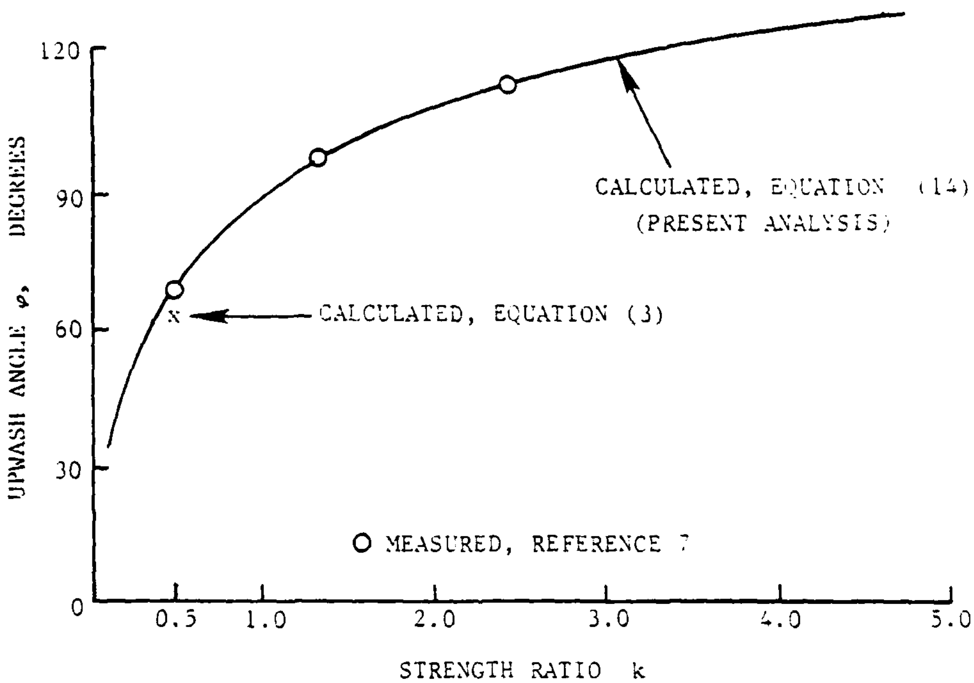

FIGURE 5 - Upwash Angle Vs. Strength Ratio Of Two Jets

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