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Entrainment by Axisymmetric Jets Impinging on a Flat Plate

- by -

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Summary

An experimental technique is described for the determination of the entrainment in an axisymmetric gaseous jet impinging normally on a flat plate situated below the nozzle.

Typical results are given of experimental work carried out using this technique for an air jet flowing into a like atmosphere of similar density.

These results suggest that the relationships describing the entrainment are:

(a) $^{m}/m_{o} = 0.3\ ^{h}/d$ for the axial jet, and

(b) $^{m}/m_{o} = 0.6\ ^{R}/d$ for the wall jet.

It is also deduced that the growth of the wall jet is described by the equation:

$\delta \propto r$ approximately.

Some experimental results are given for a jet at a higher temperature than the surrounding atmosphere.

Notation

d	=	diameter of jet orifice
h	=	height of jet orifice above flat plate
H	=	clearance between entrainment chamber and flat plate
m_o	=	nass flow rate of air to nozzle
m_1	=	mass flow rate of entrained air
m	=	total mass flow rate in jet = $m_o + m_1$
ΔP_t	=	gauge total pressure in chamber
r	=	radius of wall jet
R	=	radius of wall jet enclosed by chamber
δ	=	thickness of wall jet
ρ_o	=	density of jet
ρ_1	=	density of secondary air

Introduction

Advances made in the science of aeronautics have enabled aircraft to be designed for higher flight speeds. The consequent increase in the speeds for both take-off and landing necessitate the use of longer runways for conventional aircraft operating without such aids as assisted take-off units, braking parachutes and thrust reversors.

Another problem encountered during movements at major airports is that of noise, e.g. bye-pass engine compressor whine during the landing phase. The problem is more serious at take-off, and the engines of large jet aircraft have to be throttled back during climb over the perimeter in order to reduce the noise in the environs of the airport to an acceptable level.

These factors, together with the increasing density of air traffic, have caused designers to give more consideration to vertical and short take-off and landing (V/STOL) aircraft. One advantage offered by this type of aircraft, and which particularly commends its use for military applications, is its ability to operate from more-or-less unprepared air-strips. The ship-borne aircraft is another obvious application.

Jet engine powered V/STOL aircraft are not without their problems, however, and these may be divided into two categories, those arising during transition from vertical to horizontal flight, and those due to the effect of ground proximity. The former is basically one of stability, while the latter includes ground erosion and the associated problem of debris damaging the undercarriage, aircraft and power plants, heating of the undercarriage, tyres and landing/take-off surface (e.g. ships' decks) by the hot jet efflux, deterioration of engine performance due to ingestion of hot exhaust gases, change in thrust of the lifting engine and change in aerodynamic lift of the aircraft caused by pressure changes underneath the airframe. The effect of these pressure changes on the lift may be beneficial, negligible or adverse depending on the combined geometries of the propulsion system and aircraft. An example of the last case, for instance, is that of an aircraft having a single vertical jet, or several jets grouped close together near the centre (e.g. Bell X14, Short S.C.1) as shown in Fig. 1. Air entrained in the slipstream would flow under the airframe, causing sub-ambient pressures on the underside of the aircraft with subsequent loss of lift.

It was felt that this problem required further investigation, and consequently a programme of experimental work was carried out in order to provide information on the entrainment properties of asymmetric jets of air impinging normally on a horizontal flat plate situated below the nozzle.

Experimental Technique

The method adopted for the estimation of the entrainment was to surround the jet with a cylindrical entrainment chamber into which a secondary supply of air could be admitted (Fig. 2). It was assumed that, when the mean total pressure inside the chamber was equal to the ambient air pressure outside the chamber, then the secondary air supply was just sufficient to satisfy the entrainment appetite of the jet.

Preliminary Tests

It was found necessary to carry out two tests before the main investigation could be started. The first of these was the determination of the correct clearance (H) to be left between the bottom edge of the chamber and the upper surface of the plate.

The clearance was set according to the following assumptions:

(a) If the clearance was too small, the upper part of the wall jet, being unable to escape from the chamber, would be recirculated back and entrained once again in the jet, so reducing the secondary air requirement.

(b) If the clearance was too large, and the total pressure in the chamber equal to the ambient pressure outside the chamber, the consequent sub-ambient static pressure in the chamber would induce an inflow of air between the wall jet and the lower edge of the chamber, again reducing the secondary air requirement.

For a given jet flow, therefore, the secondary air supply required to maintain the chamber total pressure equal to the ambient pressure outside the chamber would be at a maximum when the clearance was at the optimum value. This effect is illustrated in Fig. 3.

The second test was carried out to determine the effect of the pressure ratio across the nozzle on the ratio of the mass flow rates of entrained air (m_1) and jet air (m_o).

Main Tests

The purpose of the main tests was to investigate how the mass of entrained air varied with the height of the nozzle above the plate (h) and radius of the wall jet (R). Tests were carried out over a range of non-dimensional nozzle heights ($\frac{h}{d}$) and wall jet radii ($\frac{R}{d}$) of 1-10 and 4-42, respectively, using 3 nozzles (1.0", 0.75" and 0.5" throat diameter) and 3 entrainment chambers (8", 24" and 42" diameter).

Experimental Rig

The nozzles were screwed on to the lower end of the vertical nozzle tube so that the internal and external joints offered no restriction to the jet and secondary air flows, respectively. A typical nozzle design is shown in Fig. 4.

Each chamber, which was manufactured from an aluminium alloy, was fitted with 4 air supply pipes so as to ensure a low air entry velocity, in an attempt to simulate ambient conditions as closely as possible. Additional design features incorporated to achieve this aim were the fitting of a sheet of expanded metal inside the chamber below the 4 supply pipes, and a cone of fine-mesh metal gauze below this; the cone angle being chosen such that the gauze was approximately perpendicular to the anticipated direction of air flow. On account of the higher entry velocity in the 42″ diameter chamber, circular discs of metal gauze were secured to the expanded metal immediately below the 4 supply pipes.

The mass flow rates of the air to the nozzle (m_o) and chamber (m_1) were measured with orifice plates installed in the respective supply lines, and a rake of pitot-tubes connected to a Betz manometer was used for the measurement of the total pressure (P_t) in the chamber.

Results of Preliminary Tests

The values of the clearance (H) between the entrainment chamber and plate were found to be 0.75″ and 2.4″, respectively, for the 8″ and 24″ diameter chambers, suggesting that the thickness of the wall jet (δ) was approximately proportional to its radius (r). Similar relationships have been obtained by other workers, e.g. the experimental results of Bakke (Ref. 1) showed that $\delta \propto r^{0.94}$, and Glauert (Ref. 2) found, using a theoretical approach, that $\delta \propto r^{1.015}$.

The ratio of mass flow rates of entrained air to jet air was found to be unaffected by the nozzle pressure ratio for values of the latter greater than 1.4.

Results of Main Tests

A typical set of results are presented in Fig. 5 as a plot of the ratio of total air mass flow to that in the jet ($^m/m_o$) versus the non-dimensional nozzle height ($^h/d$).

It can be seen that $^m/m_o$ increases with increase in $^h/d$, but at a progressively lower rate. This is thought to be due to the fact that the diameter of the axial jet at impingement increases as $^h/d$ increases, with a consequent reduction in the area of wall jet for entrainment, which partially offsets the increased length of the axial jet. This effect will be smaller for lower values of $^h/d$ since the jet diameter increases very little in the region of the core.

For high values of $^R/d$, the increase in axial jet diameter at impingement will have little effect on the total entrainment, and the variation in entrainment will approximate closely that for a pure axial jet. Based on this assumption, the rate of entrainment was found to be represented by the equation:

$$^m/m_o = 0.3\ ^h/d$$

This relationship agrees reasonably well with that obtained by Ricou and Spalding (Ref. 3) for an axial jet, viz:

$$^m/m_o = 0.32\ ^h/d.$$

The results have also been cross-plotted in the form, $^m/m_o$ versus non-dimensional wall jet radius $^R/d$ for constant values of $^h/d$, as in Fig. 6. It would seem reasonable to suppose that the curve for the low value of $^h/d = 1.5$ would represent, closely, a radial wall jet. Based on this supposition, the entrainment rate in a radial wall jet was found to be given by the relationship:

$$^m/m_o = 0.68\ ^R/d$$

The curves for values of $^h/d$ of 3 and 10 are displaced vertically above that for $^h/d$ of 1.5 (representing the radial wall jet) due to the additional entrainment requirements of the axial jet. The increased slopes of these two curves at low values of $^R/d$ are again due to the effect of increase in the axial jet diameter at impingement.

Other Work

Later experiments have been carried out (Ref. 4) with hot jets to investigate the effect of density on the entrainment. The results of one of these tests have been plotted in Fig. 5 in the form $(^m/m_o)(^{\rho o}/\rho_1)^{\frac{1}{2}}$ versus $^h/d$ as advocated by Searle (Ref. 5).

Conclusions

For the range of conditions covered by the tests the experimental results suggest that entrainment from a like atmosphere into an axisymmetric air jet, of similar density, impinging normally on a flat plate situated below the nozzle is given by:

(a) $^m/m_o = 0.3\ ^h/d$

for the axial portion of the jet, and

(b) $^m/m_o = 0.6\ ^R/d$

for the wall jet.

Further, the thickness of the wall jet is approximately proportional to its radius, i.e.

$\delta \propto r$ approximately.

References

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3. Ricou, F.P. and Spalding, D.B. Measurements of Entrainment by Axisymmetrical Turbulent Jets. J. Fluid Mechanics, Vol. 11, 1961, pp. 21-32.

4. Arbuckle, J.A. Investigation of Density Effects on Entrainment by Impinging Jets. College of Aeronautics Thesis 18/14, 1965.

5. Searle, N. Entrainment by Axisymmetric Jets Impinging on a Flat Plate. College of Aeronautics Thesis 17/7, 1964.

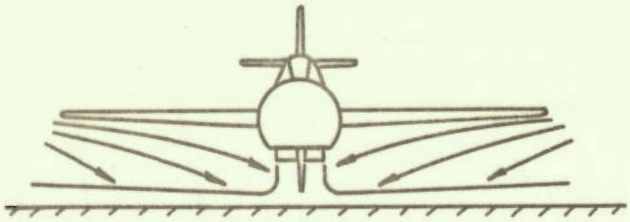

Fig. 1 UNFAVOURABLE GROUND EFFECT

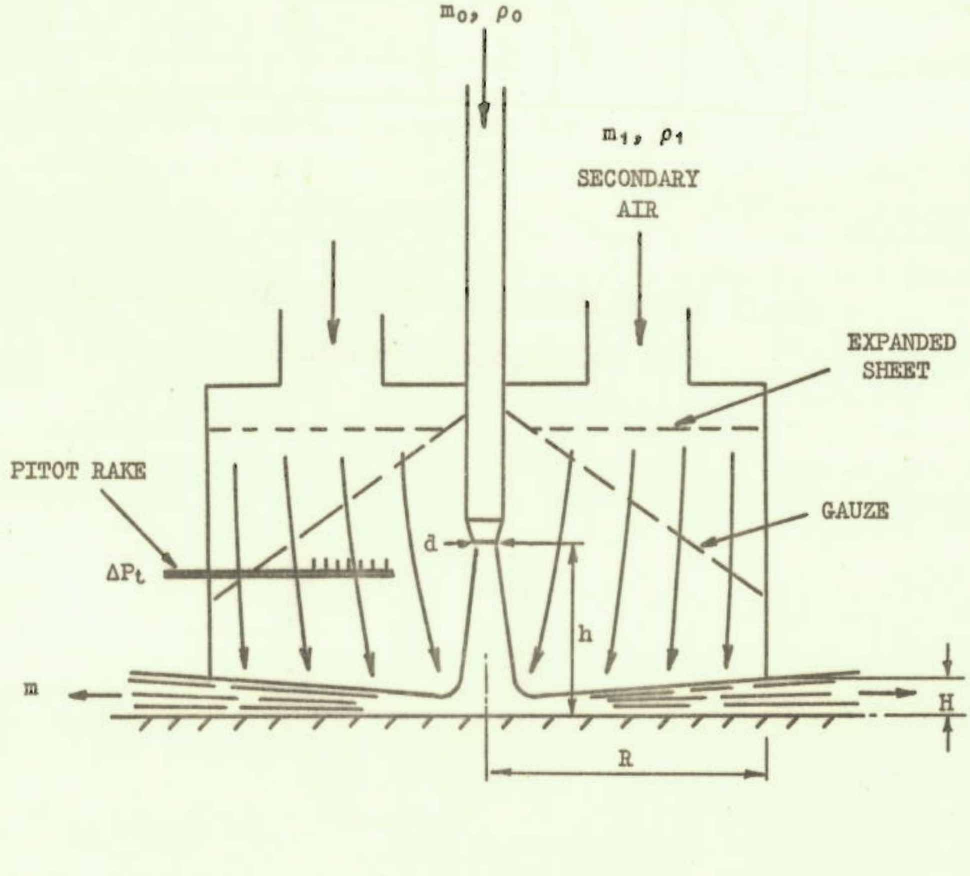

Fig. 2 EXPERIMENTAL RIG

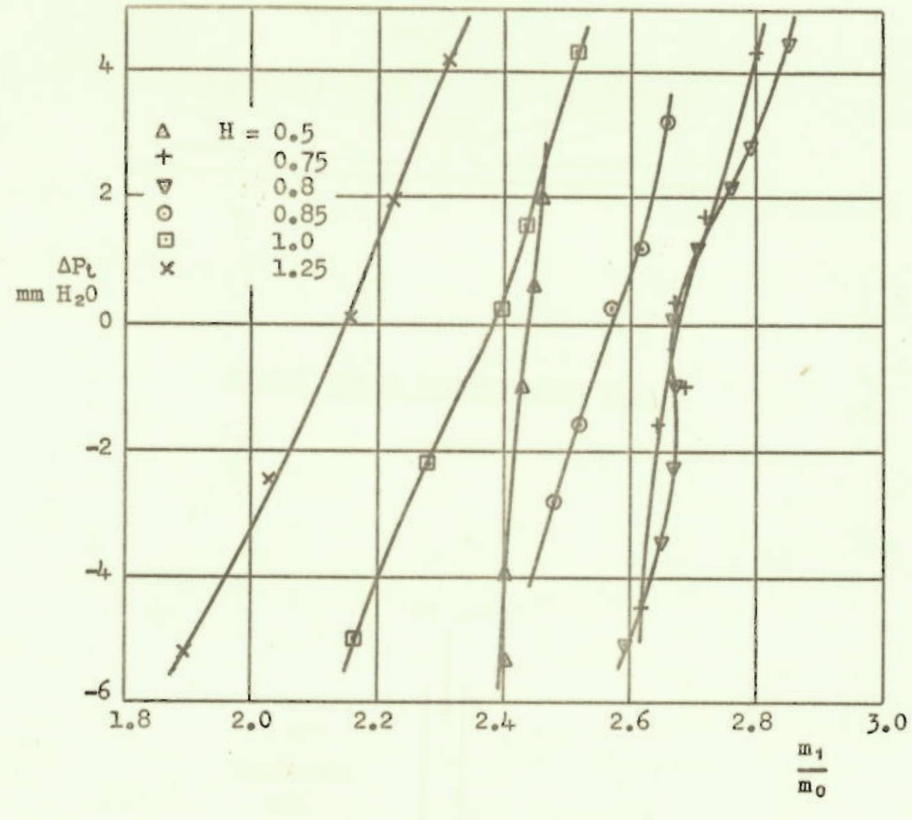

Fig. 3 TYPICAL RESULTS OF A TEST FOR THE DETERMINATION OF THE CORRECT CHAMBER HEIGHT (H)

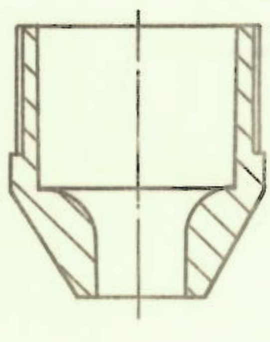

Fig. 4 NOZZLE PROFILE

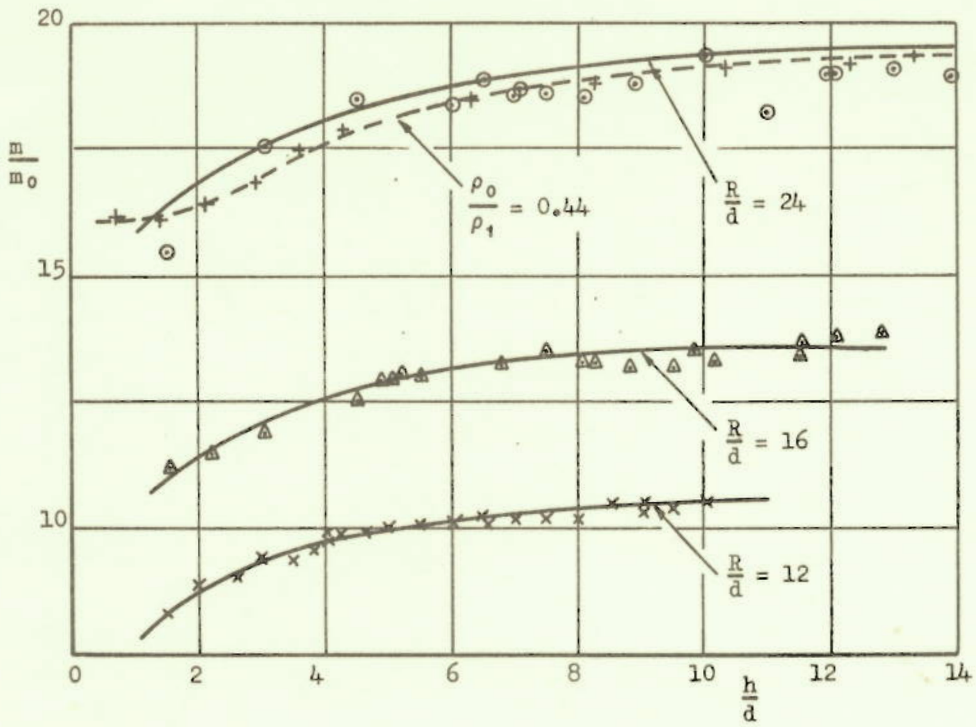

Fig. 5 TYPICAL RESULTS OF MAIN TESTS SHOWING THE VARIATION OF ENTRAINMENT WITH NOZZLE HEIGHT

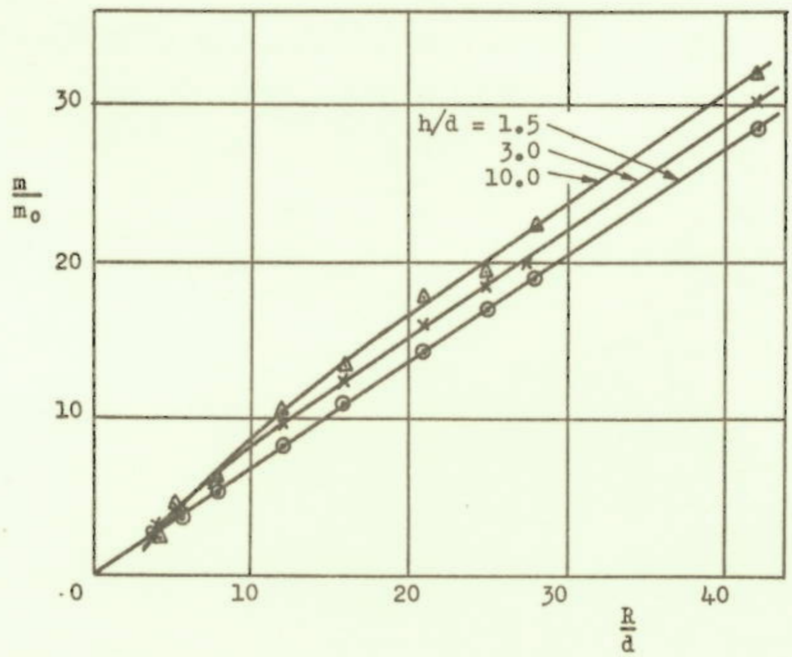

Fig. 6 TYPICAL RESULTS OF MAIN TESTS SHOWING THE VARIATION OF ENTRAINMENT WITH WALL JET RADIUS