The "Fountain Effect" and VTOL Exhaust Ingestion

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This paper presents the results of an experimental study of the ingestion and flowfield characteristics of the interaction of two parallel jets of heated air, a quiescent environment, a perpendicular "ground" plane, and a pair of inlets. The flowfield was observed visually, and the transient response of the inlet thermocouples was recorded on an oscillograph over a range of configuration and flow parameters, e.g., spacing ratios, angles, and velocities. The major contribution of this study is the obtaining of a detailed qualitative picture of the upwash flowfield and its relation to ingestion levels. Data were obtained also with the "image plane" technique (and with the addition of simulated fuselage and wings to better approximate a VTOL aircraft). Some apparent discrepancies between previous full-scale and small-scale VTOL exhaust ingestion tests are explained. This study also points out that inlet temperature fluctuations are a random process and that a statistical approach to data analysis is desirable.

Nomenclature

D = nozzle diameter
f = frequency of temperature fluctuation
H = nozzle height above ground plane
NPR = nozzle pressure ratio (= nozzle pressure/atmospheric pressure)
S = distance between nozzle exit centers
ΔT = inlet temperature rise above ambient
ΔT_m = time mean of ΔT
ΔT_j = exhaust jet temperature minus ambient temperature
V = jet exit velocity
α = nozzle cant angle
β = ground plane inclination

Introduction

AN important consideration in the design of VTOL aircraft is whether or not ingestion of the exhaust gases will occur. Ingestion of these hot gases can cause significant thrust losses and even stalling of the engines.

As is now well known, there are essentially two types of exhaust gas ingestion that are encountered in ground proximity of VTOL aircraft. These might appropriately be termed "far-field ingestion" and "near-field ingestion." Far-field ingestion occurs when the combined exhaust behaves rather like a single jet, which upon striking the ground spreads out as a wall jet for a distance of many jet diameters. The decayed wall jet is induced to move in a circulation pattern caused by a combination of sink effects (primarily due to the entrainment at the nozzle exhaust jet) and buoyancy. This can bring warmer air within the region of influence of the inlets, as shown schematically in Fig. 1a. Except when wind conditions or aircraft motion effectively aid this circulation, the path of the exhaust gases in recirculating to the inlet is long enough to bring inlet air temperatures quite close to ambient. Near-field ingestion can occur when the exhaust configuration consists of two or more split jets, as shown schematically in Fig. 1b. In this case, a "fountain" or upwash of hot gases can be generated somewhat between the jet exhausts. The hot gases in this fountain have a relatively short path to the inlets, and can accordingly be at temperatures well above ambient.

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Ingestion can cause thrust losses primarily by causing high mean inlet temperature levels. On the other hand, stall can be triggered by rapid temperature fluctuations even when mean temperature levels are quite low.[1] Thus, a designer of VTOL aircraft has to take account of expected inlet temperature levels as well as inlet temperature fluctuations in order either to eliminate or coexist with these phenomena. Large-scale tests[1,2] have shown that inlet temperature levels can indeed be very high, and that inlet temperatures can undergo large fluctuations. Such ingestion phenomena have been linked to the "fountain effect." However, some small-scale tests carried out on similar configurations have indicated an apparent lack of significant ingestion.[3-5] This could have the disturbing implication that ingestion tests, necessary to any safe design, could be carried out only on full-scale prototypes.

This paper presents the results of a study of the ingestion and flowfield characteristics of the interaction of two parallel jets, a perpendicular "ground" plane, and a pair of inlets (Fig. 2). The primary purpose of this work was to obtain a detailed understanding of the fountain effect and its relation to VTOL exhaust ingestion.

Presented herein are some data showing the results on mean ingestion levels of parametrically varying the configuration and flow characteristics. These data illustrate the sensitivity levels to parameters such as exhaust cant angle, jet velocity differential, etc. This study explains the seeming contradictions between earlier full-scale and small-scale tests men-

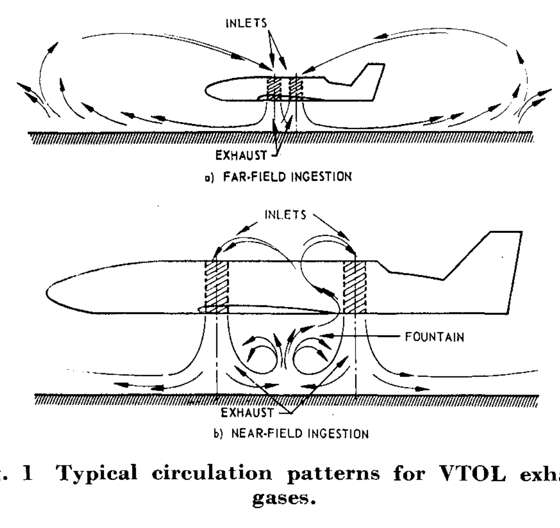


Fig. 1 Typical circulation patterns for VTOL exhaust gases.

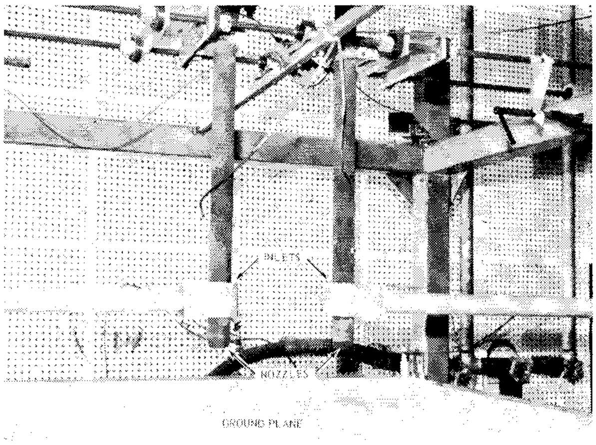


Fig. 2 Test rig.

tioned previously. It is pointed out that as ingestion and the resultant inlet temperature fluctuations arise out of random processes, a statistical approach to data analysis is desirable.

Experimental Procedure

The experiments were carried out on the test rig shown in Fig. 2. It was felt that it was important to simulate the geometry of the exhaust jets rather closely. To insure that the jets were axisymmetric and capable of being independently aligned, it was decided to generate them with straight cylindrical nozzles. The nozzles (exit diameter $D = 1\frac{1}{4}$ in.) could be moved in their own plane so as to change the inter-nozzle spacing S and both the nozzle cant angles α. The nozzles could be independently skewed out of their nominal plane in a direction perpendicular to it, and could also be moved vertically. However, the usual method for varying the nozzle to ground plane distance H was to move the ground plane itself (which was a flat asbestos board, 4 ft $\times$ 4 ft) in a vertical direction.

Air under pressure was fed into the nozzles. Each nozzle pressure ratio (NPR) could be independently varied up to 2.0. The static temperature of the heated air was usually about 500°F. However, there was provision to permit running air at ambient temperature as well.

An inlet was attached to each nozzle as shown in Fig. 2. The shape of the inlet was a semiannular ring, as shown in Fig. 3. The shape chosen for the inlets was imposed by the primary decision to use nozzles of the type shown. Although the inlets do not model typical full-scale geometries, this fact does not affect the conclusions of this study, as discussed further.

Inlet temperatures were measured with 0.005-in. iron-constantan bare-bead thermocouples positioned as shown in Fig. 3. The thermocouple output was recorded on oscillographs.

The flowfield studies utilized various visualization techniques including: smoke, tufts, vorticity meters, vanes, water-spray injection, oil-streak patterns, and sparklers.

Results and Discussion

It would perhaps be appropriate, in presenting the results, to begin with the flowfield investigation which provides the necessary insight into the ingestion studies, the results of which are presented later.

Flowfield Studies

As mentioned previously, the total qualitative picture of the flowfield was obtained by the use of a variety of techniques. The flowfield appears to be highly unsteady and complex, but nevertheless with some basic order. Documentation of some aspects of the flowfield was achieved with an oil-streak technique. A vertical plate, appropriately cut, was installed in the plane of the nozzle centerlines. Oil drops (with a luminescent additive) were placed on this plate and on the ground plane, following which the jets were turned on and the drops allowed to smear. Figure 4a shows the flow pattern corresponding to the symmetrical configuration of vertical jets, horizontal ground plane, and equal NPR's. The inter-nozzle spacing is seven nozzle diameters ($S/D = 7.0$) and the nozzle exit height is four nozzle diameters ($H/D = 4.0$).

Figure 4b shows schematically a more detailed picture of this flowfield which incorporates information obtained from all flow-visualization techniques. The flow may be divided into zones. In zone A, the flow is very similar to the wall jet arising from the interaction of a single jet with a normal plane. In zone B, the flow is very different, with a major feature being the two rather large counter-rotating vortices. The opposing flow from the two jets is forced upwards into the fountain, but the strong entrainment effects of the jets cause much of this flow to double back and form the vortices. Some of the flow carries on, where it eventually meets a downward flow moving toward the inlets and is bent back by it. The stagnation region formed here is very unstable; indeed, its existence in this instance can only be inferred.

A dramatic change takes place with the introduction of asymmetry into the configuration. Figure 5a shows the flow associated with a nozzle cant angle α of 6°. As may be seen, the left vortex has opened out, and the flow comprising it is now partially drawn into the right vortex and partially deflected over this and around the right exiting jet. The ground plane stagnation line is accordingly curved. Of major significance in this asymmetric configuration is that the direction of the flow between the jets is now directed downward because of viscous entrainment of the free air by the vortices and jets. Although the associated velocities were too low to create oil-streak patterns, visualization with smoke clearly showed that the flow was directed downwards. Figure 5b shows a more detailed picture of this flowfield, which was again determined from all the visualization techniques.

Figure 5c shows the results of increasing the asymmetry by an increase of NPR in the left jet. The pattern is essentially the same, but more of the air from the left jet now goes around the right jet. Figure 5d shows the results of raising the NPR in the left jet still further. The flow from the left has now slid under the much weaker jet on the right, as shown by the oil streaks on the vertical wall.

The loss of flow symmetry caused by small perturbations is of major interest to the ingestion problem. Thus, whereas the symmetrical fountain results in a plentiful supply of the hot exhaust gases flowing upward within the influence of the inlets, there is now in that region primarily the cooler ambient air flowing downwards. This should cause a significant drop in inlet temperature levels. Although the oil streaks show rather steady flow patterns, it must be borne in mind that at the edges of all the shear layers, the flow is highly in-

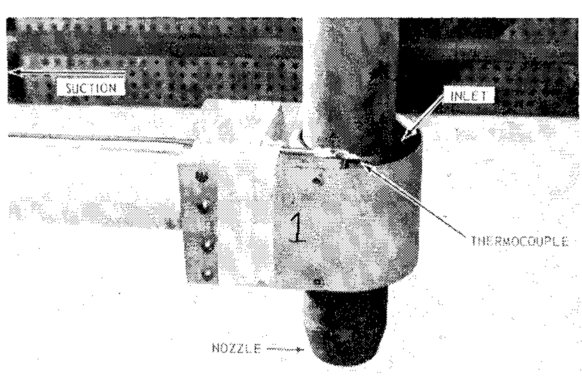
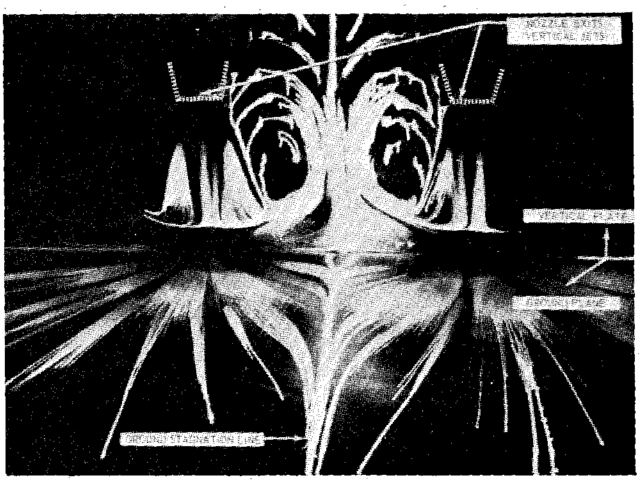
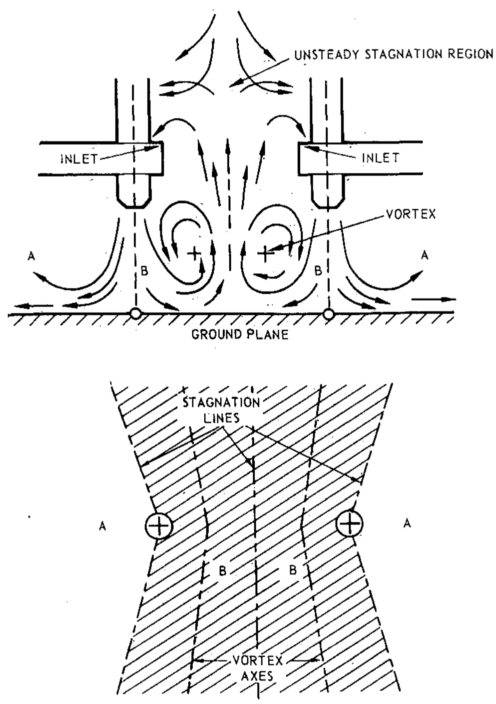


Fig. 3 Inlet with thermocouple.



a) **Oil streak visualization**

Fig. 4 Nominal flowfield with vertical nozzles.



b) **Schematic of flow**

termittent. It seems likely that this intermittent mixing will lead to significant fluctuations in inlet temperature. Also, because of this intermittency, some hot air should get into the inlets even in the asymmetric flow modes, thus causing mean inlet temperature still to be above ambient values.

The foregoing discussion has shown one cause of a lack of symmetry in the flow pattern, viz., nozzle cant. However, other factors such as NPR differential (in the absence of nozzle cant) and simulated angle of attack also result in similar changes in flow. This aspect is discussed further in the next section.

An estimate of the effect of wind on the fountain was obtained by directing a breeze parallel to the plane of the nozzles by means of a small fan. The jet exit velocities were about 1000 fps; it was found that for the nominally symmetrical configuration the velocities in the fountain at the height of the inlets were over 100 fps. A breeze from the fan of about 16 fps was sufficient to cause a complete transition from the nominally symmetrical configuration of Figure 4a to the single ground vortex flow of Figure 5a. A slower breeze of about 8 fps caused a significant shift in the fountain toward one of the inlets.

So far the flow picture that has been described is one that arises when nozzle centerlines are a few diameters apart. As physical intuition would suggest, it is found that as the nozzles are brought closer together, a critical value of spacing is reached beyond which the two jets interact with the ground very much like a combined bigger jet. This critical spacing depends on the nozzle height as discussed further below.

Ingestion Studies

Figure 6 shows some oscillograph traces of the temperature variation of the inlet thermocouples. The reference condition of operation with a single jet, but with inlets on, is shown in Fig. 6a. For this case, the inlet temperature rise ΔT is seen to be in the neighborhood of 10–20°F which, for the particular test rig/closed environment condition, can be considered the "basic" level of ingestion from which to compare the increase of ingestion severity resulting from operation with two jets.

Figure 6b shows ΔT with both jets operating for a configuration with $S/D = 7.0$ and $H/D = 4.0$ with both nozzles vertical. This configuration was taken as the nominal condition of the tests and therefore was repeated several times during the tests on various days. Comparing the results of these tests indicates excellent repeatability of inlet temperature rise histories (i.e., all runs are within 10°F of each other when proper account is taken of nozzle-supply temperature, which varied from approximately 450° to 550°F for the various runs). Based on a nondimensionalization of the inlet temperature rise ΔT with respect to the difference between jet and ambient temperature ΔT_j, the data of Fig. 6 would indicate an inlet temperature rise in the neighborhood of 200°F for turbojet exhaust temperatures. The data of Fig. 6b serve as reference data for operating conditions with both jets. The flow pattern corresponding to the configuration is, of course, that shown in Fig. 4.

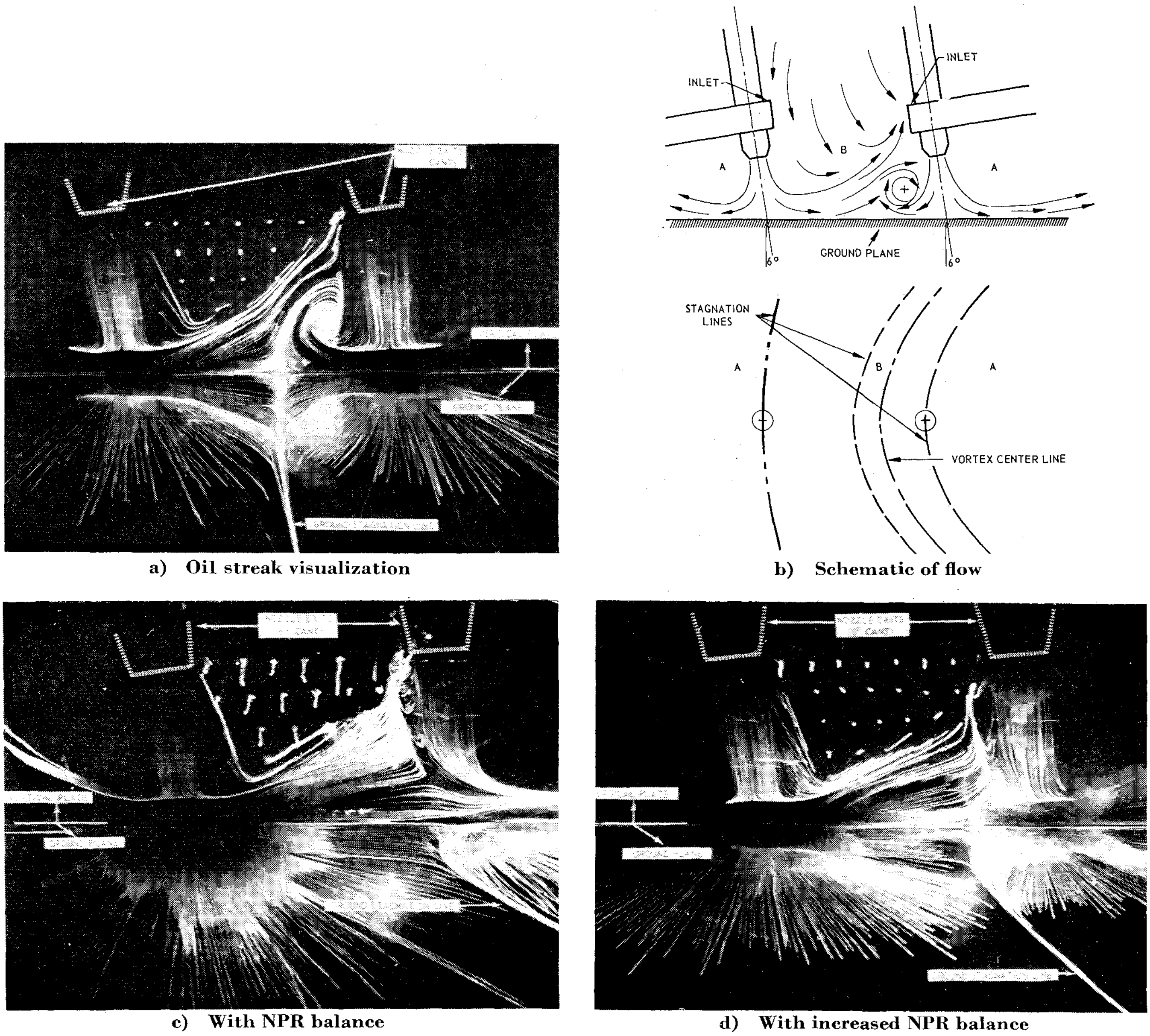
Figure 6c shows an interesting result, obtained with hot air in one nozzle and cold air in the other. The other conditions are the same as in the nominal configuration. It will be seen that the temperature rise above base level has been halved, and that both inlets have the same temperature levels. This implies that the mixing process in the fountain is very efficient. It is known that in the ground-stagnation region between the jets, heat-or-mass-transfer processes are very rapid. It appears likely that this region is also one of intense turbulent mixing between the two nozzle exit flows.

The flowfield studies suggested that nozzle canting would have a marked effect on inlet temperature levels and Fig. 6d shows that this is indeed so. With a nozzle cant α of 6°, ΔT drops to about 25°F, from the value for the nominal configuration of about 70°F, whereas it is recalled that the base level of ΔT for a single jet was 10°–20°F.

Based on limited data, it was concluded that a slight skewing (±3°) of the nozzles out of their nominal plane does not appear to affect ΔT_m significantly.

Parametric Studies

Only those parametric studies which most clearly show the relationship of the fountain to VTOL exhaust ingestion are discussed here. This is done partly for brevity and partly because a much more detailed study is now being carried out,



a) Oil streak visualization

b) Schematic of flow

c) With NPR balance

d) With increased NPR balance

Fig. 5 Flowfield with canted nozzles ($\alpha = 6°$).

which will be reported upon after completion and which examines the dependence of inlet temperature levels on a wide range of parameters.

The temperature rise data shown in these studies ΔT_m are estimated time means of the transient data obtained from oscillograph records. Figure 7 shows the effect on ΔT_m of changing configuration angle, both by changing the angle of attack (β, the ground plane angle) and the nozzle cant angle α. As may be seen, the effect is quite marked; for angles of over about 6°, the inlet temperature levels are essentially the same as the base ingestion levels due to a single jet. The effects of β change appear to be very similar to the effects of α change. The data shown are for the nominal geometrical configuration of $S/D = 7.0$ and $H/D = 4.0$. The data for other values of these spacing ratios are very similar, provided that spacing was such as to cause a fountain at zero values of α and β.

Figure 8 shows the results of NPR imbalance (or equivalently, a jet-velocity imbalance) on ΔT_m. The NPR for nozzle 2 was kept constant at 1.8 while that for nozzle 1 was varied. As would be expected, this caused a breakdown in the flow-pattern symmetry very like that due to angle change. The flow structure then became like that of Fig. 5. The effect on ΔT_m of the lack of symmetry and variation of NPR differential is evidently great. The effect on temperature levels of changing NPR's but keeping them equal for the two nozzles is much less marked, as would be expected. Thus, there is a slight increase in ΔT_m, which changes from about 70° to 90°F while the NPR's change from 1.2 to 2. This slight rise would seem to be due to the fact that higher NPR's (i.e., higher jet velocities) would tend to increase somewhat the flow of hot air in the fountain.

Figure 9 shows ΔT_m as a function of nozzle spacing for three heights above the ground plane. The inlet temperature rise is seen to be relatively independent of nozzle spacing above a critical value of spacing (which depends upon H/D), as indicated by the dashed line. At nozzle spacings less than the critical value, the two jets tended to merge before reaching the ground, thereby eliminating the strong fountain that was associated with the wider spacings.

The effect on inlet temperature levels of varying the inlet flow was also investigated for the nominal configuration ($S/D = 7.0$, $H/D = 4.0$) over a range of inlet flows corresponding to a Mach number range of 0 to 0.4. The effect of inlet flow was found to be negligible. This indicates that at least for such a geometry, the inlet has negligible influence on the two-jet interaction.

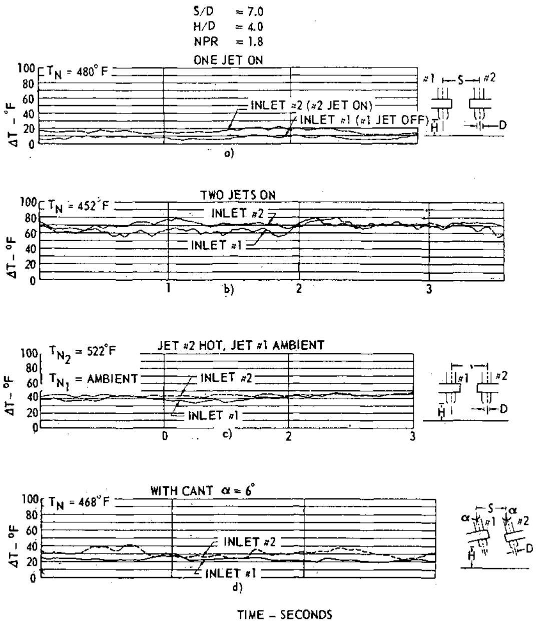


Fig. 6 Transient inlet thermocouple rise for various configurations.

On Small-Scale Modeling of VTOL Ingestion

As the foregoing discussion has shown, the fountain affects ingestion by providing a mechanism for directing a substantial upwash of hot gases. Of course, whether high inlet temperatures will actually result depends on whether the upwash subsequently meets blockages, whether the inlets are suitably positioned, etc.

The qualitative effects of a blocking airframe were also investigated in this study, some data being obtained with a centerbody being fixed between the two nozzles, and also with a further addition of simulated wings attached thereto. The resulting inlet temperature changes were qualitatively very much as expected. Thus, the centerbody by interfering with the upward flow in the fountain lowered ΔT_m by about 10°F when added to the nominal configuration ($S/D = 7.0$, $H/D = 4.0$). The addition of the "wings" further reduced ΔT_m by a similar amount.

An interesting aspect of this investigation was the attempt to resolve the major differences between the small-scale tests

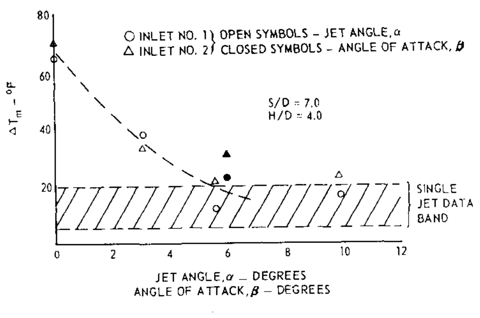


Fig. 7 Effect of jet angle relative to ground plane on inlet temperature rise.

of Speth and Ryan[3] and the full-scale tests of McLemore and Smith[1] and Lavi.[2] Two important conclusions of the small-scale study were that inlets located on the top of the fuselage of typical VTOL aircraft would experience very low ingestion temperatures (about 10°–15°F above ambient for engine exhausts of 1200°F) even in split jet configurations, and major configuration changes would not be expected to change this outcome. These findings were in direct contrast to the full-scale tests, which showed that inlet temperatures of about

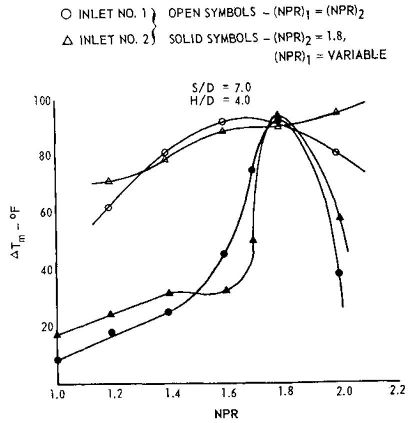


Fig. 8 Effect of pressure ratio and pressure ratio bias on inlet temperature rise.

150°F were quite commonly induced by the fountain effect, and that these temperatures were found to undergo large fluctuations. In all, the results of the full-scale tests were such as to raise serious concern about both severe thrust loss and engine stall in VTOL aircraft operating with split jet configurations in ground proximity.

The only significant procedural difference between the full-scale and small-scale tests mentioned previously seemed to be that in the latter the thermocouple readings were made by a multipoint recorder in a cyclic manner, rather than continuously on oscillographs. It was felt that, although this might mask some temperature fluctuations, it could not account for the large differences in mean temperature levels. However, on examination of a more detailed report on the small-scale study[4] it was discovered that the exhaust jets were not completely vertical but, in fact, had small cant angles of 2° and 7°. In view of the sensitivity of the structure of the fountain (and hence of ingestion temperatures) to cant angles it was decided to investigate the effect the foregoing angles would have on ingestion. Figure 10 shows the configuration that was tested at the same value of S/D as used by Speth and Ryan. Iron-constantan thermocouples made from 30-gage wire were used to measure inlet temperatures following the work of Speth and Ryan. It was found that the canting of the nozzles resulted in a highly asymmetric flow pattern with low ingestion. Figure 11 shows the variation of ΔT_m with H/D, both for the case of vertical jets and for canted jets. Temperature measurements in the latter case were also made by a Brown recorder in a cyclic fashion in addition to the oscillograph. Both methods of recording temperature yielded essentially the same temperature levels. It is obvious from this study that the major reason for the discrepancy between the aforementioned small-scale and full-scale tests is the fact that the exhausts in the former were not quite vertical. This emphasizes the importance of duplicating the details of the

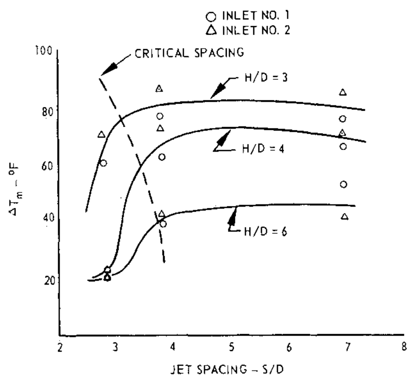


Fig. 9 Effect of jet spacing on inlet temperature rise.

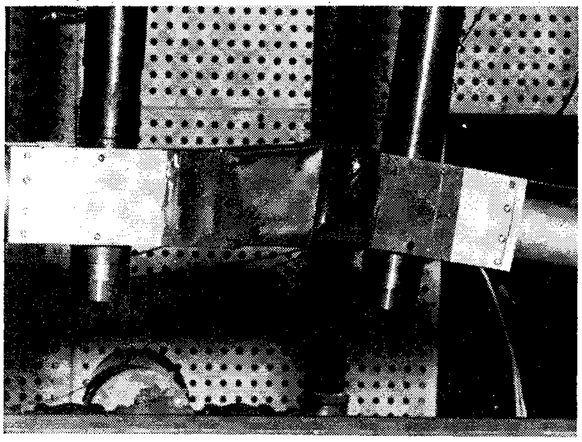


Fig. 10 Simulation of model used by Speth and Ryan.

full-scale near-field jet interactions in any small-scale test. This in turn requires close simulation of jet angles relative to each other and the ground plane, as well as simulation of relative jet momenta (i.e., usually relative NPR's). In view of the sensitivity of the ingestion results to small perturbations in geometry and flow conditions, it would seem advisable that any model study include a perturbation about nominal conditions to establish a "range of validity" of the results.

On the Validity of the Image-Plane Technique

It was decided to investigate ingestion using an image plane (Fig. 12 shows this schematically) for two reasons. Firstly, image planes have been used in small-scale ingestion studies. Secondly, in a recent small-scale study[5] in which this technique was used along with a configuration and jet temperatures similar to the present study, it was found that inlet temperatures were significantly lower than observed here, and had much less fluctuation.

It was found that the effect of the image plane (which was a flat plate clamped in the plane of symmetry) was to make the flow run up the plane as a well-defined wall jet, with a much higher velocity and lower shear-layer thickness than existed in the free fountain. Apparently, the presence of the plate prevents interaction between the opposing jet flows, which causes the fountain to become much more intermittent and to decay more rapidly. It would therefore be expected that given equal distances of the inlet from this central plane of symmetry and equal inlet flows, the faster wall jet with the image plane would contribute less to ingestion than the fountain. Figure 13 shows the variation of ΔT_m with S/D for $H/D = 3.0$, both with the two jet interaction and the image plane. The data show that the use of the image plane in models can indeed lead to significant errors in predicting inlet temperatures because of the failure to reproduce correctly the near-field flow.

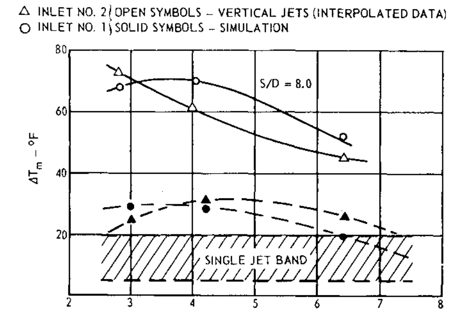


Fig. 11 Comparison of vertical jet configuration and simulated configuration of Speth and Ryan.

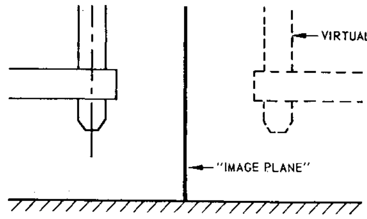


Fig. 12 Illustrating the image plane technique.

On the Statistical Analysis of Ingestion Data

As seen in Fig. 6, typical data from inlet thermocouples show random fluctuations. Although an estimate of the mean value of ΔT (i.e., ΔT_m) may be made fairly simply, any other numerical characterization of the data by inspection alone is difficult. It was felt that a spectral analysis of these data would offer the most significant method of objective characterization (i.e., a characterization independent of the observer). However, the data which had been obtained were in the form of oscillograph records, which were perhaps not of sufficient duration each run to enable reliable statistical information to be extracted. Nevertheless, the temperature histories for a few runs were analyzed.

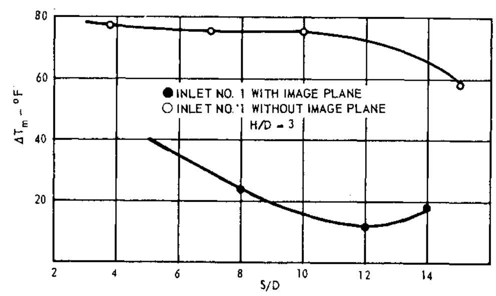


Fig. 13 Effect of image plane on inlet temperature rise.

A typical spectral analysis is shown in Fig. 14, which shows an analysis of the results obtained with $H/D = 3.0$, $S/D = 7.0$. As may be seen, there is a sharp falling off of the spectrum with increasing frequency, with almost all the temperature fluctuation being under 5 cps. Thermocouple lag could have accounted for only a very small fraction of this falling off, as the thermocouple time constant was about 35 msec. The jagged nature of the spectrum is largely due to the shortness of the sample analyzed (20-sec run).

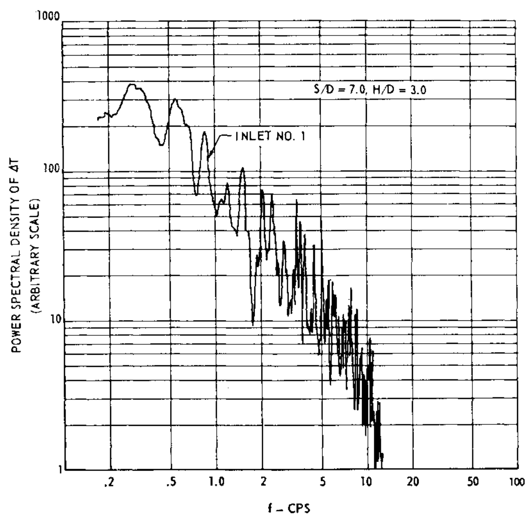


Fig. 14 Spectral analysis of ΔT for a typical run.

It is suggested that thermocouple data be subjected to spectral analysis in future studies on ingestion. Such an analysis yields the three most important items of information in the data, viz., mean temperature level, rms temperature fluctuation, and a qualitative picture of the frequency distribution. It seems reasonable, a priori, to suspect that if true similarity exists between full-scale and small-scale ingestion tests, then the spectra of an appropriate nondimensional frequency (perhaps spectra of $\Delta T/\Delta T_j$ vs Df/V) should be the same in both cases.

Conclusions

1) The qualitative nature of flowfield structure associated with the "fountain effect" has been determined in detail.

2) Inlet temperatures for split jet configurations can be very high and can show considerable fluctuation even in small-scale VTOL models.

3) In modeling ingestion phenomena, great care must be taken to duplicate the details of the full-scale near-field. This will require close simulation of jet exit angle, ground-plane angle, and relative jet momenta. On the other hand, close simulation of inlet flow conditions would not appear to be nearly so critical.

4) As ingestion is very sensitive to small perturbations in geometry and flow conditions, it is recommended that any model study include a perturbation about nominal conditions, to establish a "range of validity" of the results.

5) The image-plane technique for replacing a jet pair by a single jet and a wall at the plane of symmetry can lead to significant error in the simulation of the two jet interaction.

6) Data on VTOL inlet temperature fluctuations are random in nature, and a statistical analysis is desirable. Spectral analysis appears to be a useful method of objective characterization of such data.

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