Studies of Exhaust-Gas Recirculation for VTOL Aircraft

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The ingestion of hot, recirculated exhaust gas is an important consideration for VTOL aircraft since it can lead to serious performance penalties and engine handling problems. Model scaling laws have been established by other investigators and the reliability of the scaling has been confirmed by unpublished results of model and full-scale tests on the P.1127 VTOL strike fighter. This paper discusses the model techniques and their limitations, which have been used by Hawker Siddeley Aviation to study exhaust-gas recirculation for VTOL transport aircraft. Typical results are given from intake temperature measurements and flow visualization experiments using smoke and ground surface oil flow patterns. The results show that very useful information on the position of hot gas "fountains" can be obtained from a rudimentary half-model but that a study of transient temperatures during realistic VTOL maneuvers requires a complete, moving model. It is shown that in some circumstances a synthesis of results from a fixed model can be misleading.

Nomenclature

D = diameter
e = base of hyperbolic logarithms (2.71828)
h = height of nozzle above the ground
l = total length of gas path from nozzle to given point
p = static pressure
P = total pressure
q = dynamic pressure
r = length of gas path along the ground
t = time
T = total temperature
ΔT = total temperature minus ambient temperature
ϵ = time const
η = empirical function equal to $\frac{1}{2}(1 + \sin\theta)$
θ = angle
ρ = air density

Subscripts

f = full scale
in = intake
j = jet conditions at the nozzle
L = lift engines
m = model scale
o = ambient air
p = propulsion engines
w = wind
x = conditions at given point

1. Introduction

HAWKER Siddeley Aviation (HSA) Ltd. has a long-established interest in fixed-wing, high-speed, vertical takeoff and landing aircraft, and the HSA P.1127 VTOL strike fighter is now in production for the RAF following Tripartite trials conducted with the U.S.A. and Germany. In addition, a large number of design studies have been made for VTOL transport aircraft, and recently work has been done in collaboration with the Dornier Company of Germany on developments of the Do.31.[1] At an early stage, HSA appreciated the importance of studying the recirculation of hot exhaust gases, and, in view of the prohibitively high cost of full-scale tests, model techniques were developed in conjunction with the National Gas Turbine Establishment, which was working on the fundamental model scaling laws.[2,3]

The purpose of this paper is to describe the techniques used and the results obtained from small-scale model tests on several jet lift transport aircraft configurations. The principles are, however, applicable to all types of VTOL vehicles, including those employing very high bypass ratio lift fans such as the XV-5A.[4] The potential magnitude of the hot-gas ingestion problem may be gaged from the fact that with a uniform intake temperature distribution the engine thrust loss is approximately 3% for a 10°F rise in intake temperature and the engine jet temperature may be as high as 1700°F for a jet lift engine (see Table 1).

The aim of the HSA studies, therefore, was to find configurations that would give a minimum loss of performance due to high mean intake temperatures and which would also avoid problems of engine surge due to local temperature peaks. It was soon found to be necessary to examine these recirculation patterns, not only in a few idealized conditions, but also under all the transient conditions likely to be experienced in practice by the full-scale aircraft.

2. Scaling Laws for Model Tests

The basic scaling parameters that are used to study airflow patterns for jet flaps, thrust reversers, etc., must be re-examined for the study of hot-gas recirculation on VTOL aircraft where the long-term recirculation effects due to buoyancy forces may be important.

Cox and Abbott of the National Gas Turbine Establishment (NGTE)[2,3] have examined the influence of buoyancy and momentum forces on hot-gas recirculation, and their work has shown that the important relationships are the following:

A constant ratio of model to full-scale momentum for all jets, intake flows and wind, i.e.,

$$\frac{(P_j - p_o)_m}{(P_j - p_o)_f} = \frac{(P_{\text{in}} - p_{\text{in}})_m}{(P_{\text{in}} - p_{\text{in}})_f} = \frac{(P_w - p_o)_m}{(P_w - p_o)_f} \tag{1}$$

A constant ratio of jet temperature rise above ambient for all engines, i.e.,

$$\frac{(T_{jL} - T_o)_m}{(T_{jL} - T_o)_f} = \frac{(T_{jp} - T_o)_m}{(T_{jp} - T_o)_f} \tag{2}$$

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Table 1 Typical jet conditions for lift engines

Bypass ratio	0	4	8
Mean jet velocity, fps	2100	900	650
Mean jet temperature, °F	1700	420	260

Intake and nozzle diameters to the same scale as the aircraft, i.e.,

$$\frac{(D_{\text{in}})_m}{(D_{\text{in}})_f} = \frac{(D_j)_m}{(D_j)_f} = \text{general model scale} \quad (3)$$

The ratio of buoyancy to momentum forces to be the same on the model as full scale in order to represent correctly the effect of free thermal convection, i.e.,†

$$\left\{\frac{(P_j - p_o)T_j^{1/2}}{(T_j - T_o)D_j}\right\}_m = \left\{\frac{(P_j - p_o)T_j^{1/2}}{(T_j - T_o)D_j}\right\}_f \quad (4)$$

In Eq. (1) the use of total pressure minus ambient static pressure is recommended as a better basis for comparing jet momentum than the more usual thrust/area or $\rho_j V_j^2$ term since jet decay was found experimentally to correlate better with $P - p$ than $\frac{1}{2}\rho_j V_j^2$.

If there are two or more types of engines with different jet conditions to be represented (e.g., lift and propulsion engines), it is not possible to satisfy relationships (2) and (4) completely. In such cases it has been found that the best approach is to satisfy relationship (2) and allow relationship (4) to be violated on the jet for which buoyancy forces are less likely to be important.

The relationship between model time and full-scale time has been calculated from

$$\frac{t_f}{t_m} = \frac{[D_j/(P_j - p_o)^{1/2}]_f}{[D_j/(P_j - p_o)^{1/2}]_m} \quad (5)$$

$D_j/(P_j - p_o)^{1/2}$ has been used rather than D_j/V_j since the recirculation time is dependent on the rate of velocity decay which is again found to correlate more reliably on a $P - p$ basis.

Typical full-scale jet conditions are shown on Table 1 for three lift engines with bypass ratios from 0–8. Figure 1 shows the corresponding relationship between the model jet conditions and model scale to satisfy the Cox criterion [Eq. (4)]. Figure 1 is applicable to each of the engines shown on Table 1 since the relationship between jet velocity and temperature required by the Cox criterion is very nearly obtained in practice for a family of fan lift engines based on the same gas generator. A given rig air supply temperature and pressure can therefore be used to represent full-scale engines with a wide range of bypass ratio, although different model nozzle areas would be required to maintain a given model scale.

The choice of model jet temperature and velocity is influenced by two further considerations. 1) The jet temperature should be as high as possible to enable accurate intake temperature measurements to be made. 2) Model time should not be much faster than full-scale time. (This is particularly important if some manual movements are involved during the tests). The desirable, minimum, model jet temperature is about 200°F, if reasonable accuracy is to be achieved in the intake temperature measurements. A practical limit for the model-time-scale factor is about 2.0 (i.e., model actions twice as fast as full scale), and this restricts the use of high model jet temperatures and velocities to large models.

The correlation between full-scale measurements and the intake temperatures predicted by model tests has been checked by the NGTE using a tenth scale model of the P.1127, and the results show that the recommended relationships can be used with confidence to predict not only the correct full-scale mean intake temperature, but also the correct temperature distribution within the intake.

† This is a simplified form of the parameter given in Refs. 2 and 3 and assumes similar ambient conditions and similar exhaust gases for the model- and full-scale states.

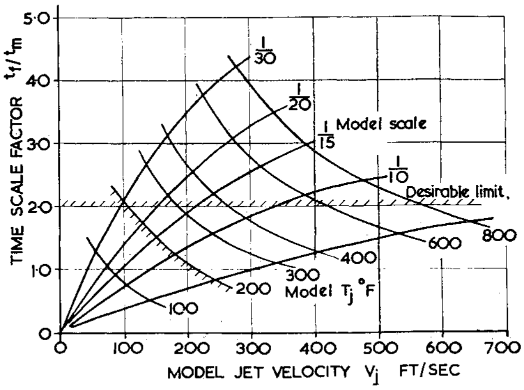


Fig. 1 Relationship between model jet parameters and model scale to satisfy the Cox criterion. Full-scale jet conditions as shown in Table 1.

3. Types of Model and Their Limitations

Three different types of model have been used for the study of hot-gas recirculation effects on VTOL transport aircraft. In each model, however, separate inlet suction and jet exhaust air supplies have been used as the simplest means of simulating the lift and propulsion engines.

3.1 High-Jet-Velocity Half-Model

Figure 2 shows the $\frac{1}{18}$th-scale half-model of the HS.129 military transport, which was designed to use nearly full-scale jet velocities and temperatures. The air supply for the jets was heated by passing it through a Bristol Siddeley Proteus combustion chamber burning paraffin. The model detail was representative of the full-scale aircraft except that small elbows were used on the lift jet outlets in place of the cascades on the full-scale aircraft. The wing was machined from "Sindanyo," a heat-resistant asbestos-type material, but the fuselage and undercarriage were constructed from untreated mahogany, which proved to be quite satisfactory despite jet temperatures on the model of 1200°F.

The advantages are 1) model scale temperatures are high and air temperatures around the model can be measured easily, and 2) the model can be used for pressure plotting to determine jet interference forces. The disadvantages are 1) model time is only $\frac{1}{18}$th of full-scale time and model is therefore not suitable for the study of transient temperatures, and 2) Cox criterion [Eq. (4)] cannot be satisfied on a model with

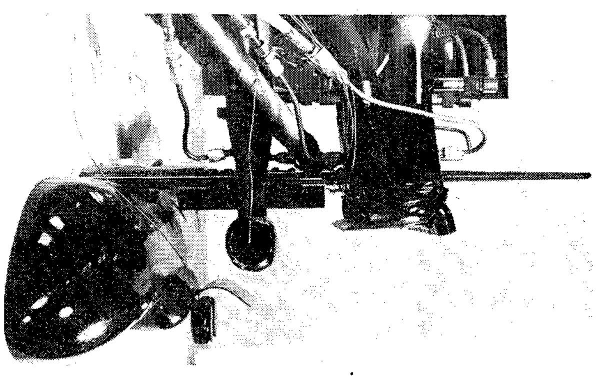


Fig. 2 HS.129 half-model ingestion rig.

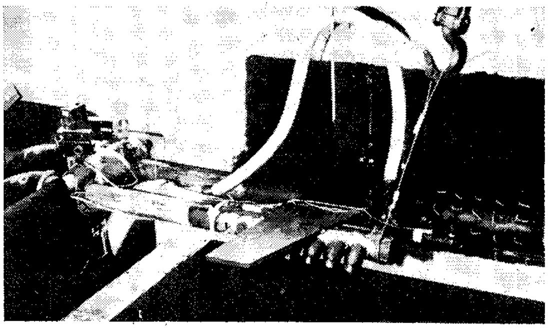


Fig. 3 Rudimentary half-model rig.

full-scale jet velocities and temperatures, and long-term recirculation effects are therefore unreliable.

3.2 Low-Jet-Velocity Half-Model Rig

Figure 3 shows the low-jet-velocity half-model rig used for general configuration studies. The rig was approximately to $\frac{1}{15}$th scale and was designed to use jet velocities of about 150 fps and jet temperatures of 230°F in accordance with the NGTE scaling rules.

This very simple rig used standard water-pipe components to represent the lift and propulsion jets and was originally only intended to produce the ground-flow patterns shown on Fig. 9. However, it was found that very useful comparative intake temperature results could also be obtained.

Since the main area of interest with this model was the recirculation of hot gas in the region between the lift and propulsion engines, the unrepresentative flow conditions on the vertical boundary wall had little influence on the results. Mean temperature readings for the lift and propulsion engines were found to agree very closely with the results from the complete model discussed in Sec. 3.3. The main difference between the full-model and half-model results lay in the intake temperature fluctuations. The half-model flow patterns were quite stable and the temperature traces were generally quite repeatable to within ±10% of temperature rise. On the full model, however, asymmetry of the flow on the two sides of the aircraft could sometimes be detected and substantial variations (±20 to 30%) were recorded in the intake temperature rise.

The advantages are 1) simplified geometry permits a wide range of configurations to be examined quickly and cheaply, 2) problems of flow instability under the fuselage are eliminated and do not mask the effect of configuration changes, and 3) quick reliable comparative answers can be obtained for near-field effects at fixed height. The disadvantages are 1) temperatures can only be assessed relatively since some important flow characteristics are not represented on a half-model, 2) fixed-height model cannot be used to measure transient temperatures, and 3) important crosswind conditions cannot be evaluated.

3.3 Low-Jet-Velocity Complete Moving Model

Figure 4 shows the complete moving model that was built to study in more detail the promising configurations shown up by the half-model rig. The complete model was also to about $\frac{1}{15}$th scale (model wing span 4 ft 6 in.) and again used low jet velocities and temperatures (lift jet velocity 180 fps, lift jet temperature about 270°F) in accordance with the Cox criterion, since it was considered important to simulate correctly the effect of buoyancy forces on the hot-gas recirculation, particularly during landing maneuvers.

The model was continuously controllable in height up to 70-ft full scale and over horizontal distances of up to 300-ft full scale. The aircraft pitch attitude could also be continuously controlled over a range of 30°. Roll and yaw angles of up to ±10° could be preset between tests. The lift-engine jets could be deflected fore and aft between ±70° from the vertical and laterally from 20° inboard of the vertical to 75° outboard. A slightly greater range of angles was available on the propulsion jets. The longitudinal and lateral jet deflections were related by means of cams so that any type of deflector geometry could be simulated by an appropriate choice of cam profile.

The intake and jet air supplies, the jet deflection and model movements were all remotely controlled from the "pilots'" console so that complete runup, takeoff, and landing maneuvers could be correctly simulated using manual movements similar to those on the full-scale aircraft. It was found to be simpler to design the model for forward movement than to conduct the tests in a rudimentary wind tunnel, since rapid and controllable changes in forward speed are required during takeoff and landing maneuvers. The moving-model technique also avoids the problem of hot gas creeping forward in the boundary layer of a wind tunnel that has a static ground board.

The advantages are 1) intake temperatures can be measured over the full range of flight maneuvers likely to be encountered in full-scale operation, and 2) reliable transient temperature studies can be made. The disadvantage is that model jet temperatures are rather low, and care is required in the control of the test cell air temperature to give a reliable datum for the measurement of small intake temperature rises.

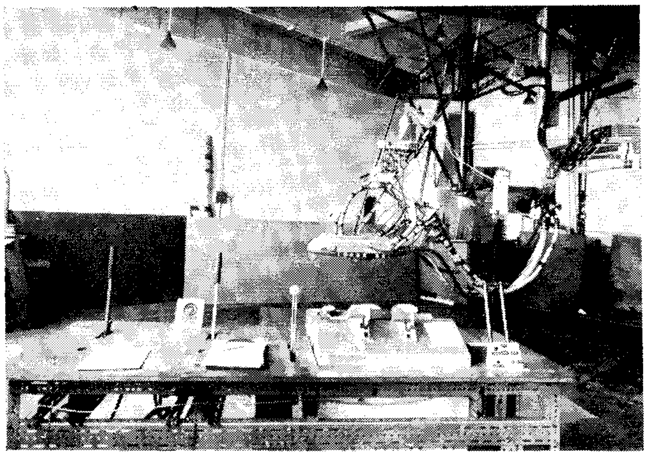


Fig. 4a Moving model rig and control console.

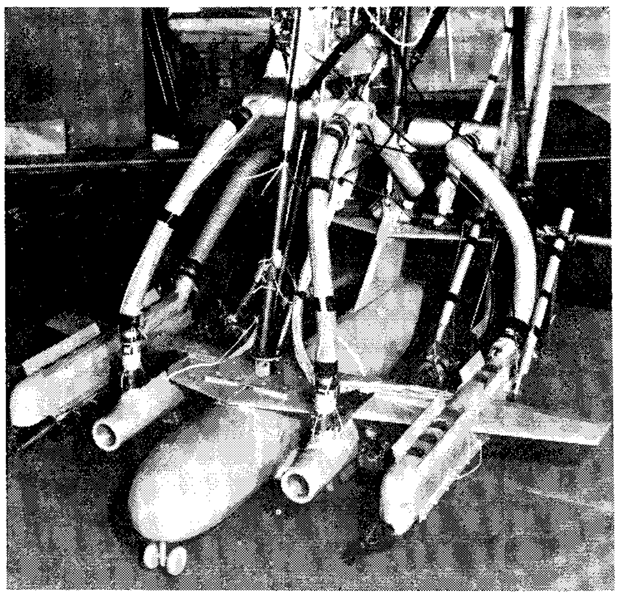


Fig. 4b Jet-lift VTOL transport model.

4. Instrumentation and Recording of Data

4.1 Temperature Measurement

In all of the tests with these models it was found that the essential requirement for a correct understanding of the results was the use of thermocouples with low response times. For the moving model the thermocouples consisted of a cromal-alumel wire junction that was made by rolling the 0.0124-in.-diam wires to a thickness of 0.001 in. and then welding them together. Figure 5 shows the response time for these thermocouples and the effect of varying the air speed over the thermocouples. Three thermocouples were connected in series in each of the propulsion intakes and, for the six-engined lift pod, in lift intakes numbers (1 and 3–6 on the port side and the numbers 2 and 5 on the starboard side). There were also three thermocouples in each of the suction manifolds of the two lift engine pods. Further thermocouples measured the temperature of the air supplied to the nozzles and the ambient temperature. The signals from the thermocouples were fed to mirror galvometers for recording on a 50-channel uv recorder.

4.2 Engine Thrust

Lift and propulsion engine thrust were recorded on the uv recorder from the outputs of suitably calibrated pressure transducers with pickups in the lift and propulsion pods.

4.3 Model Movements

All model displacements and horizontal and vertical velocities were continuously recorded on the uv recorder. Linear inductors were used to measure aircraft pitch attitude and lift and propulsion engine jet deflector positions. Tachometers were used for the horizontal and vertical velocities and multiturn variable resistors for the horizontal and vertical displacements.

5. Test Technique Problems

5.1 Model Heat Capacity

The heat capacity of the model can be an embarrassment when rapid and precise control of jet temperature is required for the study of transient intake temperatures. The solution adopted by HSA has been to soak the model at the required jet temperature by running the model over a ventilated pit in the floor of the test room.

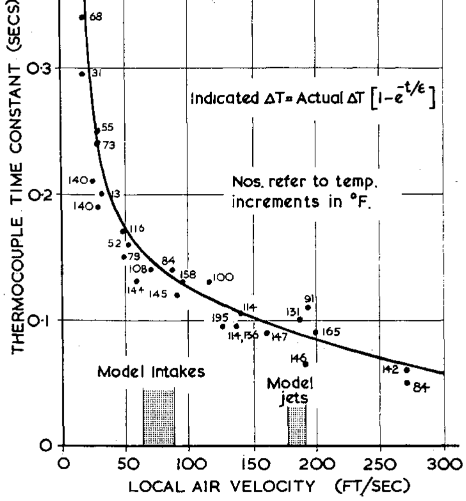


Fig. 5 Effect of local air velocity and temperature on thermocouple response. Test results for a Cromal-Alumel junction.

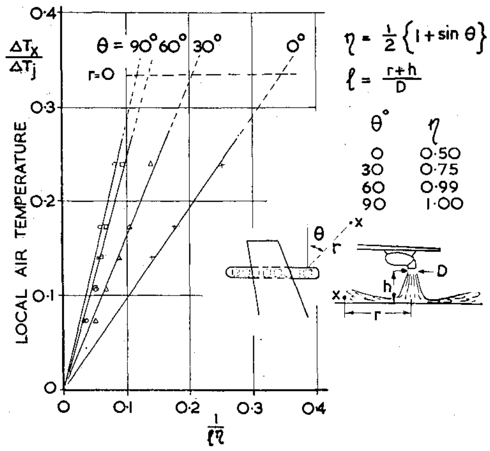


Fig. 6 Decay of temperature for exhaust gases spreading along the ground from a pod of eight engines.

A few seconds before the test run, the air to the model is switched off and exhausted through an external dump valve and the model is moved to the center of the room ready for the test. In this way, the maximum jet temperature can be obtained within 0.2 sec of switch-on.

5.2 Room Ambient Temperature

At the low jet temperatures required for small-scale models, great care is required in the control and measurement of the ambient air temperature, since a 1° error in the ambient temperature measurement could mean a 7° error in the predicted full-scale temperature, for the model described in Sec. 3.3.

The test room used was 35 ft long by 31 ft wide by 15 ft high, and it was therefore found to be important to ventilate the room thoroughly between each test run to remove any hot-gas pockets and establish a uniform ambient temperature. This was done by opening all of the doors and windows and running two large ventilating fans in the roof of the test room. It was found to be equally important to seal the room off during tests to avoid stray air currents since a 5-fps model scale can represent up to 40-fps full scale.

5.3 Apparent Flow Asymmetries

Appreciable asymmetry of the recirculating flow was noticed in the initial tests with the complete model under nominally symmetrical conditions. The flow pattern also exhibited a considerable hysteresis when symmetry was restored by differential throttling. Most of the flow asymmetry was found to disappear, however, when the control of the model jet flow was improved by using high-pressure air to each individual nozzle, where the air was expanded through a large number of small choked holes to the required velocity of 180 fps at the nozzle. Fundamental flow instabilities can, nevertheless, occur depending on the aircraft configuration.

6. Typical Test Results

6.1 Jet Spread from a Single Group of Engines

When the exhaust gases from a single group of engines strike the ground, they will, if there is no wind, spread out close to the ground for a distance of about 65 nozzle diam before they are lifted by the influence of buoyancy forces. The rate of decay of the air temperature close to the ground is shown on Fig. 6 for a row of eight lift engines, and the changeover from a three-dimensional jet spread spanwise

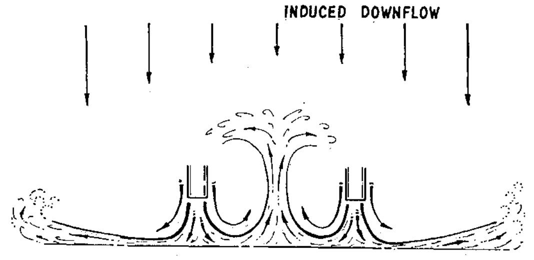


Fig. 7 Fountain formed between opposing jet flows.

(θ = 0°) to a two-dimensional spread chordwise (θ = 90°) may be seen.

6.2 Jet "Fountains" with Two or More Groups of Engines

Figure 7 shows the general flow pattern with two or more groups of engines. When the nozzles of the two groups are more than 2 or 3 diam apart, the gas trying to escape between them is forced upwards to form a hot-gas "fountain." This is further illustrated on Fig. 8 for the HS.129 jet lift transport project which used only partial deflection of the propulsion jets. Here the fountain forms under the fuselage and helps to give an increased lift when the aircraft is near the ground. The temperature of the gas in these fountains is, however, very high, and it is essential to choose configurations that keep the engine intakes well away from these fountains.

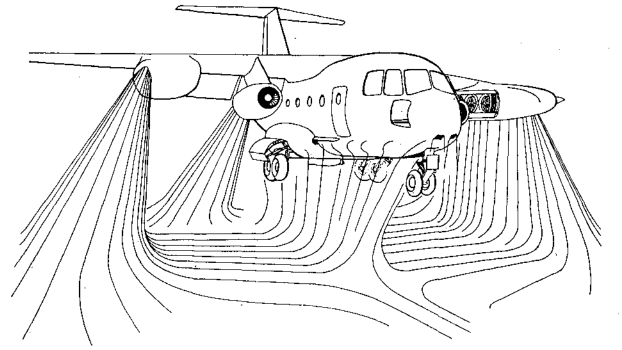
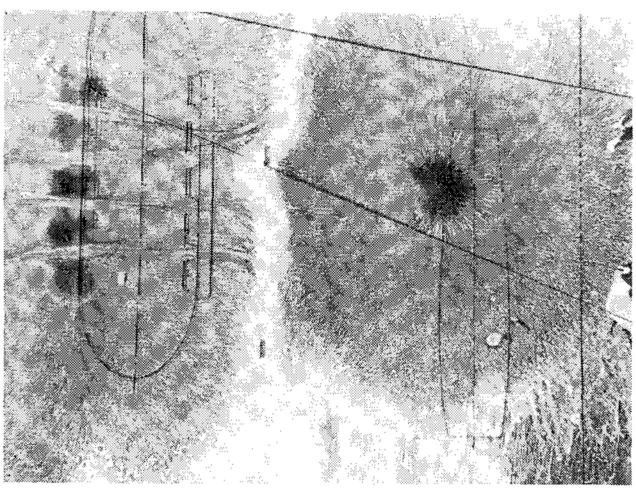
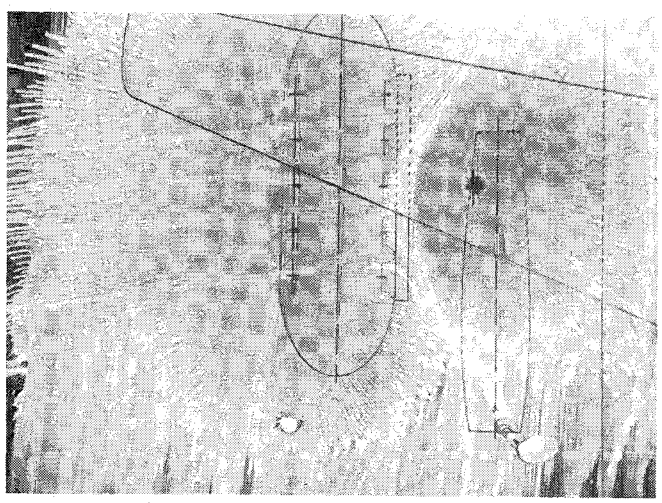


Fig. 8 Flow pattern for HS.129 (partial propulsion jet deflection).

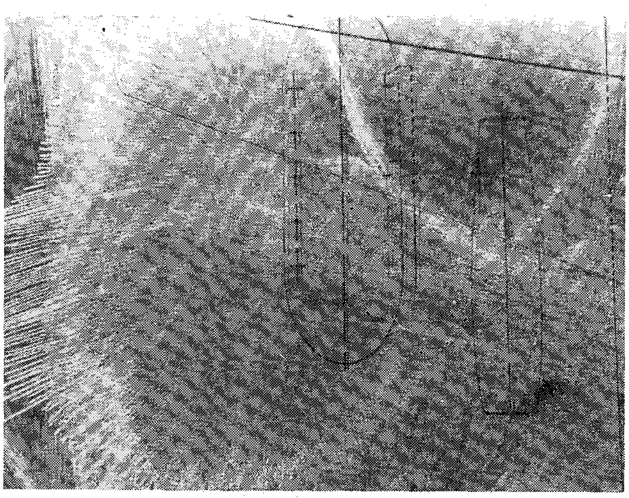
The flow pattern is further complicated if the propulsion jets are also deflected downwards, as fountains can then form between the lift and propulsion pods. The position of the fountains was found on the half-model rig by running the jets over a ground board coated with a suspension of titanium dioxide in paraffin. Typical results are shown on Fig. 9 for an aircraft with 5 lift engines mounted horizontally in a pod under each wing. On Fig. 9a the lift engine intakes are on the inboard side of the pod and the dark areas on the outboard side of the pod show where the jets strike the ground. The point of impact of the propulsion jet can also



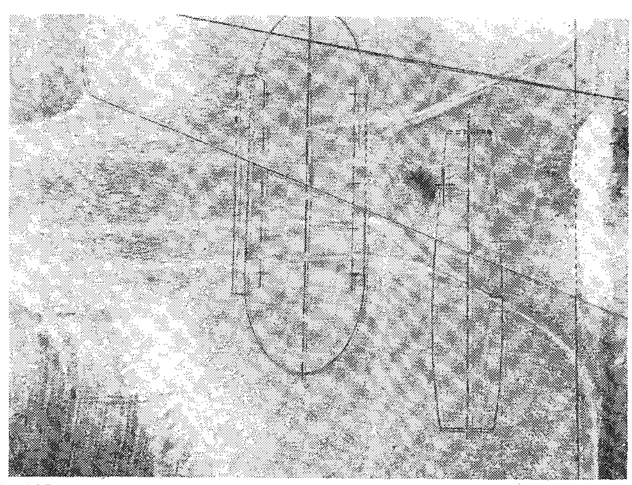
a) All jets vertical—wing-tip lift pod



b) All jets vertical—midspan lift pod



c) Lift jets 15° forward; propulsion jet 26° aft



d) All jets vertical—lift pod reversed (intakes face outboard)

Fig. 9 Visualization of ground flow pattern to determine fountain positions. (Five horizontally mounted lift engines and one propulsion engine.)

be seen. The thick white line between the lift and propulsion engines indicates the position of the hot-gas fountain. The thinner white lines between the lift engines are only the boundaries between the individual jets as they spread out horizontally, and they do not imply an upflow of hot gas. As the lift pod is moved inboard, Fig. 9b, the line of the fountain becomes curved and is in danger of entering both the lift and propulsion intakes. The upflow is very much weaker, however, at the extremities of the fountain away from the point of jet impingement, and in the region of the propulsion intake the fountain height is restricted by the induced downflow of cool air as discussed later.

Figure 9c shows that the fountain can be removed entirely from the region of the propulsion engine intake by deflecting the propulsion jets slightly aft and the lift jets a small amount forward to maintain a zero net horizontal force. The lift engine intakes can be kept clear of the hot gas, either by mounting the engines vertically so that their intakes are above the wing, or by reversing the lift pod so that the intakes are on the outboard side of the pod as shown on Fig. 9d. In this case, even with all jets vertical, the hot-gas fountains are very weak and are kept well away from the lift and propulsion intakes.

6.3 Downflow of Air Induced by the Jets

The height to which hot gas rises in a fountain is generally limited by an opposing downflow of cool air induced by the jets as indicated by the sketch on Fig. 7. This induced

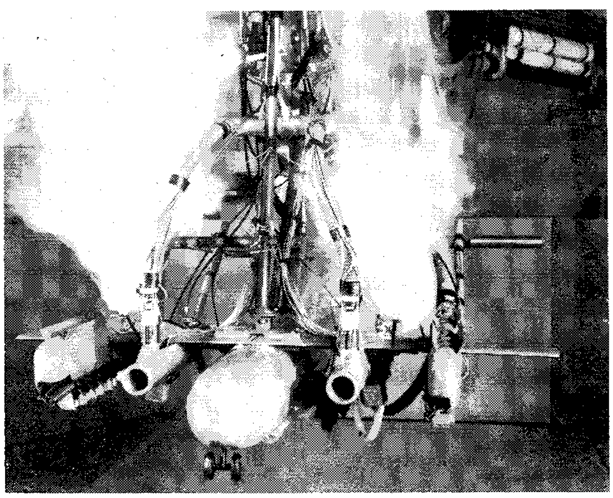


Fig. 10a Smoke rising from generators with jets switched off.

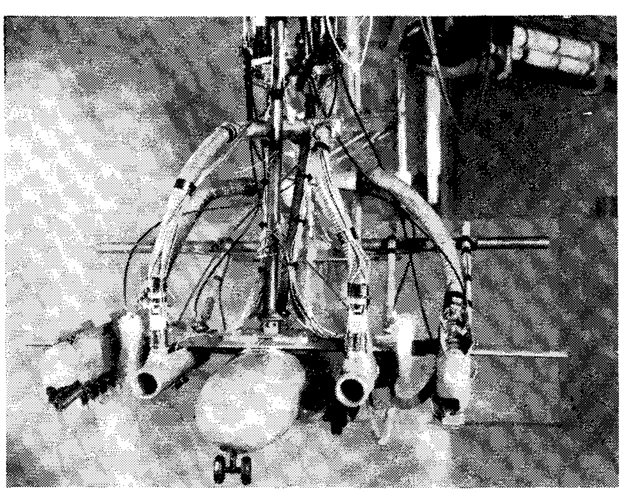


Fig. 10b Smoke pulled down by induced flow with jets on.

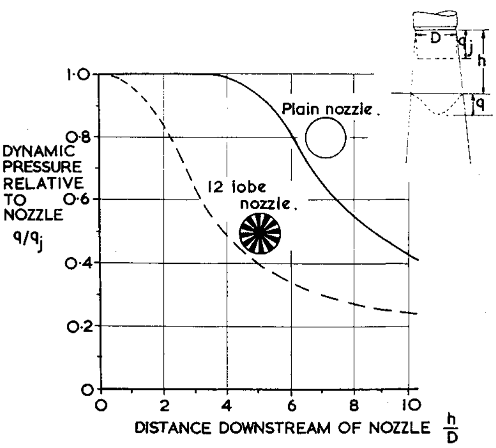


Fig. 11 Dynamic pressure decay for plain and multilobe nozzles. Model test results for a nozzle jet velocity of 200 fps.

flow has been studied on the model by placing smoke generators between the lift and propulsion engine pods as shown on Fig. 10. When the jets are switched off, the smoke rises because of its own heat (Fig. 10a), but as soon as the jets are turned on, the smoke is pulled down by the induced flow (Fig. 10b).

The induced flow can be strengthened locally by increasing the rate of jet mixing with multilobe nozzles, and 12-lobe nozzles of the type indicated on Fig. 11 have been tested on the complete moving model for a configuration with six vertically mounted lift engines per pod (four in front of the wing box and two behind). These nozzles, which were originally proposed to alleviate ground erosion, have a very beneficial effect on hot-gas ingestion, and in certain cases the propulsion engine intake temperature rise has been reduced to 25% of the rise measured with plain conical nozzles. The rate of jet decay for a single 12-lobe nozzle compared with the equivalent conical nozzle is shown on Fig. 11. The thrust loss associated with the HSA 12-lobe nozzle has not been measured directly, but NASA tests on a similar type of nozzle, designed for a much higher rate of mixing, showed a 3% penalty in nozzle velocity coefficient compared with a conical nozzle.[5,6]

6.4 Steady-State and Transient Intake Temperatures

The solid lines on Fig. 12 show typical intake temperature rises measured with the model shown on Fig. 10, fixed at different heights above the ground. At each height, the engine nozzles are set to the lift-off position and the jet thrust is increased from zero to maximum as rapidly as possible. The temperatures are related to the value measured after

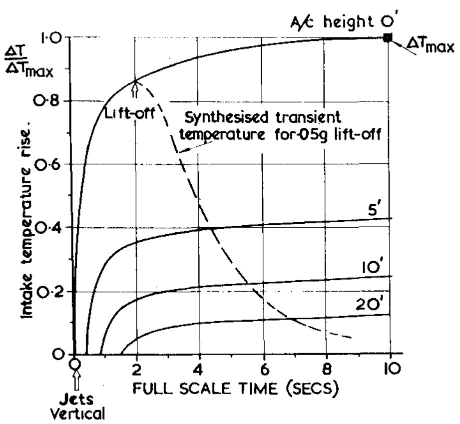


Fig. 12 Typical intake temperature curves for a fixed-height model.

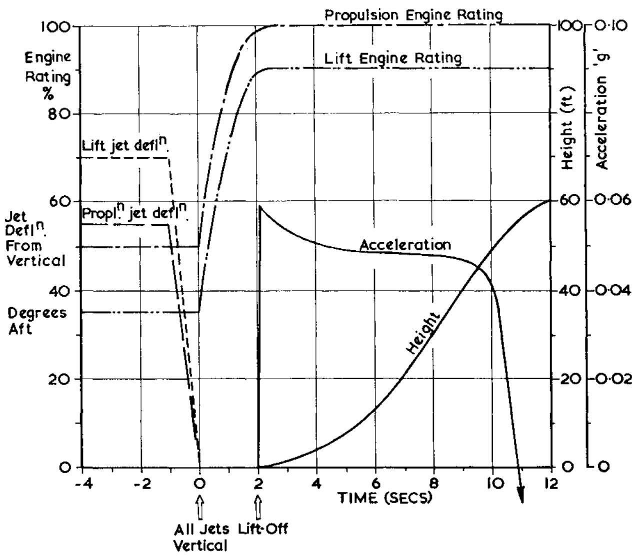


Fig. 13 Movement histories for the model performing an 0.05 *g* lift-off.

10 sec with the aircraft on the ground, this maximum temperature being determined by the configuration, type of nozzles, etc. An aircraft time/height history can now be superimposed on to these steady-state temperatures to estimate the transient intake temperatures during a vertical lift-off as shown by the dotted line on Fig. 12. (The time/height history assumed is that achieved by the moving model on Figs. 13 and 14. All values are for full scale.)

It is seen that the maximum intake temperature is very dependent on the delay time assumed for engine acceleration, and for a delay of two seconds the peak "transient" temperature is close to the maximum temperature with the aircraft on the ground. As the aircraft rises, however, the intake temperature is predicted to fall off rapidly and progressively with height.

For a true transient maneuver with the moving model, the movement histories before and after lift-off are given on Fig. 13, and the resultant intake temperature variation is shown on Fig. 14. The following are the significant features of Fig. 14. 1) There is very little rise in intake temperature until the jets are almost vertical. (Tests have shown that this is a sensitivity to jet angle rather than thrust and that a rearward jet deflection of only 15° will almost quarter the amount of hot gas flowing forward from the model); 2) the initial temperature rise is very similar to that measured with a fixed model, and the peak temperature is again only slightly less than the maximum steady-state temperature with the aircraft on the ground,; 3) after lift-off the temperature fall-off with height is less than that predicted by a fixed-height model, and, at a height of about half a wing span, there is a sudden rise in temperature.

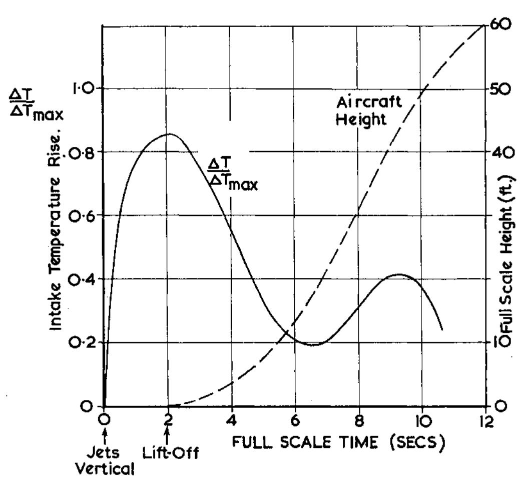


Fig. 14 Actual transient temperature measured with a moving model for a nominal 0.05 *g* lift-off. (ΔT_{max} is temperature reached after 10 sec with aircraft on the ground.)

Similar curves have also been obtained for the landing case, and the occurrence of a double temperature peak is again evident. Whereas the first temperature peak is very sensitive to configuration and can be reduced drastically by moving the fountain position, the second peak appears to be associated with longer-term recirculation and shows little response to configuration changes. Although this second peak is generally smaller than the first peak, it could be critical since it may occur at a height at which engine failure must be considered in addition to the performance losses caused by hot-gas ingestion. Close-to-the-ground engine failure can be ignored, and there is then a substantial thrust margin available to cover ingestion losses.

7. Conclusions

1) The recirculation of hot exhaust gas from jet-lift or fan-lift engines in VTOL aircraft can be studied successfully with small-scale models using low jet velocities and temperatures.

2) Flow-visualization techniques have shown the following three primary characteristics of the exhaust gas flow. a) With no obstruction or opposing wind, the exhaust gas from a single source will spread out along the ground and will experience a rapid decay in temperature and velocity. b) Relatively high temperatures can occur in hot-gas fountains which may be formed when two jet flows meet. c) There is a strong downflow of cool air induced by the jets which can be used to sweep hot gas away from the intakes.

3) The near-field fountain effects that can give rise to high intake temperatures can be studied with very simple fixed-height models, and small changes in the engine intake and jet configuration can produce very large reductions in intake temperature.

4) The far-field, longer-term recirculation is relatively insensitive to configuration changes and requires the use of a complete moving model for its analysis. A synthesis of results from fixed-height models can be misleading.

5) Multilobe, rapid-mixing nozzles desirable for the alleviation of ground erosion can also be used to reduce the recirculation of exhaust gas into the engine intakes.

References

[1] Brown, D. G. and Jagger, D. H., "Military V/STOL Transport Aircraft. A Review of the Background to Current Jet Lift Tactical Transport Proposals," *Aircraft Engineering*, May 1966.

[2] Cox, M. and Abbott, W. A., "Studies of the Flow Fields Created by Single Vertical Jets Directed Downwards upon a Horizontal Surface," Current Paper C.P.912, Oct. 1964, Aeronautical Research Council.

[3] Abbott, W. A., "Studies of Flow Fields Created by Vertical and Inclined Jets when Stationary or Moving over a Horizontal Surface," Current Paper C.P.911, Oct. 1964, Aeronautical Research Council.

[4] Kirk, J. V., Hickey, D. H., and Hall, L. P., "Aerodynamic Characteristics of a Full Scale Fan-in-Wing Model including Results in Ground Effect with Nose Fan Pitch Control," TN D-2368, July 1964, NASA.

[5] Higgins, C. C. and Wainwright, T. W., "Dynamic Pressure and Thrust Characteristics of Cold Jets Discharging from Several Exhaust Nozzles Designed for VTOL Downwash Suppression," TN D-2263, April 1964, NASA.

[6] Higgins, C. C. et al., "Exhaust Jet Wake and Thrust Characteristics of Several Nozzles Designed for VTOL Downwash Suppression," CR-373, 1966, NASA.