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Design Concepts for Minimizing Hot-Gas Ingestion in V/STOL Aircraft

R. E. Kuhn*
Newport News, Virginia

The reingestion of hot exhaust gas can seriously reduce the performance of V/STOL aircraft. Past research on hot-gas ingestion is reviewed and design concepts that can be used to minimize ingestion are identified. Both the near field effects of the fountain flows created by multiple-jet configurations and the far field effects of wind or aircraft forward motion are considered. Techniques for minimizing hot-gas ingestion that are discussed include jet exit arrangements to simplify the fountain flow, shields designed to favorably redirect the fountain flow that impinges on the aircraft, minimizing the amount of hot gas projected ahead of the aircraft, and locating the inlets as high as possible.

Nomenclature

d = diameter of individual jet, m
h = height of jet exit above ground, m
L = length of shield, m
M = Mach number of air entering inlet
q_0 = freestream dynamic pressure, N/m^2
q_n = dynamic pressure of jet at nozzle, N/m^2
T_j = jet temperature, °F
V = freestream velocity, knots
W = width of shields, measured from side of body, m
X = forward extent of hot-gas cloud, m (see Fig. 10)
Z = height of hot-gas cloud, m (see Fig. 10)
ΔT = increase in temperature of air entering inlet, °F

Introduction

THE ingestion of hot exhaust gases into the engine inlets can seriously reduce the performance of V/STOL aircraft. An increase in the temperature of the inlet air of only 10°C (18°F) can cause a thrust loss of 2-5% depending on the engine. In the extreme case of very high temperature rise or large variations of temperature across the inlet face, or large variations with time, compressor stall and complete loss of thrust can be encountered.

The flowfields associated with hot-gas ingestion can be divided into two classes: near field and far field flows. In the case of far field flow (Fig. 1a) the exhaust gases flow radially outward from the impingement point in a thin wall jet. This wall jet is entraining ambient air above it and inducing a gentle downward and inward flow around the configuration. This entrainment as well as the boundary layer being developed between the wall jet and the ground causes the wall jet to lose energy with radial distance. Eventually the point is reached where the buoyancy of the hot gases causes them to separate from the ground and rise to mix with the ambient air and be drawn back toward the inlet by the entrainment induced downflow. Because of the extensive mixing that takes place on the long path from the jet exit out to the separation point and back to the inlet the temperature rise associated with far field flow is relatively low.

The near field flow case arises with multiple jet configurations. With multiple jets an upflow or "fountain" is created where the outward flowing wall jets from two adjacent jets meet (Fig. 1b). This fountain can impinge on the body of the configuration and carry hot gases into the vicinity of the inlet. High levels of hot-gas ingestion are usually associated with near field flows.

There have been many investigations of the mechanism of hot-gas ingestion,[1-9] of the inlet temperature rise experienced on specific configurations, and of "fixes" to reduce the inlet temperature rise.[10-21] This paper presents the results of a review of this past work undertaken to identify and illustrate the design principles that can be used in the layout of the configuration to minimize hot-gas ingestion.

Near Field

This review starts with the near field case because the near field flows create the worst hot-gas ingestion problems.

Effect of Inlet Flow

The inlets act as sinks that, at zero forward speed, draw air inward from all directions. The effectiveness of these sinks in drawing in hot gases depends on the proximity of the sink to the hot-gas flow and on the direction and energy of the hot-gas stream.

Figure 2 shows a case in which the sink action of the inlets has no effect on the level of the inlet temperature rise. In this case there is nothing to interrupt the fountain upwash between the two isolated inlet/exit units (simulating lift engines). The fountain decays with vertical distance as it mixes with and heats the surrounding air. The downflow caused by the entrainment action of the radial wall jets on the ground brings the mixed warm air back to the vicinity of the inlets. In this case the inlet could be operated independently of the exit and it is seen in Fig. 2 that there is no difference between the temperature at the inlet face with the inlet operating or not operating. Apparently the sink effect of the inlet is not strong enough or close enough to the fountain flow to alter the flow structure and mixing process.

On the other hand, the complete model data of Ref. 14 show a major effect of inlet mass flow on the inlet temperature rise (Fig. 3). In this case the fountain is interrupted by the presence of the body and wing. The fountain flow that impinges on the bottom of the fuselage flows around the lower corners of the fuselage and is again blocked by the wing and canard. It must therefore flow spanwise and fore and aft on the bottom of the fuselage, wing, and canard. In the process of negotiating the several turns and developing boundary layers on the several surfaces over which it flows some of the hot flow loses most of its energy. There is,

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*V/STOL Consultant. Associate Fellow AIAA.

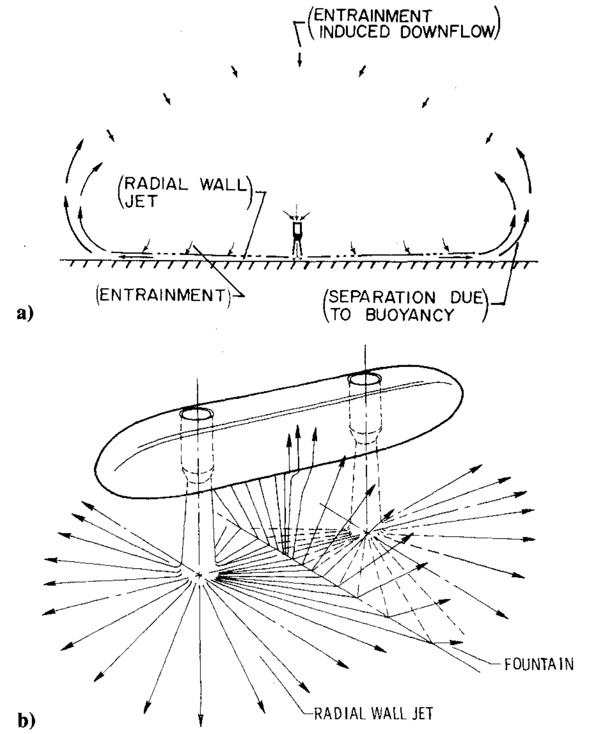

Fig. 1 Flowfields associated with hot-gas ingestion; a) far field flow, b) near field flow.

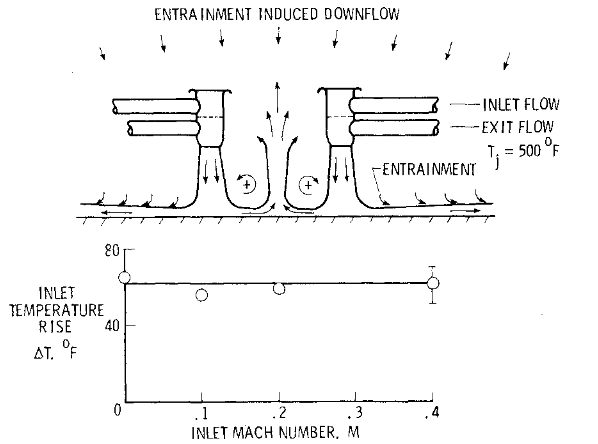

Fig. 2 Effect of inlet flow on the inlet temperature rise with two isolated simulated lift engines.[1]

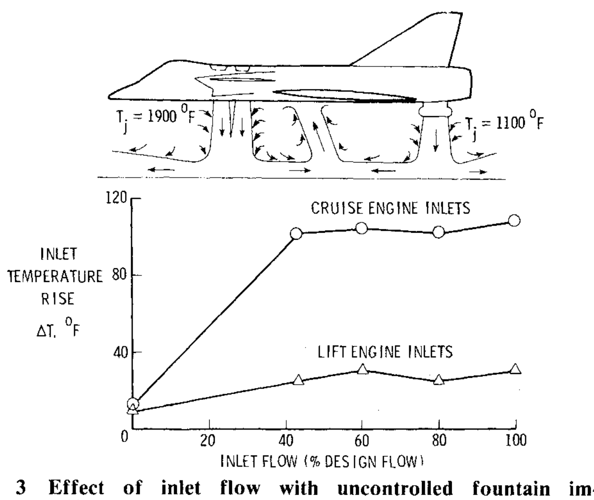

Fig. 3 Effect of inlet flow with uncontrolled fountain impingement.[14]

therefore, nearly stagnant hot air in the vicinity of the inlet that can be sucked in with the inlet mass flow.

The above observations suggest that the fountain should be deflected away from the inlet before significant losses in energy occur. This idea is supported by a study of the effectiveness of inlet shields reported in Ref. 3 and discussed below.

Effect of Inlet Shields

The effects of adding flow deflectors or "shields" of various types and sizes at several locations were investigated by Hall in Ref. 3. This study used a simple two-jet configuration (simulating two lift engines in a body) with the same jet spacing as the isolated jets in Fig. 2.[1] As shown in Fig. 4, the presence of the body significantly reduces the hot-gas ingestion from the level obtained with the isolated jets. Apparently the body interrupting the center of the fountain significantly reduces its upward momentum and the mixed temperature levels in the vicinity of the inlets.

The addition of shields at the exit plane of the jets causes a further major reduction in the inlet temperature rise and this reduction appears to be almost independent of the size of the shields. The primary function of the shield in this case appears to be to redirect the fountain flow laterally away from the configuration so that this redirected fountain flow in effect becomes an aerodynamic extension of the shield. Thus the size need only be the minimum required to intercept and redirect the fountain flow. In addition, this redirected fountain flow has an entrainment action along the "deflected upwash boundary" (Fig. 4) which draws the relatively cooler air above the configuration down toward the inlet and opposes the tendency of buoyancy to produce an upflow of hot gas from below.

Shields at the inlet plane, however, were relatively ineffective in reducing the inlet temperature rise (Fig. 5). In this

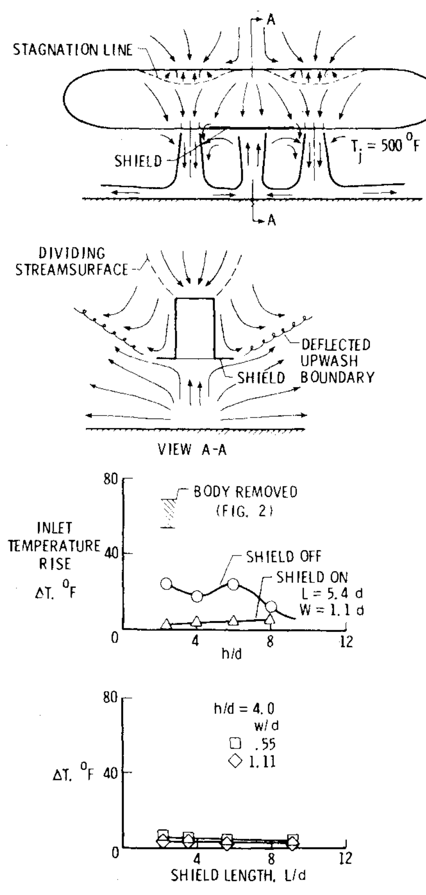

Fig. 4 Effect of exit plane shields in reducing hot-gas ingestion.[3]

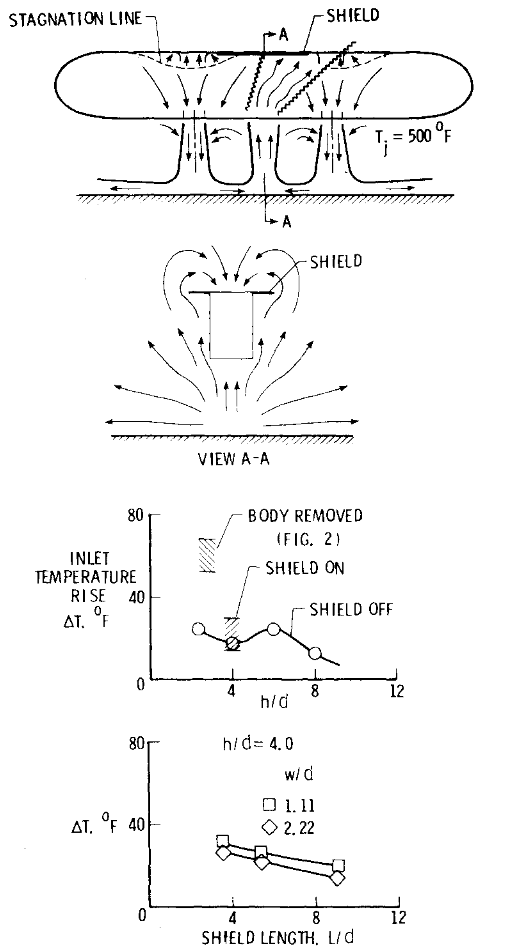

Fig. 5 Effect of inlet plane shields on hot-gas ingestion.

case, the flow about the body is very similar to that without any shields. That is, the upwash along the sides of the body has lost considerable velocity and does not have enough energy to be effectively redirected by shields at the inlet plane and become an "aerodynamic shield." Instead there is low energy air around the inlet plane shields that is easily sucked into the inlets.

The comparison of inlet and exit plane shields shown in Figs. 4 and 5 indicates that it is important to design the configuration to intercept and redirect the fountain flow with a minimum loss of energy so that this redirected flow is itself a shield. This "aerodynamic shield" protects the inlets from the hot gases and also provides an entrainment surface that pulls only the relatively cooler air above the configuration into the vicinity of the inlet as depicted in Fig. 4.

The above discussions relate to simple two-jet configurations but strongly suggest that the way to reduce the near field hot-gas ingestion problem is to configure the aircraft so that only one simple spanwise fountain is produced and to employ shields at the exit plane designed to catch and redirect the fountain flow with minimum losses. Past work has shown that it is very difficult to reduce hot-gas ingestion on multiple-jet configurations with multiple fountains (Refs. 11, 15, and 17-21, for example).

With a simple spanwise fountain deflected laterally by appropriate shields, as in Fig. 4, the level of inlet temperature rise indicates that the problem has been transferred from the near field to the far field. With far field flow (Fig. 1a) the inlet temperature rise is small because extensive mixing takes place on the long path from the exit out to the separation point and back to the inlet. The levels of inlet temperature rise shown in Fig. 4 with shields on are consistent with those associated with far field ingestion.

Far Field

Effect of Wind

In hovering, far field ingestion is low because of the extensive mixing that occurs on the long path from the impingement point out to the point where buoyancy effects causes the wall jet to separate from the ground and back to the inlet. A wind (or forward motion of the aircraft) causes a considerable change in the flowfield. The action of the freestream pushes the separation point back toward the impingement point and folds the flow from the jet back on itself forming a hot-gas bubble as indicated by the flowfield sketches of Figs. 6a and 6b. The separation point moves closer to the configuration as the velocity increases and the hot-gas bubble shrinks in size. At first this reduction in size with increasing velocity causes the inlet temperature to rise as the path length from the exit to the inlet is shortened. At higher velocities, the inlet temperature reduces again and returns to ambient when the height of the bubble is reduced to the extent that all the heated air is blown below and behind the inlet (Fig. 6a).

With a two-jet configuration aligned with the freestream (Fig. 6a), the flow in the front quadrant corresponds to that from a single jet. Only the relatively thin radial wall jet on the ground is projected forward. A strong vortex is generated between the impingement point and the line where the freestream causes the wall jet to separate and curve back on itself creating a flat hot-gas bubble. The depth of the bubble is only about half the distance from the impingement point to the separation line and the velocity at which the inlet temperature returns to ambient can be relatively low (Fig. 6a).

With a two-jet configuration in a side-by-side arrangement (Fig. 6b), the fountain flow is projected forward against the freestream as well as upward. The hot-gas bubble is considerably larger because the separation point is pushed further ahead by the greater mass of the fountain flow. Also the upflow in the fountain increases the height of the bubble to the same order as the distance from the impingement point to the separation point.[6] Under these conditions both the inlet temperature rise and the velocity for zero temperature rise are greatly increased. Shields are ineffective under these conditions because of the action of the freestream in blowing the fountain flow back to the vicinity of the inlets (Fig. 6b).

Effect of Inlet Height

On the basis of the above discussion, it would be expected that both the maximum inlet temperature rise and the velocity above which ingestion does not occur would decrease as the configuration height above the ground increases. This was found to be the case in the investigation reported in Ref. 19. This investigation was unique in that for each of the several exit configurations investigated both side and top inlets and high and low wings were tested. A sample of the data for a configuration having four jets in line is presented in Fig. 7. As expected both the maximum inlet temperature, ΔT_{max}, and the velocity at which the inlet temperature rise returns to zero, $V_{\Delta T=0}$, decrease as the height is increased. At the bottom of Fig. 7 the maximum temperature rise is plotted as a function of height for the four inlet/wing combinations. Again, as expected, the maximum inlet temperature rise for the side inlets is much greater than for the top inlets which are higher above the ground.

The maximum inlet temperature rise data of Fig. 7 are replotted as a function of inlet height in Fig. 8, which shows that the difference in temperature rise of the side and top inlets shown in Fig. 7 was almost entirely due to the difference in inlet height. The slightly higher temperatures for the side inlets, for the same inlet height, are probably due to the more forward location of the side inlets. The data of Fig. 8 indicate that for this configuration the maximum inlet temperature rise is approximately inversely proportional to the square of the ratio of the inlet height to the diameter of the front jet and

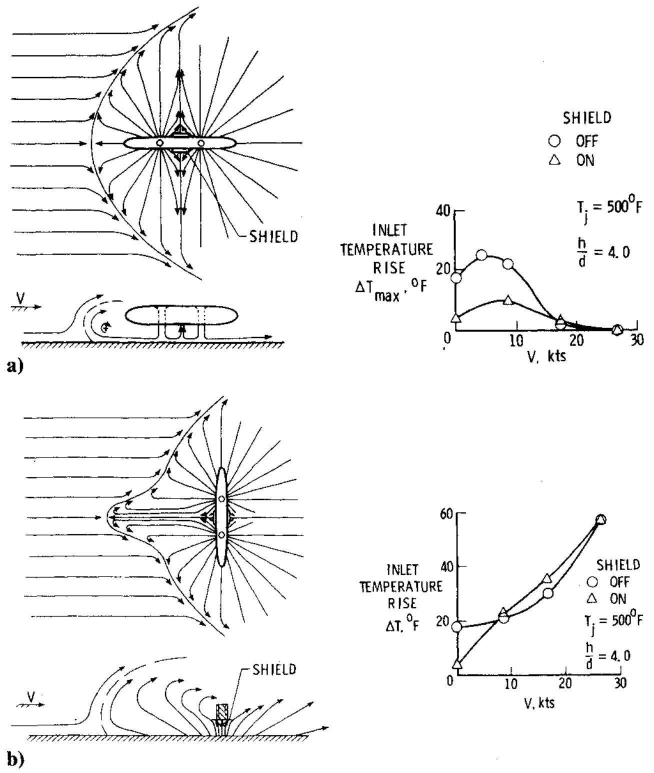

Fig. 6 Effect of velocity on flowfield and inlet temperature.[3] a) in-line jet arrangement, b) side-by-side arrangement.

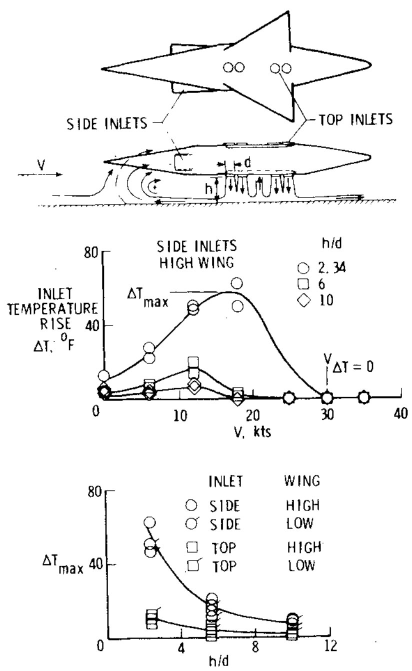

Fig. 7 Effect of height and velocity on inlet temperature rise; in-line four-jet configuration.[19]

is given approximately by

$$\Delta T_{\max} = \frac{T_j - T_{\text{amb}}}{(h/d)^2_{\text{inlet}}}$$

At the bottom of Fig. 8 the velocity at which the inlet temperature rise returns to zero is plotted as a function of inlet height. There is considerable scatter in the data, but it is in general agreement with the boundaries developed from several single jet investigations to be discussed later. These

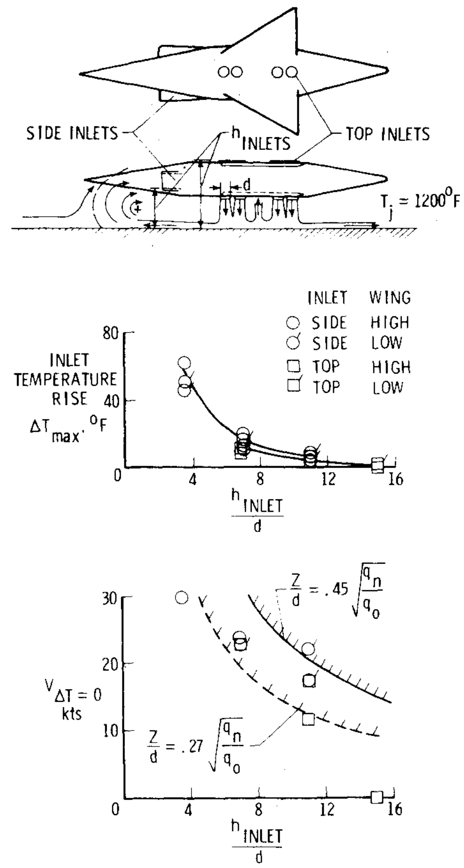

Fig. 8 Correlation of data of Fig. 7 with inlet height.

boundaries represent the height and velocity combinations which would place the inlet of a single-jet configuration above the hot-gas cloud (that is, above which there should be no ingestion).

With a rectangular jet arrangement as shown in Fig. 9, fountain flows are projected forward as well as laterally and rearward. The forward and upward projection of the fountain flow in the front quadrant increases the size of the hot-gas cloud and greatly increases the maximum temperature rise and the velocity required to avoid reingestion. It should be noted that the tests of Ref. 19 extended only up to 35 knots. While the inlet temperature rise reached a maximum within this speed range, it was insufficient to determine the speed required to avoid ingestion for some of the configurations and heights; nevertheless, it is clear that the speed required to avoid ingestion is considerably greater than would be predicted from the single-jet experience discussed below.

Size of the Hot-Gas Cloud

There have been four investigations of the effects of freestream velocity on the forward projection and depth of the recirculated flow region generated by a single-vertical-jet configuration (Fig. 10). All of the studies indicate that the forward projection of the flow, X/d, is directly proportional to the square root of the ratio of nozzle dynamic pressure to freestream dynamic pressure and that the depth of the recirculated flow, Z/d, is about half the forward projection of the flow. However, there are major differences in the extent of the forward projection, X/d, obtained from the various investigations. The differences may be due to the manner in which the freestream was produced.

Three of the investigations were conducted in a wind tunnel or with a blower to produce the freestream. The fourth[6] used the moving model technique. In a wind tunnel or with a blower, a boundary layer is created between the freestream and the ground board over which it is flowing. There is no boundary layer with the moving model technique. The wall jet moving forward against the freestream is very thin (the maximum velocity in the wall jet occurs at a height of less than about 20% of the jet diameter above the ground). When this thin wall jet is opposed by the relatively lower velocity in the freestream boundary layer rather than by the full freestream velocity, the separation point will move forward. The investigation of Ref. 4 set out to simulate atmospheric wind conditions and the boundary layer that would be present in a cross-wind situation. The boundary layer was therefore made very thick and this investigation shows the maximum forward penetration (Fig. 10). The moving model data,[6] which had no boundary layer, on the other hand, show the smallest penetration. Nothing is known about the boundary layers for the other two investigations, but a photo in Ref. 14 indicates the ground board used was relatively short so that the boundary layer may have been relatively thin.

On the basis of the above reasoning, it appears that the top of the hot-gas cloud, and therefore the inlet height above which there will be no ingestion, will depend on how the tests are run and on how the aircraft is operated. For tests in a wind tunnel, or for an aircraft hovering in a head wind, the critical height may be as high as $Z/d = 0.45\sqrt{q_n/q_0}$. The data for the in-line configuration (Fig. 8)[19] were taken in the wind tunnel and generally fall below this limit. For an aircraft moving forward with no wind the height may be as low as $Z/d = 0.27\sqrt{q_n/q_0}$.

The above discussion applies only to single-jet or to-in-line-jet configurations where the diameter of the front jet in the line appears to determine the dimensions of the flow in the forward quadrant. It also applies only to vertical jets. With jet arrangements producing a fountain flow that projects forward, Ref. 6 indicates that both the forward projection and the height of the hot-gas bubble are greatly increased.

Design Features to Minimize Ingestion

Although an aircraft cannot be designed solely on the basis of hot-gas ingestion considerations, a recognition of the features that might be employed to minimize ingestion is desirable. Such knowledge frequently permits design compromises to be made that result in large gains in one area at the expense of only a small penalty in others. The design concepts suggested by the foregoing discussion may be used to minimize hot-gas ingestion as illustrated in Fig. 11.

The jet exit arrangement should be designed so that the impingement of the jets on the ground produces only one, essentially spanwise, fountain.

Flow deflectors or shields should not be located around the inlet but should be located where the fountain flow impinges on the lower surface of the aircraft. They should be designed to redirect the fountain flow in a spanwise direction away from the aircraft with a minimum loss. In particular, care should be taken to minimize any forward deflection of the fountain flow. The size and configuration of the shields and baffles will have to be developed to accommodate the fore and aft movement of the fountain due to such factors as changes in angle of attack and differential changes in fore and aft thrust (as used for control).

Inlets should be placed as high as possible. It may be desirable to use auxiliary inlets on the top of the aircraft and to block the cruise inlet duct internally to prevent hot gas from being ingested through the cruise inlets.

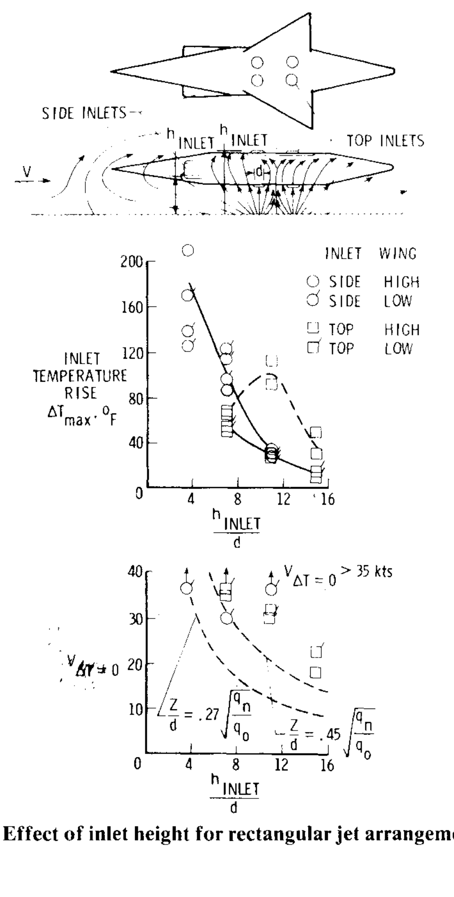

Fig. 9 Effect of inlet height for rectangular jet arrangement.[19]

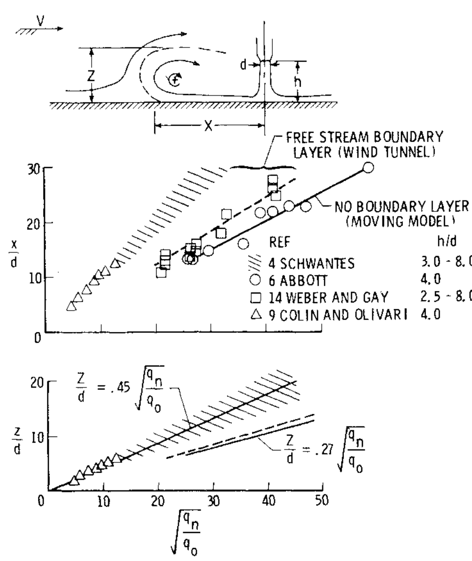

Fig. 10 Size of the recirculating flow region; single-jet configuration.

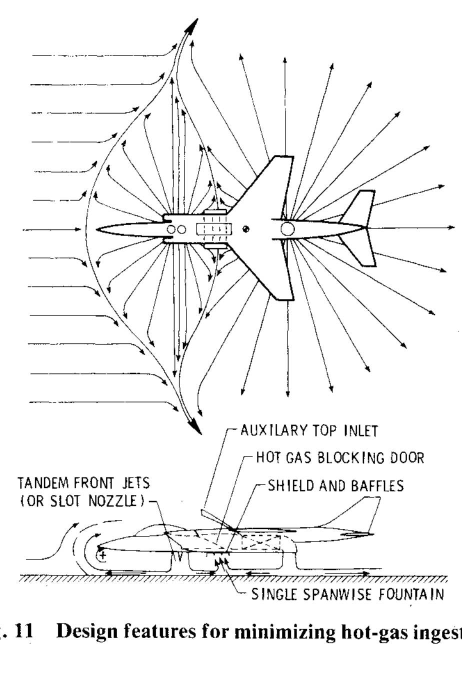

Fig. 11 Design features for minimizing hot-gas ingestion.

The front jet(s) should probably be smaller than the rear jet(s) and it may be desirable to use a slot nozzle or multiple nozzles in tandem for the front jets in order to minimize the amount of hot gas projected forward. However these measures cannot be carried to extreme or the flow from the rear jets may overwhelm the front jets and nullify the expected gains.

Unfortunately some of the design principles suggested here (particularly the fore-and-aft jet arrangement shown in Fig. 11) may not be compatible with the design features that would be used to minimize the aerodynamic lift losses in ground effect. The estimation methods presented in Ref. 22 indicate that the aerodynamic lift losses are greater for two-jet configurations than for three- or four-jet arrangements. Lift losses can be minimized by widely spreading four or more jets. A reasonable compromise would probably be a three-jet configuration with a single jet (or pair of closely spaced jets) forward and two jets aft, one on either side of the body near the wing trailing edge. Unfortunately the data base needed to trade off the aerodynamic hot-gas ingestion losses does not exist. A research program that would study hot-gas ingestion and aerodynamic ground effects simultaneously is badly needed to determine the best compromises and to provide an adequate data base.

Concluding Remarks

This paper has reviewed past research on hot-gas ingestion and identified design concepts that can be used to minimize ingestion. The primary factors include designing the exit arrangement to simplify the fountain flow, installing shields that will effectively redirect the fountain flow that impinges on the aircraft, minimizing the amount of hot gas projected ahead of the aircraft, and locating the inlets as high as possible.

Unfortunately, some of the design principles suggested here (particularly the fore-and-aft jet arrangement shown in Fig. 11) may not be compatible with the design features that would be used to minimize the aerodynamic lift losses in ground effect. The data base needed to trade off the aerodynamic and hot-gas ingestion losses does not exist. A research program that would study hot-gas ingestion and aerodynamic ground effects simultaneously is badly needed to determine the best compromises and to provide an adequate data base.

Acknowledgment

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