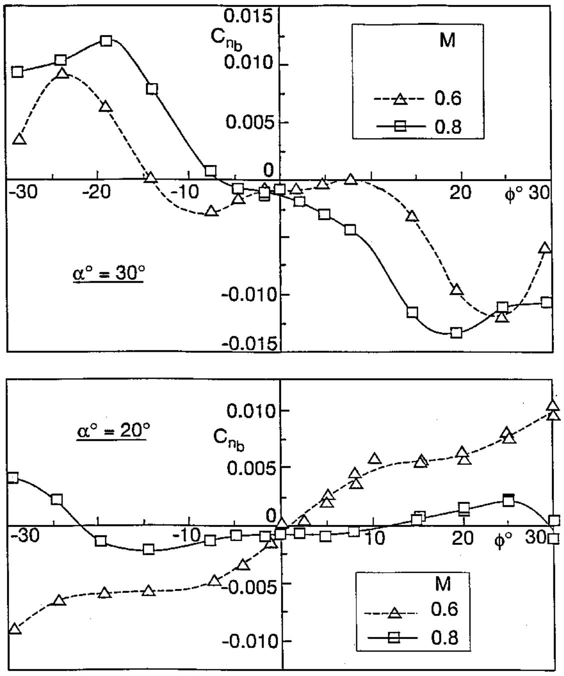

Fig. 4 Yawing-moment coefficient vs roll angle.

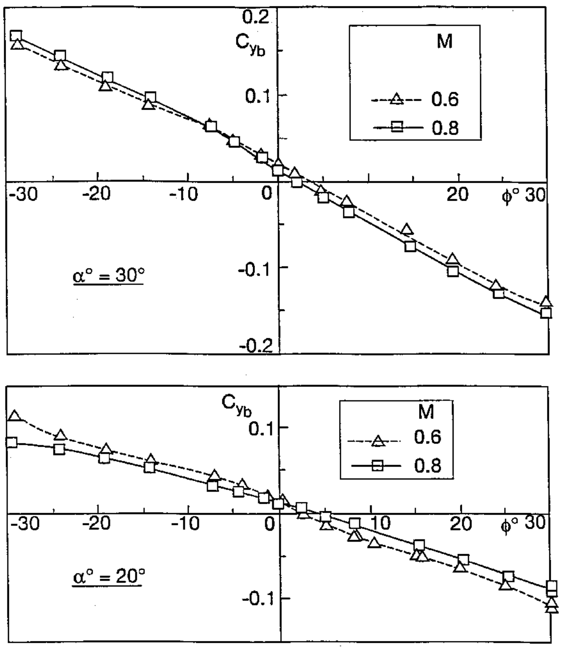

Fig. 5 Side-force coefficient vs roll angle.

nearly zero or slightly positive for $|\phi| > 14$ deg. The exact slope cannot be determined with accuracy because of the experimental uncertainties. Between $-14 < \phi < 14$ deg, $\partial C_{lb}/\partial\phi$ is negative and its value is small when the points at $\phi = 0$ and 2.5 deg are ignored.

As is well known, roll–yaw motions are inextricably coupled and meaningful conclusions on lateral behavior of the aircraft can only be derived from dynamic analysis. However, the static derivatives are still useful to give some information of the aircraft characteristics. The yawing moment C_{nb} is shown in Fig. 4. At $\alpha = 20$ deg, $\partial C_{nb}/\partial\phi$ is positive over the entire roll range for $M = 0.6$, whereas at $M = 0.8$, $\partial C_{nb}/\partial\phi$ is approximately zero for $-20 < \phi < 10$ deg. At $\alpha = 30$ deg, the curves are quite different from those at 20 deg. Large negative slopes are observed outside the range $-7.5 < \phi < 7.5$ deg. They become zero at about ± 25 deg for $M = 0.6$ and ± 17.5 deg for $M = 0.8$. Thereafter, the slope becomes positive. There are significant variations of $\partial C_{nb}/\partial\phi$ with ϕ at high α. A slight offset of the curves at $\phi = 0$ deg is observed and this is more noticeable at the higher α. An explanation for this behavior is similar to that previously given for the C_L curves. Figure 5 shows the relation between the side-force coefficient C_{yb} and ϕ. $\partial C_{yb}/\partial\phi$ is negative over the entire range of ϕ investigated and a reasonably constant slope for C_{yb} with ϕ is observed. Once more, a small offset of the curves is detected at the origin that is attributed to flow nonuniformity in the wind tunnel.

In summary, both C_L and C_D exhibit a decrease with ϕ. $\partial C_{yb}/\partial\phi$ is practically constant over the whole excursion in ϕ, and the effect of M is small. Good roll stabilty is maintained up to $\phi = 30$ deg for $M = 0.6$, whereas at $M = 0.8$, stability deteriorates and becomes marginally stable at values of ϕ larger than 14 deg. M and α effects are quite pronounced for C_{nb}.

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Aircraft Engine Bay Cooling and Ventilation: Design and Modeling

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Introduction

THE modern generation of military airplanes are equipped with low-bypass turbofans with relatively cool engine casings. In some instances the bypass ratio is very low [0.2–0.4 (Ref. 1)] and these engines are often called cooled turbojets. Because of the low temperatures at the engine surface engine, bay cooling is not, in general, as stringent a requirement as the ventilation of the bay of potentially flammable gas mixtures resulting from leaks between various modules of the engine. In flight, unidirectional ventilation air is, in general, relatively easy to achieve by a careful design of inlet scoops and outlets that take advantage of the air ram and the existence of low-pressure regions on the rear part of the airplane fuselage. The difficulty is to obtain sufficient ventilation on the ground, at static conditions.

Figure 1 shows a number of engine bay ventilation schemes implemented on some of the airplanes currently in service. Figure 1a shows the scheme adopted for the F-15. Engine bay

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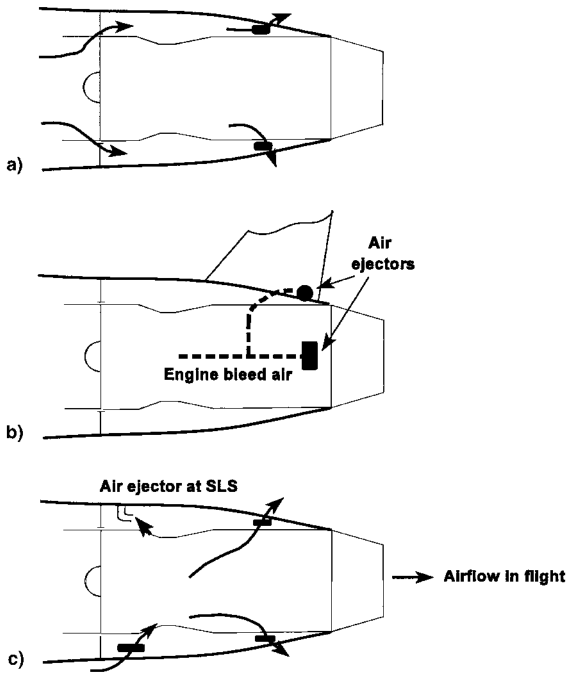

Fig. 1 Existing engine bay ventilation schemes.

cooling/ventilation air is bypassed from the inlet and transferred at the engine face through orifices into the engine bay. It exits at the rear of the bay via flush orifices. While suction of the bypassed air from the inlet has a beneficial effect on the flow quality at the engine face because of the elimination of the boundary layer formed along the inlet duct, the scheme has the disadvantage of limited engine bay cooling on the ground, at static conditions. The structure around the engine face imposes additional design constraints, and a careful design of the ventilation system is necessary to ensure a correct matching between the engine bay airflows and the inlet bypass air over the entire altitude, velocity, airplane attitude envelope (angles of attack and sideslip), and engine power setting. To overcome the ground deficiency of ventilation air, the F-16 the cooling/ventilation scheme shown in Fig. 1b includes air ejectors placed at the roots of the vertical and horizontal tails. Air bled from the engine's compressor is sent to these air ejectors to ensure sufficient, unidirectional flow in the engine bay. The entrance of the engine bay is ensured by scoops at the front end of the engine bay, while the exits are the ducts around the air ejectors. This scheme is capable of ensuring sufficient cooling and ventilation at ground static conditions, but it penalizes the engine performance because of air-bleed extraction. This use of bleed-air comes, perhaps, at conditions when the requirement for thrust is the greatest. Figure 1c shows the scheme adopted for the F-18. Engine bay cooling/ventilation air is brought through flush inlets on the lower part at the front station of the engine bay and, in flight, exists through flush exits at the rear part of the bay. For ground static conditions, an air ejector placed at the front part of the engine uses air–bleed from the engine to entrain air from the engine bay through an exit orifice on the upper surface of the airplane. This system offers sufficient ground cooling and ventilation, but at the expense of reduced performance caused by bleed extraction. Additionally, by inspection, it appears that the exit orifices at the upper-rear part of the engine bay are too small in comparison with the lower intakes at the same station and, thus, free convection ventilation in the rear portion of the engine bay at static conditions is deficient.

All of the designs shown in Fig. 1 have either limited efficiency at low-speed flight or impose penalties on the powerplant's performance. Better designs of engine bay cooling and ventilation are desirable. It is also important to make available predictive tools to assess the merits of each design. In the present work, a novel design, ensures the following:

1) A minimal penalty on the vehicle drag and performance is presented.

2) Good ventilation in flight and on the ground at static conditions via efficient free convection at the front and the rear of the engine bay is proposed.

Further, a model for predicting and analyzing the engine bay cooling/ventilation is developed to assist in the design stages of the engine bay cooling. The model accounts for pressure losses along the cooling/ventilation system path. It includes the interrelated effects of the outlets discharge characteristics and the discharged mass flow as functions of the local conditions at the location of the outlets of the system on the fuselage.

Proposed Ventilation Design Scheme

The proposed engine bay ventilation is shown in Fig. 2. The criteria under which this design emerged are the following:

1) Provide sufficient ventilation in flight and at ground static conditions.

2) Generate minimal drag addition to the aircraft configuration.

3) There is no reduction in engine thrust caused by compressor air-bleed, therefore, provisions for sufficient free-convection flows at sea level static are needed.

In response to these requirements the design features are as follows:

1) All outlets are flush and the inlets are either flush or low-height ram-scoops, which have a better pressure recovery.

2) Ventilation in flight is ensured by unidirectional airflow, as shown in Fig. 2, from the front intakes (total cross section A_i) arranged at the lower part of the fuselage (one intake) and at the upper part of the fuselage (two intakes) to the four outlets (total crossection A_0) placed at the rear station of the engine bay.

3) At ground static conditions ventilation is ensured by free convection in two regions, front and rear of the engine bay, from the intakes on the bottom to the outlets at the top. To satisfy this requirement it is necessary to implement larger orifices on the upper part of the fuselage than on the lower surface.

The size of the intakes and the outlets are determined by the requirement of specified air velocity around the engine or by the requirement to ventilate the engine bay at a certain rate. The aerodynamic conditions at the intakes/outlets locations has to be evaluated over the entire flight envelope including Mach number, angles of attack, sideslip, and external stores configuration.

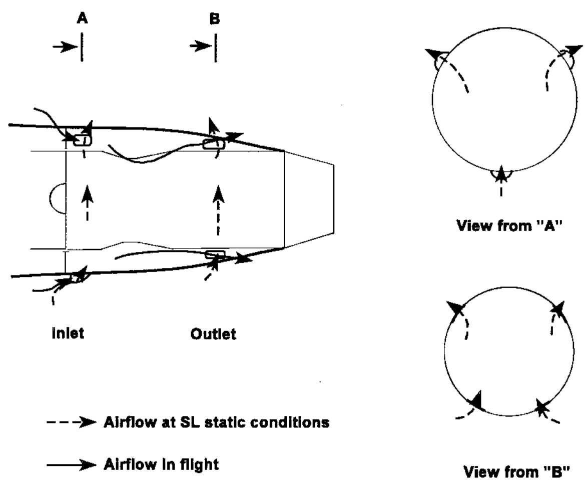

Fig. 2 Proposed engine bay ventilation scheme.

Proposed Model for Assessing the Ventilation Design

The algorithm balances the ventilation mass flow between the intake and the capacity of the outlets to exhaust this mass flow, considering intakes pressure recovery (PR), pressure losses within the engine bay, upon discharge through the outlet and the value of the local pressure coefficient at the exhaust location $c_p = (P - P_\infty)/q_\infty$ (which is a function of the flight conditions, including altitude, angle of attack, sideslip, and the flight Mach number).

Two distinct situations will occur:

1) The outlet cannot pass the entire mass flow arriving at the inlet. Spillage at the inlet will result with the associated external drag increase. The outlet-to-inlet area ratio can be enlarged and the ventilation mass flow will be adjusted to the size of the inlet orifices. The internal drag caused by larger ventilation airflow is minimal since the velocities in the engine bay are, in most cases, small.

2) There is a substantial suction at the outlet caused by the external surface contour capable of transferring flow rates in excess of those arriving at the inlet. This situation is likely to occur at large flight speed. The pressure losses at the inlet will increase, in particular during supersonic flight when a shock formed at the inlet to the engine bay could be ingested.

A discussion of the parameters influencing the engine bay ventilation design is given next.

Inlet Recovery

The inlet pressure recovery is assumed for intakes submerged partially in the vehicle boundary layer $h/\delta < 1$, where h is the height of the scoop and δ is the geometrical thickness of the boundary layer. Because of the location of the engine bay, the fuselage boundary layer can be rather thick and extension of the inlet scoops beyond the boundary layer is impractical for this application. Although flush inlets exhibit low-pressure recovery in comparison with scoops extended into the flow they have a minimal impact on the vehicle drag (both subsonic and supersonic).

Engine Bay Losses

Pressure losses occur at the system's inlet because of discharge into the bay, friction losses along the engine bay, and at the discharge into the atmosphere through the outlet.

Losses upon discharging from the inlet area to the engine bay area can be estimated from the momentum equation

$$(p_b - p_i)A_b + \rho U_i A_i (U_b - U_i) = 0 \tag{1}$$

where p_b, p_i, U_b, and U_i are the pressures and the velocities in the engine bay and the inlet, respectively (note that $p_i = \mathrm{PR} \cdot p_{\mathrm{total},\infty}$). The pressure losses are given by

$$\Delta P = (p_i + q_i) - (p_b + q_b) \tag{2}$$

where q is the dynamic pressure $\frac{1}{2}\gamma p M^2$. Combining Eqs. (1) and (2), the pressure losses can be expressed as a function of the inlet-to-bay area ratio as follows:

$$\frac{\Delta P}{q_i} = \left(\frac{A_i}{A_b}\right)^2 \left(1 - \frac{A_i}{A_b}\right)^2 \tag{3}$$

In practice, pressure losses associated with sudden expansion in engine bays in excess of 70% were reported[2] for moderate expansion ratios ($A_i/A_b = 0.5$). Because of the large expansion from the intakes into the engine bay, it can be assumed, conservatively, that the pressure losses equal the entire inlet dynamic pressure. Further, considering the low velocities in the bay around the engine, the pressure losses caused by fiction within the bay are neglected.

Outlet Mass Flow Discharge

The outlet massflow m_0 results from the balance between the airflow reaching the outlet and the ability of the outlet to discharge this mass flow, considering the local external pressure on the fuselage at the location of the outlet. The local pressure coefficient depends on the location of the outlet on the fuselage, the flight conditions (Mach, angles of attack, and sideslip), and the presence of external loads that may affect the flowfield.

Of particular interest is the correct evaluation of the discharge coefficient across the outlet K, which is defined as the ratio of the actual to the ideal (calculated) mass flow $K = m_{\mathrm{actual}}/m_{\mathrm{id}}$, where $m_{\mathrm{id}} = \rho_0 U_0 A_0$. Reference 3 contains a collection of experimentally determined discharge coefficients for differently shaped outlets, both flush and recessed, expressed as a function of the discharge flow ratio and the outlet flow Mach number. The discharge coefficient is a function of the outlet shape and the external, freestream Mach number.

An additional parameter that needs to be included in the outlet analysis is the pressure loss associated with the discharge of the mass flow through the outlet. Since the expansion takes place with an area ratio $\to \infty$, this pressure loss is taken as equal to the dynamic pressure at the exit conditions

$$\Delta P / \tfrac{1}{2}\rho_0 U_0^2 = 1 \tag{4}$$

This pressure loss is a function of the air velocity across the outlet that is affected by the discharge coefficient via mass flow. In turn, the discharge coefficient is a function of the mass flow. To introduce this interdependence, the density, ρ_0 in Eq. (4) is evaluated from the equation of state for an ideal gas $p_0 = \rho_0 RT$, and the velocity U_0 is substituted from continuity $m_0 = \rho_0 U_0 A$. Equation (4) becomes

$$\Delta P = \frac{1}{2}\frac{w_{\mathrm{id}}^2 RT}{A^2 p_0} \tag{5}$$

or, after introducing the definition of the discharge coefficient:

$$\Delta P = \frac{1}{2}\frac{w_{\mathrm{actual}}^2 RT}{K^2 A^2 p_0} \tag{6}$$

It should be noted that the model requires an iterative calculation of the outlet, since the pressure losses and, hence, the flow rate, are functions of the discharge coefficient that in turn is affected by changes of the flow rate. The balance between the inlet mass flow, the pressure losses, and the outlet ability to transfer this mass flow may cause, depending on the design parameters selection, spillage at the inlet (if the losses downstream are large) or, if the outlet is placed in a very efficient location, shock ingestion at the ventilation system inlet.

Sample Calculation and Discussion of the Results

For the purpose of illustration, the following example has been selected: $A_i = 121\ \mathrm{cm}^2$, $A_0/A_i = 3$, flight at sea level, and 10 km, a constant pressure coefficient at the exit for all flight conditions $c_p = -0.1$, and pressure recovery and discharge coefficient as shown in Fig. 3. The engine diameter is assumed 1.5 m with a gap of 2.5 cm between the engine and the fuselage. Figure 4 shows the resulting mass flow. It can be noticed that substantial airflow rates can be achieved with this selection of parameters, ensuring a ventilation of several engine bay volumes per second. As the flight Mach number increases, shock-induced losses at the inlet, in the supersonic regime, result in a leveling of the mass flow.

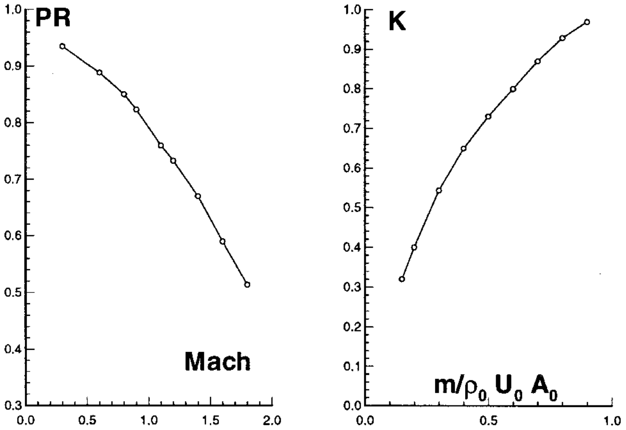

Fig. 3 Pressure recovery for an inlet immersed in boundary layer (h/δ = 0.3) and discharge coefficient for flush outlets.[3]

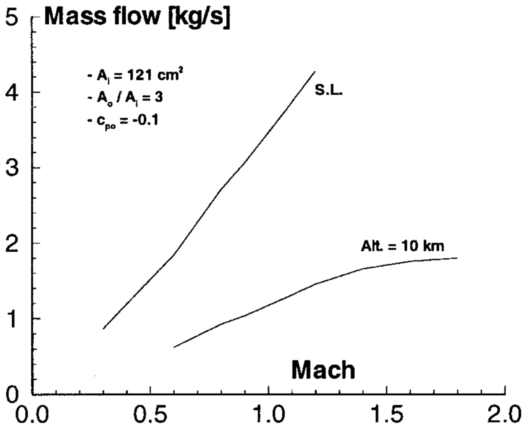

Fig. 4 Ventilation mass flow; A_i = 121 cm², c_p = −0.1, and A_0/A_i = 3.

Figure 5 shows the effect of selection of A_0/A_i on the mass flow. There is clearly a minimal increase in the mass flow for the range of exit-to-inlet area ratios for relatively low Mach numbers. However, as the Mach number increases, the suction at the outlet causes an increase in the pressure losses at the inlet. This has a detrimental effect on the pressure losses at the outlet via the discharge coefficient, which drops because of the reduction in the discharged mass ratio. This negative effect on the discharge coefficient could be avoided by use of a different type of outlet, for example, a recessed outlet, which exhibits higher discharge coefficient at very low discharge mass ratios.

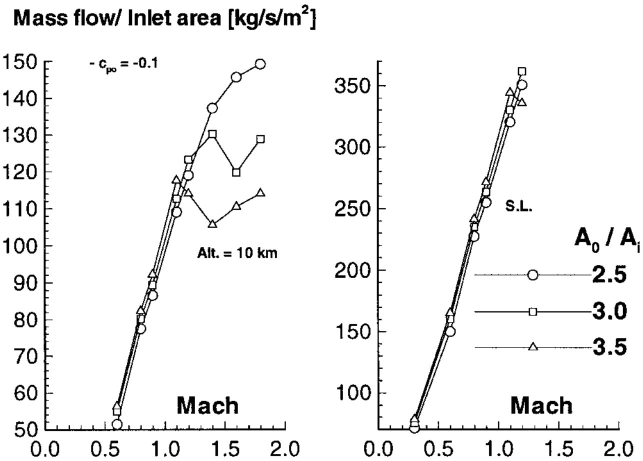

Fig. 5 Effect of A_0/A_i on ventilation mass flow.

Summary and Conclusions

A design for aircraft engine bays is presented that offers the following advantages:

1) Low impact on the aircraft performance because of minimized external drag and the absence of engine bleed requirements.

2) This design ensures good ventilation both on the ground, at static conditions via free convection at the front and the rear areas of the engine bay, and in flight via unidirectional flow from the intakes at the bay's front to the rear outlets.

A one-dimensional model for the analysis of the system is presented that balances the mass flow captured by the intakes with the capability of the outlet to expel this airflow overboard. The model includes the interrelated effects of the discharge coefficient and the discharged mass flow, as well as the pressure recovery of the inlet and the pressure coefficient at the outlet. The internal losses are handled via the assumption of dynamic pressure loss upon discharge into the bay and negligible friction losses within the engine bay. It is noted that at very high suction at the outlet, the inlet may ingest a shock wave, resulting in substantial pressure loss and flow rate reduction. The system can thus be optimized by selection of the inlet shape, the outlet-to-inlet area ratio, and the position of the outlet on the fuselage (via the pressure coefficient).

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