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Engineering Notes

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Review and Experimental Survey of Flapped Exhaust Performance

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Introduction

PRESSURE-RELIEF doors (PRDs) are used on engine nacelles to vent excess air to the freestream in the event of a burst of, or leak from, high-pressure supply lines in the interior of the nacelle. In the event of a duct burst, the resulting overpressure would compromise the nacelle structure, but the pressure difference across the PRD generates force sufficient to open a latch, allowing the door to swing open. Once the transient dynamics have settled out, the resultant steady casing pressure is dependent on the discharge flow rate, which is itself dependent on the ratio between the casing and external pressures, the angle at which the PRD settles, the external Mach number, and the size of the opening created.

Historically, little research has been done on this subject, and most of the current designs have been based on NACA experimental data regarding the discharge characteristics of flapped, curved duct outlets in transonic flows [1]. There are a number of passing mentions of experimental studies specifically related to flapped outlets in papers concerning more generalized auxiliary air systems [2,3]. When discharge into the mainstream is not transient, the effect of auxiliary air exhausted is of importance because it can produce drag or thrust. Outlet flow interacts with the boundary layer, leading possibly to separation or drag reduction depending on the configuration. For the purpose of classification, outlets can be divided into recessed, flush, and flapped types. Recessed outlets are characterized by a downstream ramp that is recessed below the surface. The flow over a recessed outlet will entrain and help to pump the outlet flow and, provided the ramp radius is large, the outflow will exhaust at a small angle relative to the freestream, thus recovering all the exhaust momentum. Flush outlets are generally holes in the surface, and they can be of the ducted or thin-plate types. For ducted outlets, the flow momentum is initially directed by the inclination of the outlet, whereas the outlet flow of a thin-plate type is a jet perpendicular to the mainstream. For ducted outlets at moderate inclination angle, the thrust obtained is approximately equivalent to the jet thrust. Flapped outlets usually exhibit a drag coefficient close to the base pressure coefficient, the value of which is lowered if the aspect ratio of the flap is larger than unity. However, as will be the case in this paper, when outlet mass flow is considered, a square flap configuration experiences a larger discharge coefficient than higher aspect ratio doors because of the larger flap suction. Information on the performance of inclined auxiliary outlets [4,5] shows that the discharge performance for given flow conditions is better for outlets with flaps than without.

A detailed and thorough investigation into the performance of flapped outlets was carried out by Vick [1] using a rectangular cross-sectioned duct with a curved axis. A number of flap models were considered, allowing a study of aspect ratio, hinge point, and flap angle. During the experiments the mass flow through the duct $\dot{m}$ was controlled and metered upstream and a dynamometer was also fitted to allow for force measurements. An important feature of Vick's experiment is that when the flap angle is null, the mass flow rate does not drop to zero because a significant gap still exists between the flap tip and the downstream end of the exhaust.

The results of the investigation showed that the stagnation pressure ratio (SPR) of outlet stagnation pressure to freestream stagnation pressure required to attain a given value of discharge flow ratio (DFR) decreases markedly with increasing flap deflection and varies strongly with freestream Mach number. In this context, DFR is defined as

$$\mathrm{DFR} = \frac{\dot{m}}{\rho_\infty V_\infty A} \tag{1}$$

where ρ_∞ is the freestream density, V_∞ is the freestream velocity, and A is a reference area corresponding to the minimum outlet cross-sectional area, determined by the distance between the flap and the opposite wall of the curved outlet duct. As the flap hinge point moves forward, the value of DFR decreases, with the flaps with an aspect ratio of one producing better discharge performance than those with an aspect ratio of two. However, the flaps with higher aspect ratio have shorter chords, meaning less of the flap is exposed above the boundary layer to the high-velocity freestream, leading to lower drag. At low values of DFR, the difference between the measured thrust and the measured drag (at zero outlet flow) was generally greater than calculated from momentum considerations, the difference being the result of the effect of the jet acting on the flap.

Following this review, it can be inferred that there is a lack of recent research in the area, because there has been no real study of the complex flow dynamics in and around auxiliary outlets. Furthermore, no consideration has been given to ventilation of cavities or plenums from a flapped outlet, with upstream boundary conditions more representative of that imposed by a core cowl.

In response to the relative lack of updated research in the area, a recent computational study [6] used the experimental work performed by NACA [1] as the basis of computational fluid dynamics (CFD) validation. A commercial CFD package (Fluent 6.1) was used on a combination of hexahedral mesh and tetrahedral in

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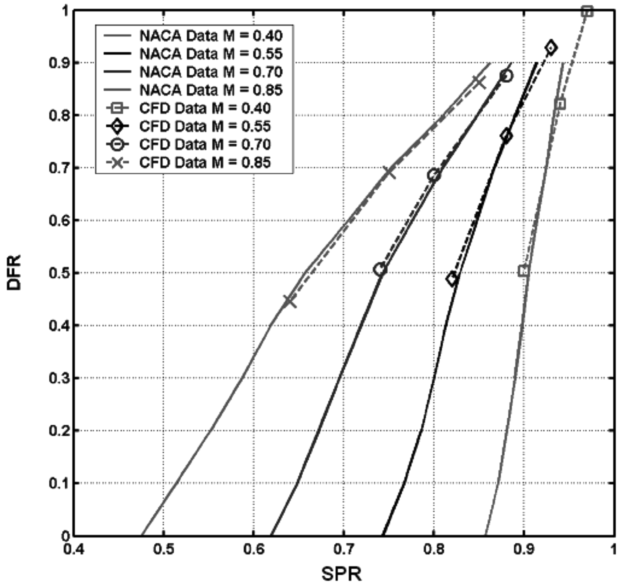


Fig. 1 Measured [1] and predicted [6] discharge coefficients as functions of pressure ratio for a flag angle of 25 deg.

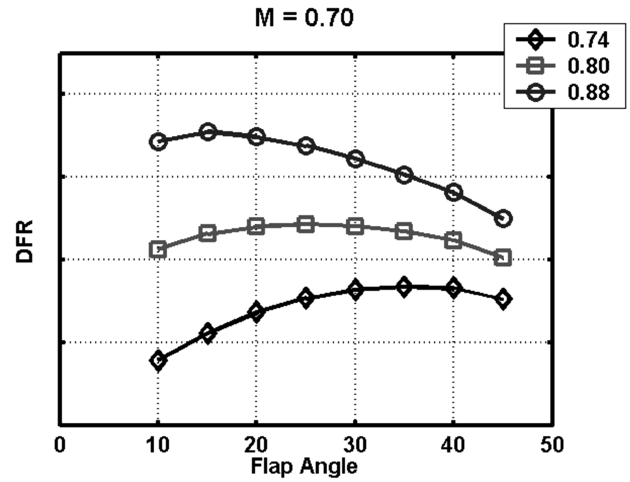


Fig. 2 Simulated DFR against flap angle for a range of pressure ratios [6].

the region of the flap and the duct exit. The compressible Reynolds-averaged Navier–Stokes equations were modeled with an implicit second-order upwind discretization and the use of a realizable k-ε turbulence model with standard wall functions. The side walls of the computational domain and the wall opposite the exhaust duct were defined as symmetry planes. A mesh dependence study indicated that meshes containing about 160,000 cells insured that the total pressure deficit in the core of the vortex that streams off the side edge of the flap was fully resolved.

Flap angles of 15 to 45 deg were studied at freestream Mach numbers varying from 0.4 to 0.85. As a result, the ratio of boundary-layer thickness to orifice length was approximately 0.1. The pressure ratio was varied between 0.64 and 0.97 to obtain the range of DFR required.

For example, DFR and total pressure ratio data for the given flap angle and freestream Mach number shown in Fig. 1 were extracted from the numerical predictions for a single flap angle and compared favorably with the corresponding data [1].

Another practical outcome from the study is the identification of the optimal flap angle for maximum discharge. DFR is plotted in Fig. 2 against the angle for each pressure ratio available and for one Mach number that is representative of typical flight conditions. In each case, DFR increases with flap angle up to a maximum before falling off. The angle at which this maximum occurs decreases with increasing pressure ratio. Increasing the Mach number also reduces the angle at which maximum discharge occurs. The maximum value of DFR increases with increasing pressure ratio but decreases with increasing Mach number.

Extrapolation of the predictions shows that for the majority of combinations of pressure ratio and Mach number, the zero pitching moment coefficients occurred in the range of 10 to 15 deg. A freely hinged, weightless flap would therefore achieve a trimmed balance in that range of angles. Increasing Mach number decreases this angle, whereas increasing pressure ratio increases it.

The limitations of the computational study were more obvious when the thrust generated by the outlet was considered: at the larger values of DFR, the CFD results overpredict the generated thrust, with the points lying just outside the envelope of experimental data, with an error between 5 and 10%.

When flow structure is considered, it can be seen that flap angle has a pronounced effect on the discharge performance of the outlet. Previous studies [2,3] indicated that flaps or other protrusions generated areas of low pressure over the outlet that increased discharge through suction. The computational study [6] demonstrates that the mechanism behind this is the formation of a pair of longitudinal vortices, shed from the edges of the flap. As the flap angle increases, the strength of the vortices increases until a maximum angle is reached. A marked difference between small and large flap angles can be identified: at large flap angles, a much stronger initial vortex pair is present, leading to a larger flow structure further downstream. For that configuration, the structure is lifted away from the surface more rapidly, weakening its interaction with the boundary layer. The lower pressure imposed by the vortex pair on the duct outlet may be expected to be an important factor in the DFR.

Experiments

Although it was demonstrated that CFD models are capable of assessing global performance as well as flow details, the available experimental database is limited to modest pressure ratios and flap angles (for a square geometry). Therefore, a research program was set up to extend the experimental database by covering larger pressure ratios than those tested in the NACA experiment. A cavity beneath the pressure relief orifice was included; this is a feature not considered in previous studies.

The experimental investigations were performed at Queen's University of Belfast in a 101.6-mm-square transonic suckdown intermittent tunnel that had a running time of 15 s, limited by the 80 m^3 volume of the driving vacuum tank. Therefore, the stagnation pressure and temperature are close to atmospheric conditions: on average, $p_o \approx 100$ kPa and $T_o \approx 294$ K. The freestream turbulence is approximately equal to 0.35%. The roof of the test section was an integral longitudinal slotted and perforated liner, each slot being 2.5 mm wide and 4 mm deep, with the spacing between slots at 7.5 mm. The base of each slot was drilled through a series of 2-mm-diam normal holes evenly spaced at 3 mm, giving the floor an open area of 9.6%. The cavity at the rear of the liner was ventilated at the end of the test section. The Mach number in the wind tunnel was measured with a sidewall pressure orifice upstream of the flap and was controlled by a downstream choke. Freestream Mach number was limited to approximately $M = 0.7$ to minimize blockage effects at the largest flap angle.

The model was a 20-mm square with a hinge located at 305 mm from the start of the test section. At that location, the estimated boundary-layer thickness was 7 mm. The uniform flap thickness was 2 mm, a value close to the average thickness of the slightly beveled NACA flap. Angles of 18, 27, 36, and 45 deg and stagnation pressure ratios between 1 and 1.5 were tested.

The feed to the plenum beneath the flap was provided by a Roots 1.6b compressor and a dryer unit. The cavity was 400 mm long, 88 mm wide, and 105 mm deep, and the bottom was covered by a screen placed at the interface between a wide-angle diffuser and the cavity. The flap hinge was located 80 mm downstream of the front wall of the cavity. Because of the use of a dryer unit in the line, the plenum stagnation temperature was only slightly higher than the

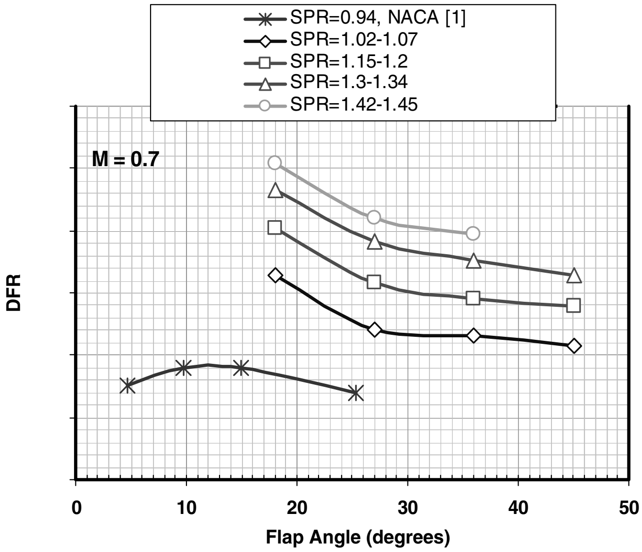


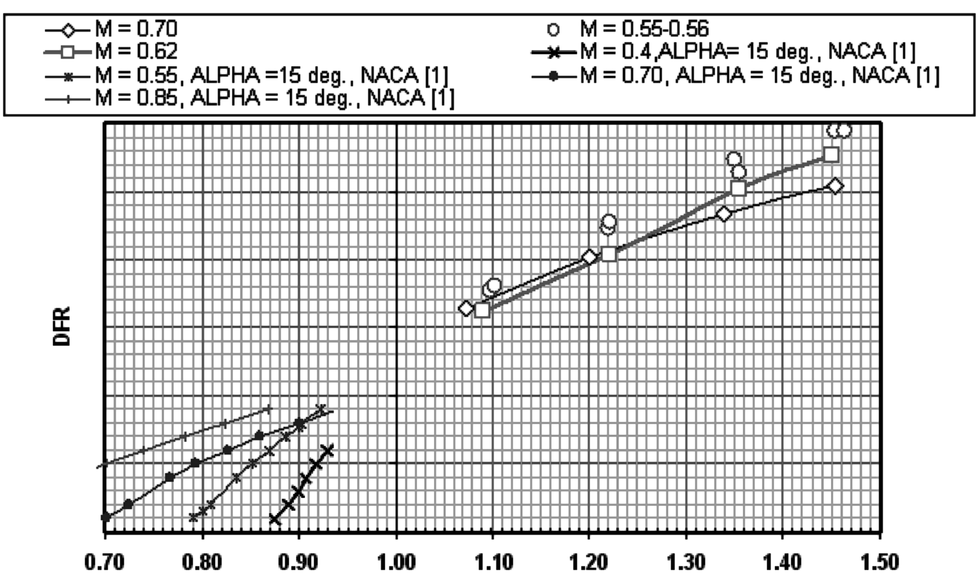
Fig. 3 DFR vs flap angle.

tunnel stagnation temperature, with the difference not exceeding 1 K. Estimated accuracies on SPR and DFR are 1 and 8%, respectively.

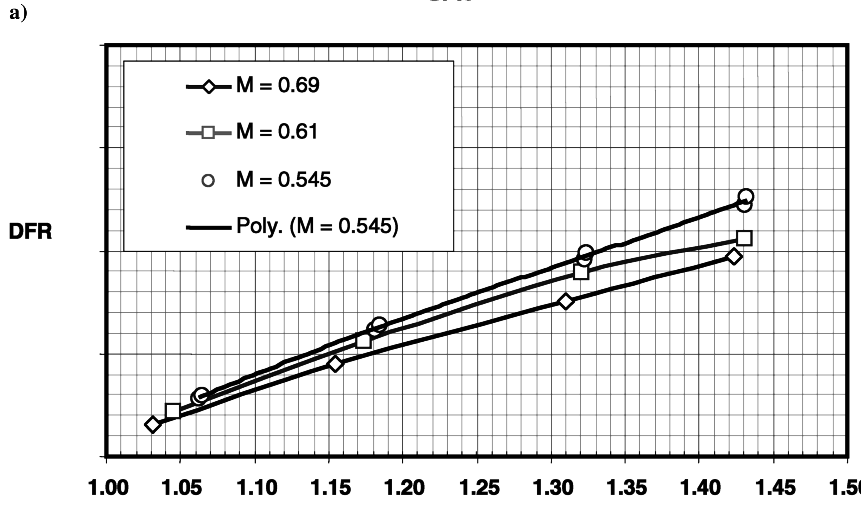
Typical results are presented in Fig. 3, which represents the change of discharge coefficient with flap angle at Mach 0.7. The curves are representative of results obtained at a lower Mach number. They indicate that DFR is much more sensitive to flap angle at pressure ratios above unity. Comparison with the NACA results suggests that it is possible that the DFR value peak occurs at angles below those tested; for example, at $M = 0.7$, there may exist an optimum angle in the region of 10 deg.

Schlieren visualizations tend to confirm the calculations: in contrast to the relatively smooth flow topology observed at small flap angles, the downstream boundary layer appears to be dominated by large structures when the flap is deployed at a large angle. The vortex system on each side of the flap appears to interact strongly with the jet, leading to large flow structures downstream that are likely to dissipate a significant part of the energy injected by the jet. This interaction of the jet with the shear-layer/flap tip vortices could explain the lower flow discharge coefficient at large opening angles.

As depicted in Fig. 4a, there is a marked effect of compressibility on the discharge performance at low pressure ratios, as shown in the NACA tests, with the discharge coefficient increasing with the Mach number. In contrast, the trend at SPR > 1 is the opposite: the role of Mach number in the discharge characteristics, at a given flap angle,



a)



b)

Fig. 4 Discharge coefficient functions of pressure ratio: a) 18-deg flap angle and b) 36-deg flag angle.

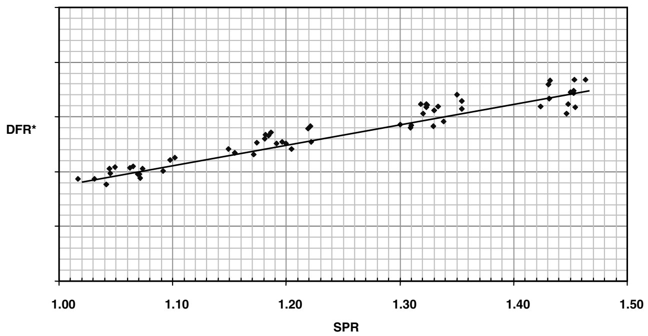


Fig. 5 Modified discharge coefficient function of pressure ratio.

then seems to be limited. Figure 4b demonstrates that this remark is also valid at large flap angles.

Within the range of angles tested beyond the peak of discharge, the results obtained can be reduced to a simple correlation. The notion of a modified discharge ratio DFR* is introduced to take into account that the effective minimum area of discharge is not equal to the geometrical projection:

$$\mathrm{DFR}^* = \frac{\dot{m}}{\rho_\infty V_\infty A_{\mathrm{flap}} (\sin\alpha)^\beta} \tag{2}$$

where A_{flap} is the flap area, α the flap angle, and β an empirical constant that optimizes the collapse of data points. The choice of $\beta = 0.6$ provides a linear fit to DFR* within the tested range of SPR (Fig. 5). The parameter β is more generally a function of the flap geometry and it seems to capture the degree of three-dimensionality of the flow.

Conclusions

An extension to work by NACA was presented for a square flap opening from a large cavity to a transonic turbulent boundary layer. For flap angles from 18 to 45 deg, the discharge coefficients decrease at given stagnation pressure ratio between the cavity and the freestream. This loss of performance is likely linked to competitive flow features. At a given flap deflection and Mach number, dimensionless discharge increases nearly linearly with pressure ratio.

Acknowledgments

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