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Boundary Layer Separation in a Centrebody Nozzle with Parallel Shroud

By

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LONDON: HER MAJESTY'S STATIONERY OFFICE

1966

PRICE 3s. 0d. NET

C.P. No. 853

U.D.C. No. 621-225.1:532.526.3

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September, 1965

SUMMARY

A nozzle has been tested with conical centrebody and a parallel outer shroud long enough to give a large measure of internal expansion. Centrebody pressure distributions have been obtained corresponding to both laminar and turbulent boundary layers. The critical Reynolds number criteria, previously deduced for convergent-divergent nozzles, are found to apply fairly well to the present shape.

Replaces N.G.T.E. Report R.271 - A.R.C.27 306.

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ILLUSTRATIONS

1.0 Introduction

Previous work on boundary layer separation in supersonic nozzles has been almost exclusively concerned with plain convergent-divergent shapes; Reference 1 summarises the present state of knowledge in this field. In the absence of mechanical variability, the off-design performance of this type of propelling nozzle in an aircraft is governed by internal over-expansion of the flow, thus depending upon separation characteristics, and hence upon the state of the boundary layer - whether laminar or turbulent. It has been suggested that a critical level of Reynolds number can be used as an indicator of whether the boundary layer in a nozzle is fully turbulent, and a value for this critical Reynolds number has been deduced[1] for axisymmetric convergent-divergent nozzles.

Of current interest for certain aircraft applications are propelling nozzles which consist of a centrebody and parallel outer shroud[2,3] (see Figure 1). It is normally arranged that the shroud is translated relative to the centrebody, so as to avoid internal over-expansion of the flow - indeed, this is the guiding principle behind the success of this design. Internal separation per se, in these nozzles, is not therefore of great importance. But a knowledge of the state of the boundary layer is nevertheless necessary, especially for instance in estimating the effects of friction. Thus it would evidently be of interest to discover whether a similar criterion in terms of a critical Reynolds number obtains in the case of a centrebody nozzle as in a convergent-divergent. And the most convenient means of exploring boundary layer state in a nozzle is by a study of separation behaviour.

2.0 Test equipment

The experimental arrangement was the same as that described in Reference 2, with provision for testing in both quiescent air and external flow.

The model, shown diagrammatically in Figure 1, was of similar type to those previously tested[2,3]. (Details of construction may be seen in Figures 5 and 6 of Reference 2.) In this case the conical centrebody half-angle was 15°, the design pressure ratio nominally 20, and the shroud used throughout was No. 6 in the series mentioned in Table I of Reference 3. This gave a value of approximately 17 for the internal expansion pressure ratio†. A large number of static pressure tappings was fitted in the centrebody surface from throat towards the tip, 28 being used in these tests.

Dry air was supplied to the rig at pressures up to 5 atm and at around 30°C.

3.0 The flow system

When a centrebody nozzle of this type, with shroud sufficiently long to give a large measure of internal expansion, is operated at low exhaust pressure ratio, a flow pattern will be created after the manner

†This quantity is based upon plane annular areas and one-dimensional isentropic relations.

of Figure 2. Separation shocks must develop from both shroud and centrebody; when these are generated far enough upstream, they will intersect and produce branches which impinge on opposite walls of the annular divergent passage. One may therefore expect to see, under certain conditions, a centrebody pressure distribution consisting of two regions of compression, corresponding in turn to the initial centrebody separation shock, and to the impinging shroud separation shock.

It seems likely that the pressure rise at separation on both shroud and centrebody will, under appropriate operating conditions, conform approximately to the general correlation established in Reference 1 for convergent-divergent nozzles. This was found to be apparently independent of nozzle area ratio, of wall divergence angle within a considerable range, of specific heat ratio, and of whether the nozzle is axisymmetric or two-dimensional in form. The pressure rise across the shock-boundary-layer interaction which produces separation is in fact mainly governed by the local Mach number of the flow and by the boundary layer state before separation. Applying this conclusion to an annular nozzle, it is evident that the overall pressure rise experienced across an intersecting system of separation shocks, as in Figure 2, will considerably exceed the pressure rise in a nozzle with only a single wall perimeter. If, to a first approximation, the shock branches are all of similar strength, then the overall pressure rise on the centrebody would be roughly twice that on the wall of a convergent-divergent nozzle. (This, of course, ignores any feed-back effect of overall pressure rise - i.e. of effects downstream of the first shock-boundary-layer interaction - on the incipient Mach number, and hence on the position of separation. But the idea may serve to indicate a likely order for the behaviour of an annular nozzle.)

From this follows the thought that, for a given back-pressure and internal expansion area ratio, significantly more over-expansion must take place in an annular nozzle prior to separation than in a convergent-divergent. Thus the off-design thrust performance of the annular system can be expected to be worse.

4.0 Test results

The model was tested in two ways, at values of E.P.R. from 2 to 7, so as to produce considerable differences in level of Reynolds number. First it was run in quiescent air, the results for which are shown in Figure 3, and secondly in external flow at $M_\infty = 2.5$, producing Figure 4.

Two forms of Reynolds number are quoted. The first, Re_X, is an equivalent flat plate Reynolds number, based on estimated conditions at the point of incipient separation - taken to be where the pressure distribution curve leaves the running-full line. This should truly characterise the local boundary layer state. The second, Re^*, is the throat Reynolds number, based on sonic flow conditions and a dimension which, following Reference 2, is taken as the diameter of a circle having the same area as the nozzle throat ($D^* = 2.0$ in.). An obvious alternative dimension would be the annular throat height ($H^* = 0.32$ in.); this will be discussed further later on. Throat Reynolds number is often used as a convenient reference quantity.

Marked in Figures 3 and 4 is the position where the shroud ends, and it can thus be seen that the pressure distributions given correspond entirely to the internal expansion region of the nozzle. With a centrebody nozzle, it is of course necessary to distinguish between pressure rises from shocks occurring in the internal and external expansion fields. The former are clearly due to boundary layer separation; the latter (e.g. Figures 27 and 28 of Reference 3) are not.

On curves A to D of Figure 3 are indicated by means of circular symbols the limits of pressure rise for a convergent-divergent nozzle with turbulent separation occurring at the same Mach number, taken from Reference 1. It is interesting to compare these circular points with the dashed line, drawn approximately where the second phase of compression is deemed to start. This, as discussed in Section 3.0, corresponds to the arrival of the shock originating on the shroud (see Figure 2). For curves E and F, this would lie beyond the band of pressure tappings used. It seems from this comparison that the pressure rise across the shock-boundary-layer interaction producing separation on a centrebody is quite similar to (slightly less than) that occurring in a convergent-divergent nozzle at the same Mach number. The latter in turn is similar to the pressure rise on a flat plate with induced separation[1].

There seems no doubt that the boundary layer in Figure 3 was turbulent at separation, at least for curves B to F; curve A shows what could be a laminar foot. On the other hand, in Figure 4 the boundary layer was clearly laminar throughout. Reference 1 suggests that a critical value of Re_X exists around 0.7 million for convergent-divergent nozzles, and this is broadly consistent with Figures 3 and 4, implying that this criterion may also be sensibly applied to nozzles of centrebody form. Such, indeed, might be expected.

However, Re_X is not suitable for general use in predicting boundary layer state in the divergent portion of a nozzle. For one thing, it grows from a value close to zero at the throat. A more convenient if less meaningful quantity is Re^*, and for convergent-divergent nozzles with wall half-angles in the range 10^o to 15^o, Reference 1 suggests taking as a guide a critical value in the neighbourhood of 1.0 million. It is certainly not obvious whether this can be applied equally well to centrebody nozzles: in the first place, there is the possible and uncertain effect of wall angle outside the range given; furthermore, there is legitimate doubt as to the characteristic dimension of an annular throat.

Of considerable interest, therefore, is the evidence of Figures 3 and 4 that the boundary layer is laminar at or below $Re^* = 0.61$ million and turbulent above 1.46 million, using the dimension D^*. This is in very fair agreement with the criterion for convergent-divergent nozzles cited from Reference 1. Since H^* is approximately one-sixth of D^*, it is quite certain that the same criterion does not apply to centrebody nozzles if H^* is used as characteristic dimension. This result, namely that boundary layer properties may be compared on a basis of D^*, could be of use in assessing frictional losses (see Appendix III of Reference 2).

5.0 Conclusions

A nozzle has been tested with conical centrebody and a parallel outer shroud long enough to give a large measure of internal expansion. Centrebody pressure distributions have been obtained corresponding to both laminar and turbulent boundary layers.

Because of the flow pattern in an annular nozzle, with separation shocks generated on both centrebody and shroud, there are two phases of compression on the centrebody; the overall pressure rise within the internal expansion region may be approximately double that on the walls of a convergent-divergent nozzle when separation occurs at the same Mach number.

The critical separation Reynolds number criterion for convergent-divergent nozzles can be applied sensibly to a centrebody: this gives 0.7 million as the lowest value for the boundary layer at separation to be naturally turbulent. As a general guide to boundary layer state, a throat Reynolds number is convenient; this has to exceed a critical value of around 1.0 million to ensure a turbulent boundary layer in the divergent portion of a convergent-divergent nozzle, and the same criterion also seems applicable to a centrebody, provided that the characteristic dimension is taken as the diameter of a circle having the same area as the nozzle throat.

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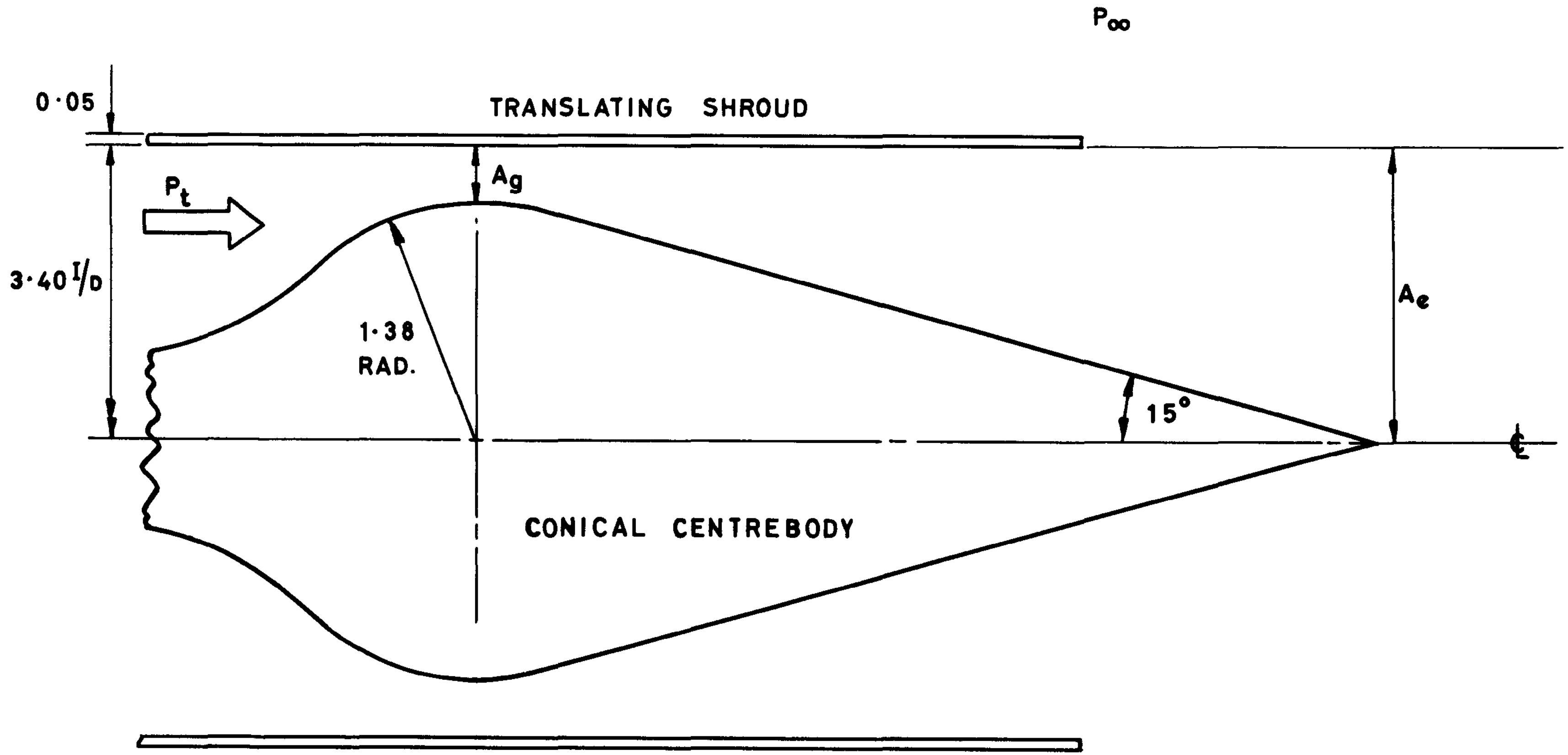
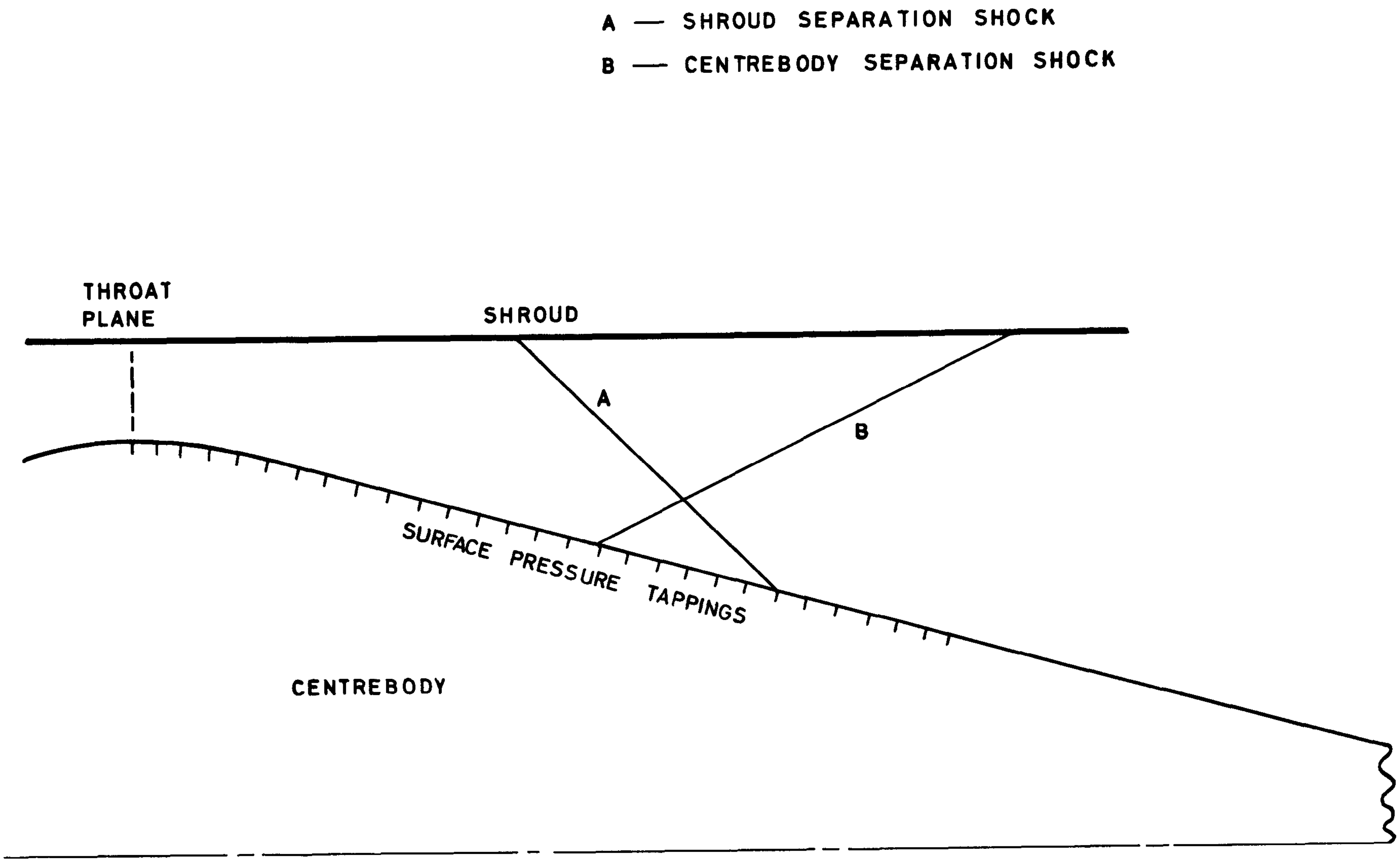
Notation and definitions

A_g	geometric nozzle throat area
A_e	nozzle exit area
D^*	diameter of a circle having the same area as the nozzle throat
H^*	annular throat height
M_∞	external Mach number
P_t	nozzle entry total pressure
P_∞	ambient or freestream static pressure
E.P.R.	exhaust pressure ratio $= \frac{P_t}{P_\infty}$
D.P.R.	design pressure ratio, corresponding to the area ratio A_e/A_g
I.E.P.R.	internal expansion pressure ratio, corresponding to the ratio of plane flow areas at shroud lip and nozzle throat
Re_X	separation Reynolds number, based on the equivalent flat plate length - i.e. that length over which a boundary layer growing at a constant Mach number equal to the local Mach number would attain the same thickness as the actual local boundary layer at incipient separation
Re^*	throat Reynolds number, based upon sonic flow conditions and dimension D^*



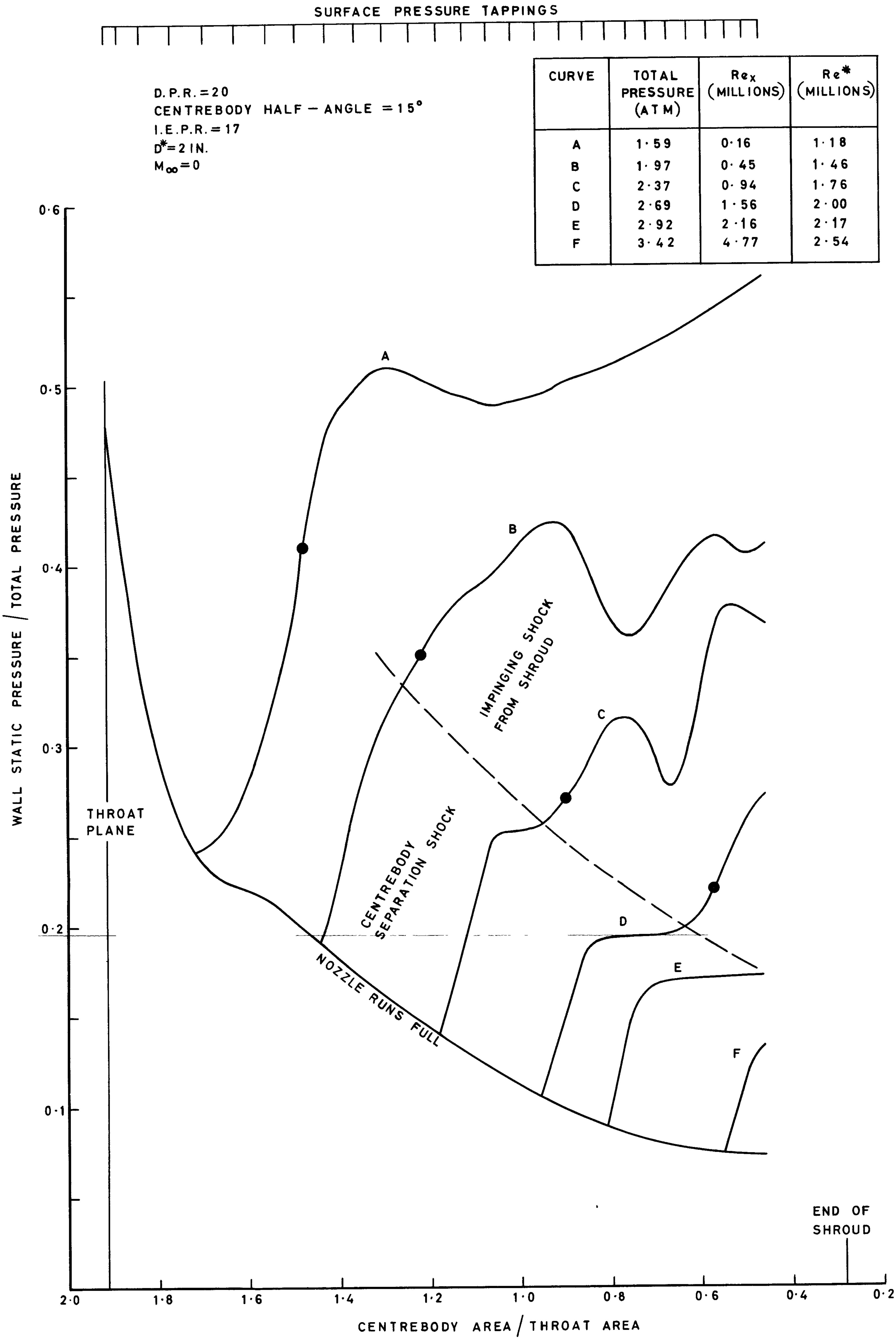
NOZZLE ARRANGEMENT.

FIG. 1



SEPARATION SHOCK PATTERN.

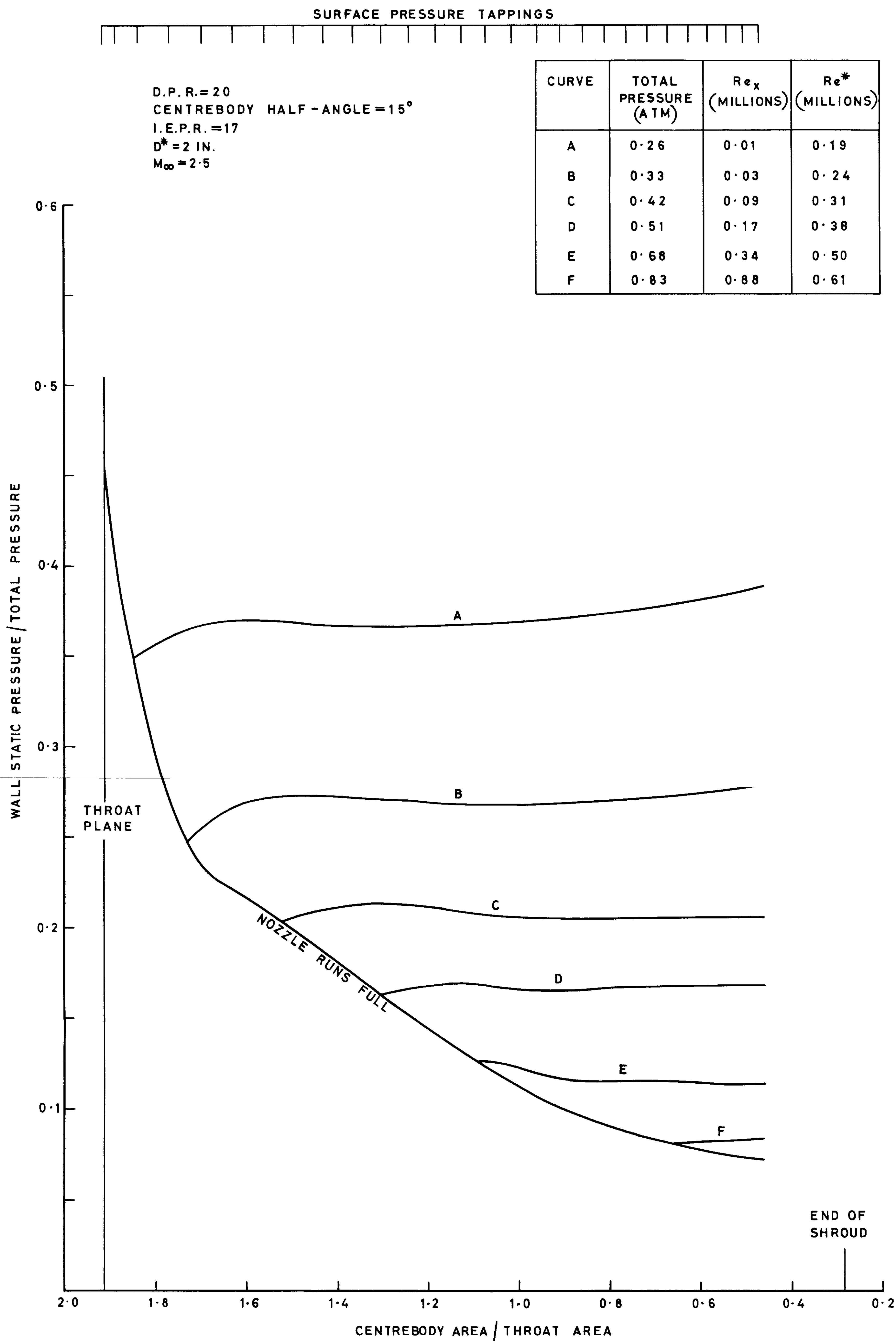
FIG. 2



CURVE	TOTAL PRESSURE (ATM)	Re_x (MILLIONS)	Re^* (MILLIONS)
A	1·59	0·16	1·18
B	1·97	0·45	1·46
C	2·37	0·94	1·76
D	2·69	1·56	2·00
E	2·92	2·16	2·17
F	3·42	4·77	2·54

CENTREBODY PRESSURE DISTRIBUTION — I.

FIG. 3



CURVE	TOTAL PRESSURE (ATM)	Re_x (MILLIONS)	Re^* (MILLIONS)
A	0·26	0·01	0·19
B	0·33	0·03	0·24
C	0·42	0·09	0·31
D	0·51	0·17	0·38
E	0·68	0·34	0·50
F	0·83	0·88	0·61

FIG. 4

CENTREBODY PRESSURE DISTRIBUTION — II.

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BOUNDARY LAYER SEPARATION IN A CENTREBODY
NOZZLE WITH PARALLEL SHROUD

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C.P. No. 853

S.O. Code No. 23-9016-53