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The Efficiency of a Pitot Intake Inclined to the Air Stream

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Summary.—In an earlier report on intake ducting for supersonic flight[1], the efficiency of a 'pitot' type intake was discussed and shown to have a marked effect on the performance of gas turbine engines.

The present report is supplementary in that it describes the effect of inclining the pitot intake to the main air stream direction in the transonic Mach number range 0·7 to 1·5, an effect which is at present incalculable. Curves are presented showing the influence of inclination on intake adiabatic efficiency and air mass flow into the intake. These experimental results are then illustrated by application to the performance of a typical turbine engine and a propulsive duct in sonic and supersonic flight. At a flight Mach number of 1·5, it is found that, for both turbine engine and propulsive duct, an inclination of 5 deg reduces the net thrust by roughly 2 per cent compared with the normal flight thrust. For inclinations greater than 5 deg, however, thrust falls off more rapidly, and at 10 deg inclination, it is reduced by roughly 6·5 per cent for the turbine engine and 7·5 for the propulsive duct.

1. *Experimental Investigation.*—A sketch of the model is shown in Fig. 1. The pitot intake (a half-scale model of that employed in the investigation of Ref. 1) consisted of a straight taper, divergent duct of 7 deg total internal angle, the entry internal diameter being 0·5 in. and the area ratio four to one.

The static pressure (P_e) at the delivery end of the divergent duct was measured over a range of air mass flows at approach Mach numbers 0·7, 0·9, 1·0, 1·3, 1·5, for a range of inclination $\theta = \pm 15$ deg in intervals of 3 deg.

The airstream, approximately 2·5 in. square in cross-section, was supplied by Busemann nozzles for Mach numbers greater than unity, while for the sonic and subsonic streams a non-divergent nozzle was used.

2. *Discussion of Results.* 2. 1. *Efficiency.*—The variables involved are overall adiabatic efficiency, Mach number of the approach stream, air mass flow and angle of inclination (θ). The intake adiabatic efficiency, η_i, is based on delivery static pressure P_e, no correction being made for any difference between delivery static and total head pressures. That is

$$\eta_i = \frac{(P_e/P_a)^{(\gamma-1)/\gamma} - 1}{(P_{\text{tota}}/P_a)^{(\gamma-1)/\gamma} - 1} = \frac{(P_e/P_a)^{(\gamma-1)/\gamma} - 1}{\frac{1}{2}(\gamma - 1)\, M_a^{\,2}}$$

where P_{tota} total head pressure of approach stream.

P_a static ,, ,, ,, ,,

In Figs. 2 to 6, this efficiency is shown plotted against the ratio of actual mass flow to the maximum mass flow at zero inclination, for the five approach Mach numbers, with angle of inclination as parameter. Each curve is the mean of two experimental curves, one for positive, the other for negative angle of inclination. Fig. 7 gives an indication of the scatter of the experimental points. Within the chosen range of inclination, that is $\pm$ 15 deg, there is no effect of inclination on efficiency at zero mass flow, which is perhaps to be expected since the intake is then acting as large pitot tube.

It will be seen that for zero inclination at supersonic approach velocities, there is a fairly well defined mass flow below which the efficiency remains constant, and above which the efficiency rapidly falls to zero. The first region of the curve corresponds to the state in which a curved shock surface is located ahead of the intake, delivery pressure being comparatively independent of mass flow. With increasing mass flow, this shock wave approaches the intake and becomes less concave, until in theory a plane shock wave is located across the entry, and the mass flow reaches a maximum 'correct' value equal to the mass of air impinging on the entry. This condition corresponds to the region in which the curve turns over sharply. Any further reduction in delivery pressure leads by 'over-expansion' to higher supersonic velocities in the diffuser, followed by a complicated system of shock-waves.

In practice, the theoretical curves are approached only at high Mach numbers, and below an M_a of about 1·5 the abrupt change in direction of the curves becomes more gradual. As is to be expected, inclination of the intake to the approach stream direction also gives the curves a gradual sweep, since a plane shock wave can obviously not occur across the entry. Subsonically, this tendency is much more marked.

2. 2. *Reduction of Mass Flow.*—Inclining the intake to the approach stream leads to a reduction in the maximum mass flow which can pass into the entry (Fig. 8). As this effect is most marked at subsonic approach velocities, some additional curves have been added down to a Mach number of 0·5. For the lowest Mach numbers, the reduction in back pressure was limited by the orifice meter and straightener plate, and curves are given only for small angles of inclination. It is seen that an angle of inclination of 10 deg leads to a mass flow reduction of 1·5 to 3 per cent over the Mach number range 0·8 to 1·5, but to a much greater reduction at lower Mach numbers. At zero angle of inclination, the mass flows calculated from intake conditions are in reasonable agreement with those measured by the air-flow meter.

Also shown are points, indicated by circles and squares, corresponding to the possible laws of mass-flow ratio varying as $\cos\theta$ and $\cos^2\theta$ respectively, where θ is the angle of inclination.

3. *Engine Thrust in Supersonic Flight.*—By virtue of the influence on intake efficiency, inclination of an aircraft with pitot intake to its flight path will affect the engine thrust. In order to illustrate this effect, calculations have been carried out for a typical gas turbine engine and for a propulsive duct in supersonic flight, the following characteristics being assumed at isothermal height.

Gas Turbine Engine.

Compressor temperature rise	=	200 deg C
Bypass air mass flow/Compressor air mass flow	=	2
Fan temperature rise	=	35 deg
Engine T_{max}	=	1100 deg K
Augmentor T_{max}	=	1500 deg K
Compression efficiency (including combustion pressure loss)	=	75 per cent
Fan efficiency	=	80 per cent
Turbine efficiency	=	84 per cent
Augmentor combustion pressure loss as for propulsive duct below		

Propulsive Duct

T_{max}	=	1500 deg K
Combustion chamber inlet velocity/aircraft velocity	=	0·1
Jet efficiency	=	95 per cent

The combustion chamber pressure loss is assumed to be made up of an aerodynamic loss of four inlet velocity heads together with the fundamental heating loss. That is

$$\frac{\text{Combustion chamber pressure loss}}{\text{Combustion chamber inlet velocity head}} = \frac{T_{\text{tot max}}}{T_{\text{tot inlet}}} + 3$$

In both cases the assumption of constant volume flow is made (for the propulsive duct the combustion chamber inlet velocity is taken constant for a given forward speed), so that it is possible to find a relation between intake efficiency and mass flow ratio for each approach Mach number, provided that a design mass flow is assumed. For the thrust calculations, this has been taken, for each approach velocity, as 95 per cent of the maximum mass flow which can pass through the intake at zero inclination. As noted previously, this value is reasonably well defined for $M_a = 1 \cdot 5$, occurring just before the abrupt reduction in efficiency. The same value of 95 per cent is used for lower approach velocities, although the point becomes less clearly defined. Thus in Figs 2 to 4, the dashed lines represent operating curves for both turbine engine and propulsive duct, and have been drawn for design mass flows of 95 per cent and 90 per cent of the maximum mass flow at zero inclination.

Figs. 9, 10 show the net thrust and specific fuel consumption for the turbine engine and propulsive duct respectively, relative to their values at 100 per cent intake efficiency, this basis being chosen to avoid overcrowding the curves, the slopes of which are roughly equal at flight Mach numbers of 1·5 and 1·3 but rather greater in sonic flight.

Conclusions.—At zero mass flow through a pitot-type intake, angles of inclination up to 15 deg have no effect on overall adiabatic efficiency, the intake then acting as a large pitot tube.

With increasing through-put a reduction in efficiency appears, but is not serious for angles of inclination below 5 deg until the mass flow approaches the correct value, that is the maximum mass flow at zero inclination. It is possible to plot mass flow-efficiency curves for which a constant volume of air enters the intake, and these will represent engine operating curves for given design mass flows. Choosing a design mass flow equal to 95 per cent of the correct mass flow for each approach velocity, it is found that for both turbine engine and propulsive duct at a flight Mach number of 1·5, an inclination of 5 deg reduces the net thrust by roughly 2 per cent compared with the normal flight thrust. For inclinations greater than 5 deg, however, thrust falls off more rapidly, being reduced at 10 deg by roughly 6·5 per cent for the turbine engine and 7·5 per cent for the propulsive duct. Under the same conditions, specific fuel consumption is increased by 3 per cent and 4·5 per cent for turbine engine and propulsive duct respectively.

Maximum through-put is moderately affected by inclination in the transonic Mach number range 0·8 to 1·5, the reduction being of the order 1·5 per cent to 3 per cent for 10 deg inclination. For lower subsonic velocities however, the effect is much greater.

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No.	*Author*	*Title*
1	A. G. Smith, E. L. Place, and S. J. Andrews	Intake Ducting for Supersonic Flight. Power Jets Ltd. Memorandum No. M. 1161. December, 1945.

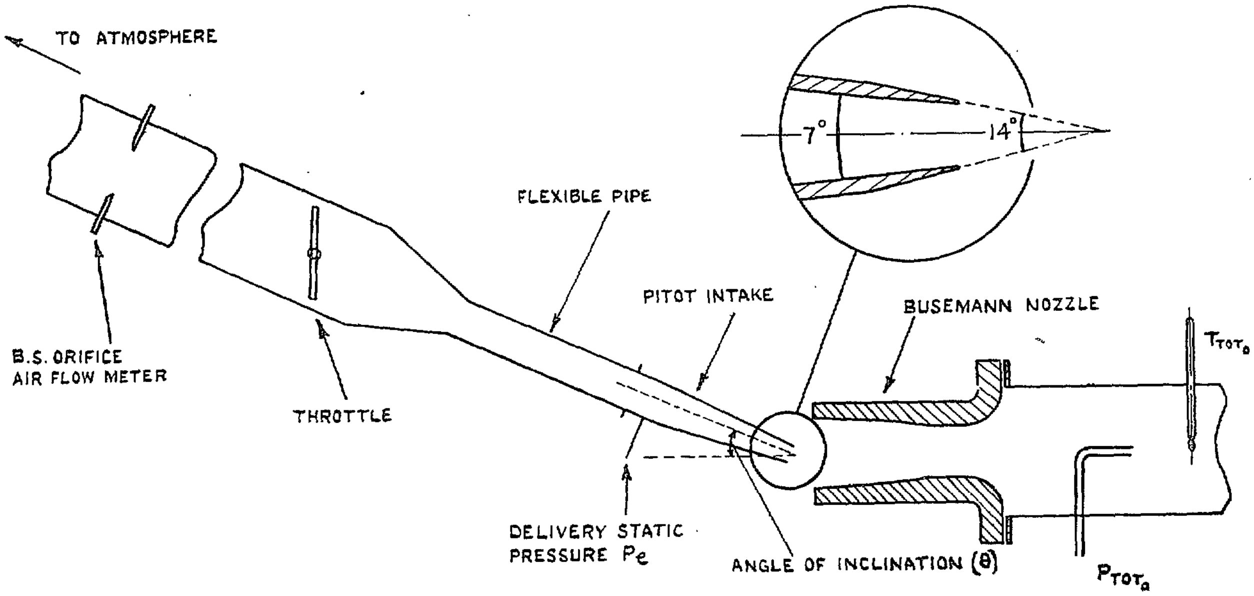

FIG. 1. Inclined pitot intake test rig.

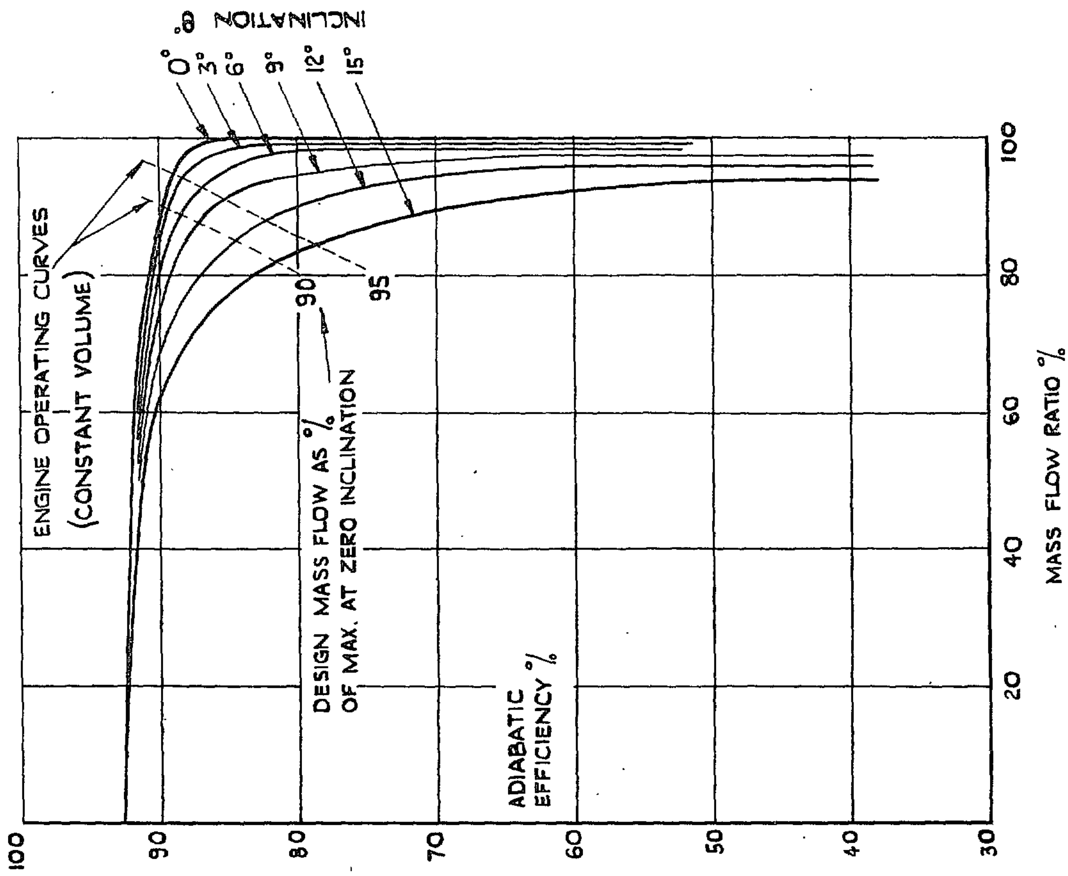

FIG. 2. Inclined pitot intake. Variation of overall adiabatic efficiency with angle of inclination. Approach Mach number = 1·52.

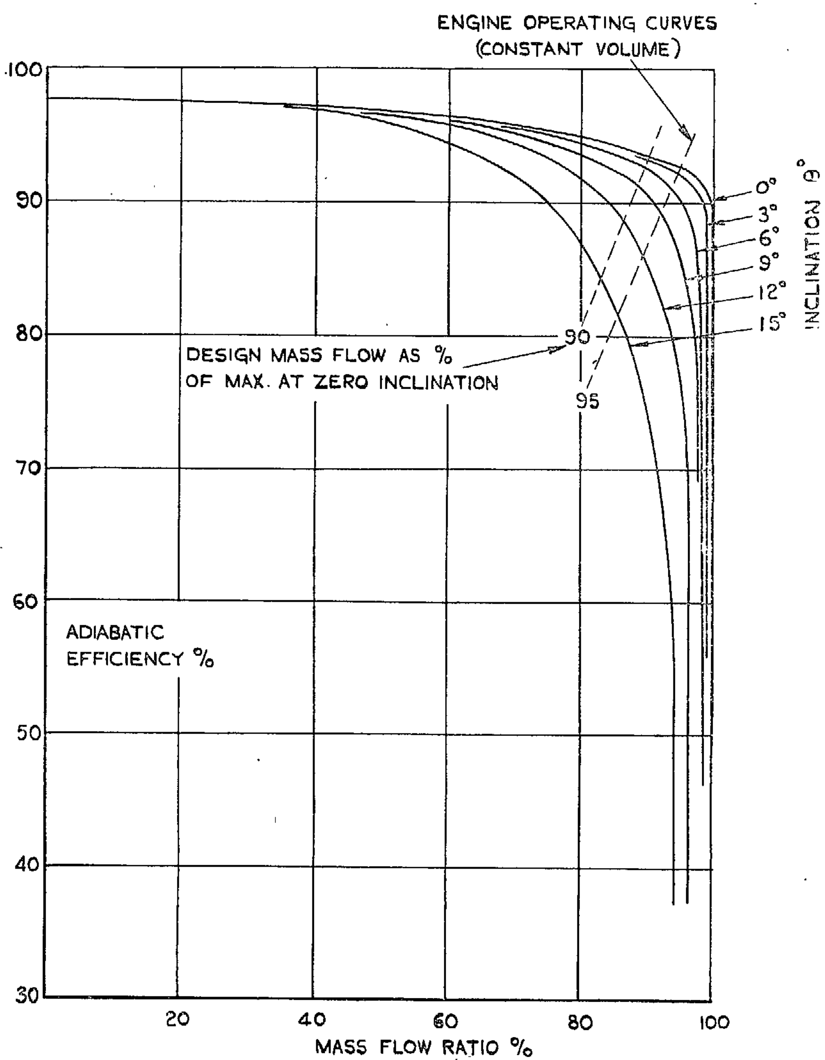

FIG. 3. Variation of overall adiabatic efficiency with angle of inclination. Approach Mach number = 1·31.

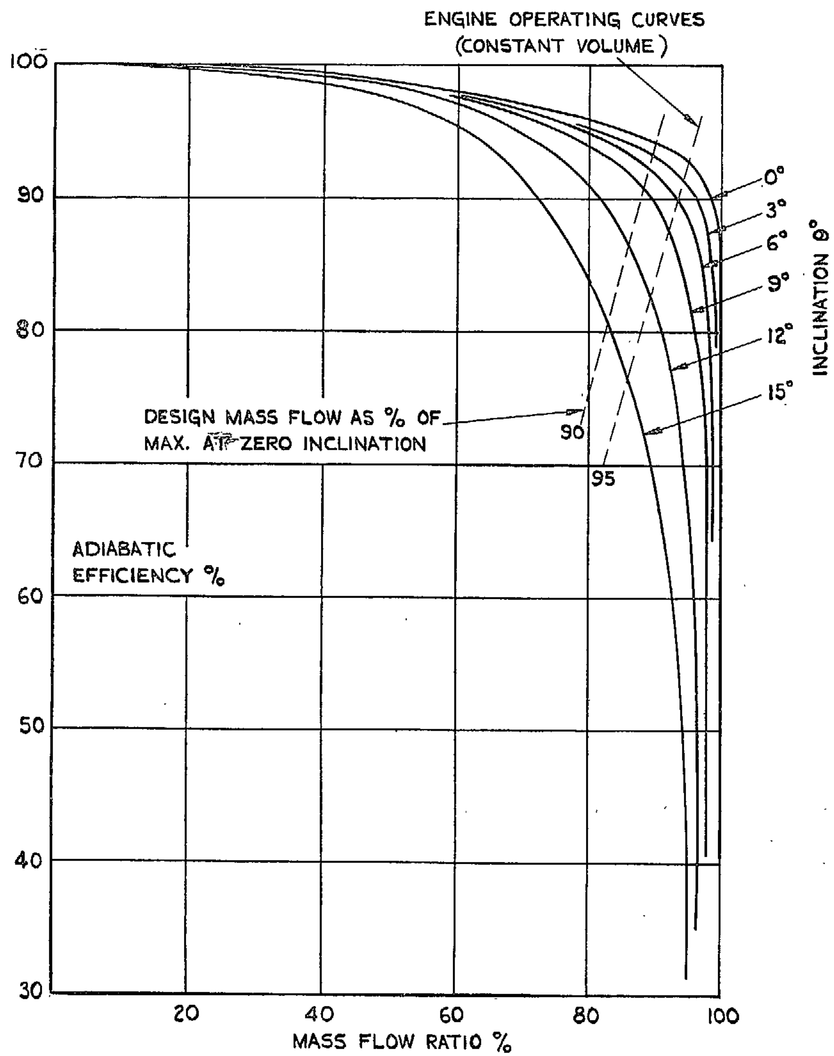

FIG. 4. Variation of overall adiabatic efficiency with angle of inclination. Approach Mach number = 1·0.

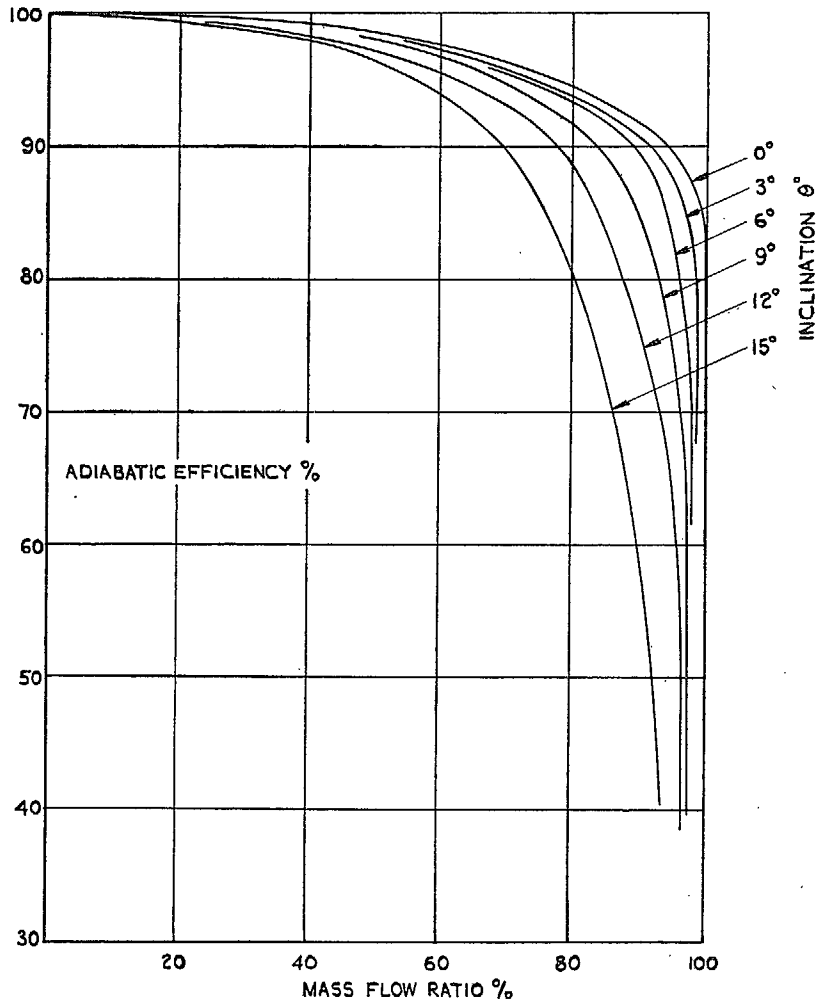

FIG. 5. Variation of overall adiabatic efficiency with angle of inclination. Approach Mach number = 0·9.

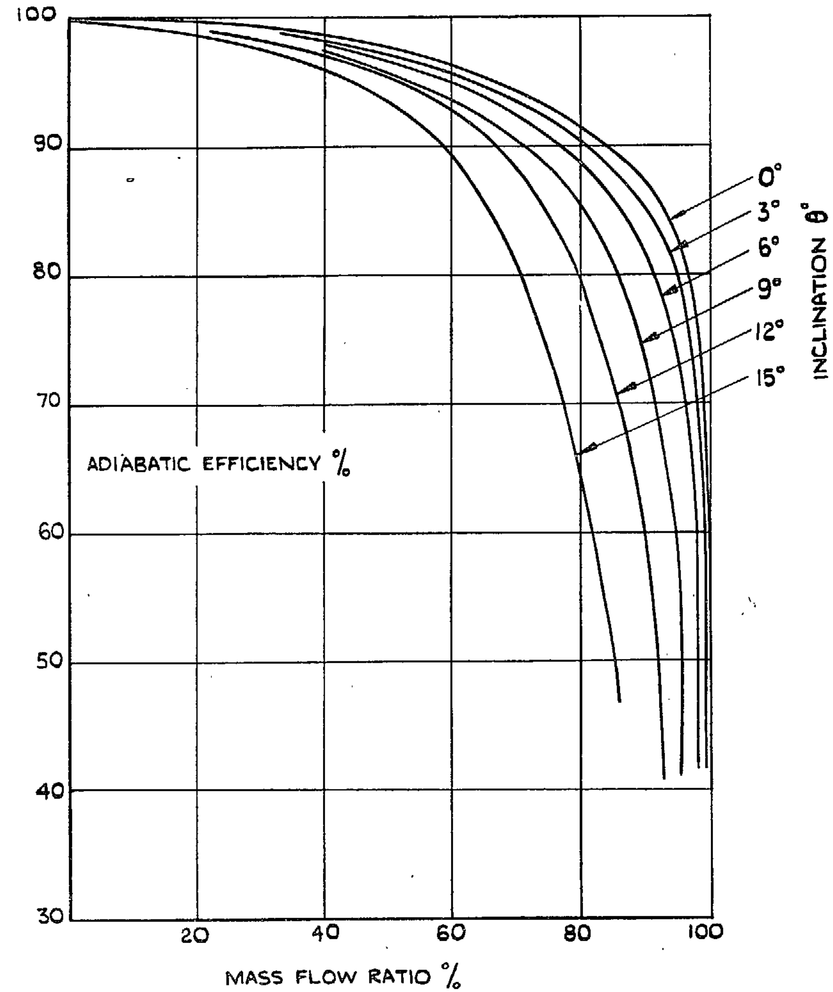

FIG. 6. Variation of overall adiabatic efficiency with angle of inclination. Approach Mach number = 0·7.

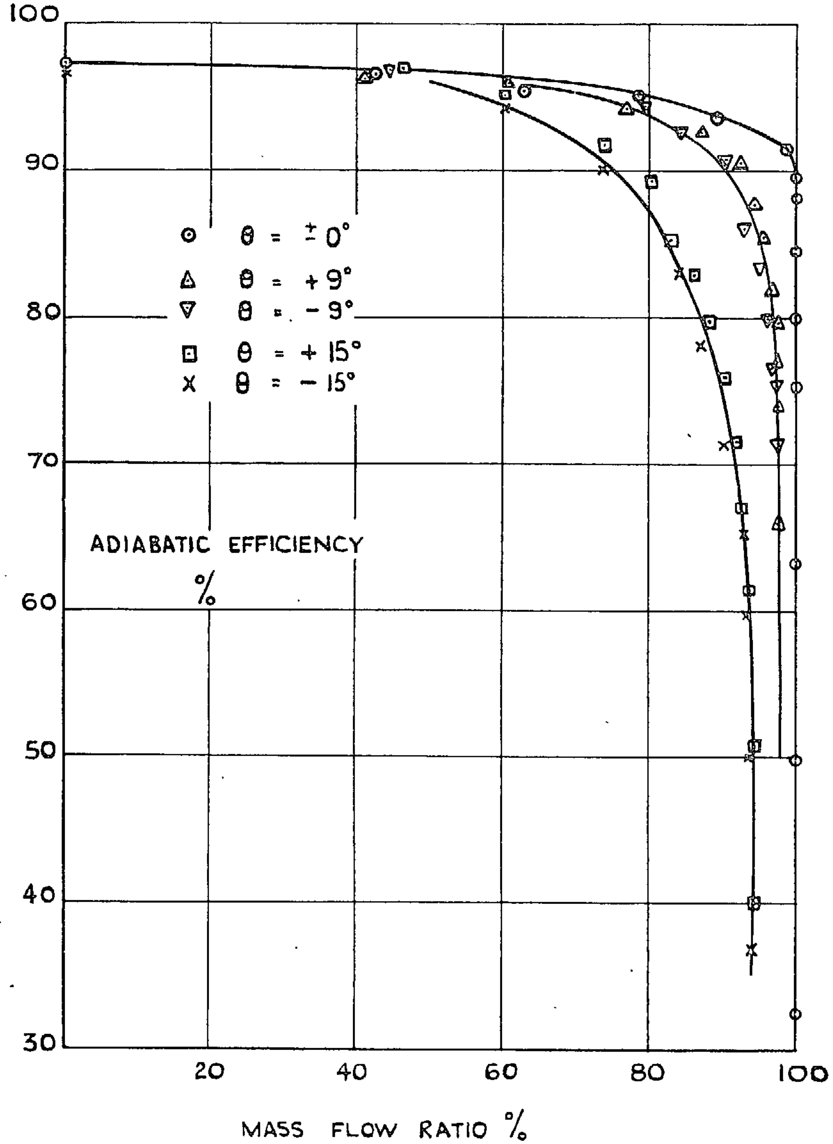

FIG. 7. Variation of overall adiabatic efficiency with angle of inclination θ.
Approach Mach number = 1·31.

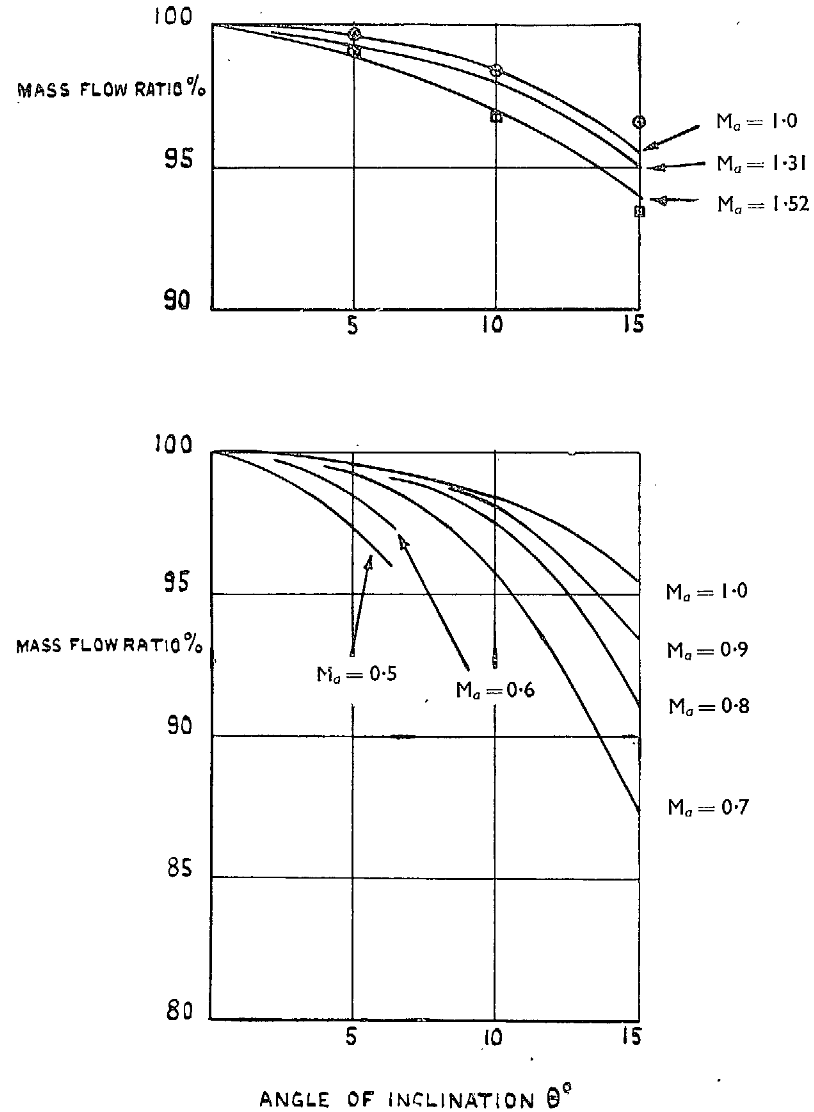

FIG. 8. Variation of maximum through-put with inclination. (Curves corresponding to mass flows obeying $\cos\theta$ and $\cos^2\theta$ laws are indicated by circles and squares respectively).

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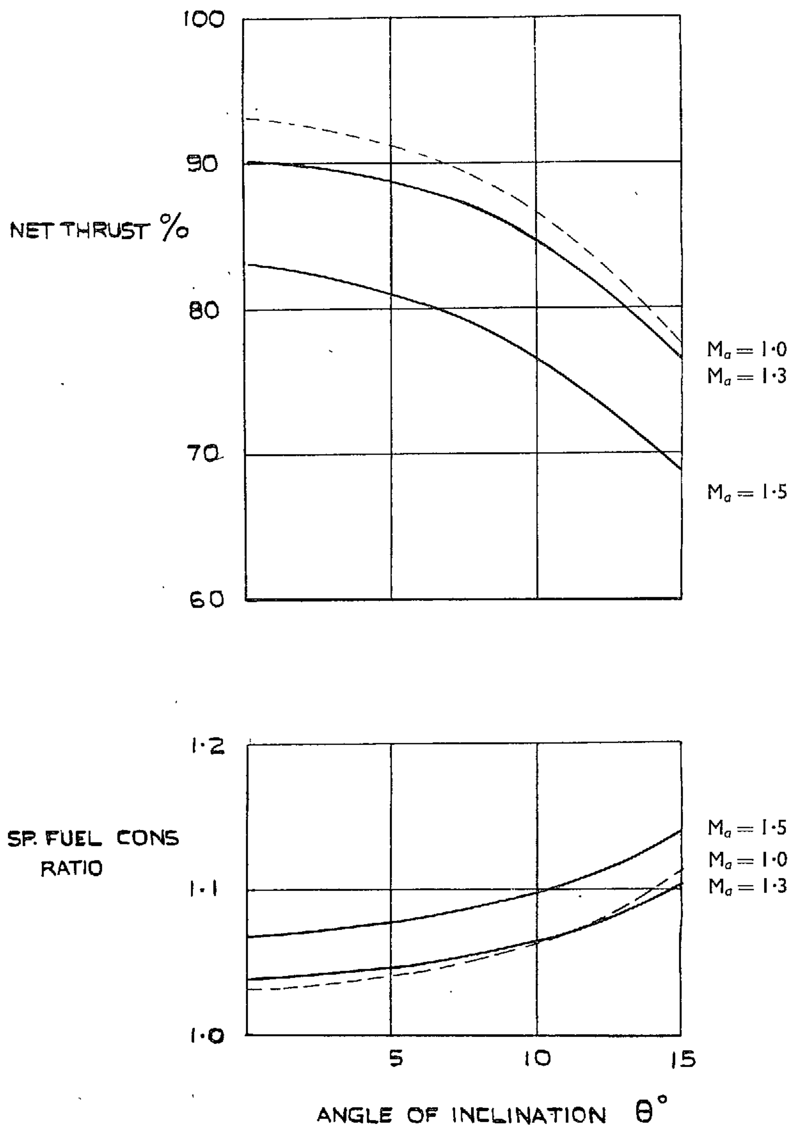

FIG. 9. Net thrust and specific fuel consumption for typical turbine engine. (Relative to 100 per cent intake efficiency). Design mass flow 95 per cent of maximum mass flow at $\theta = 0$ deg.

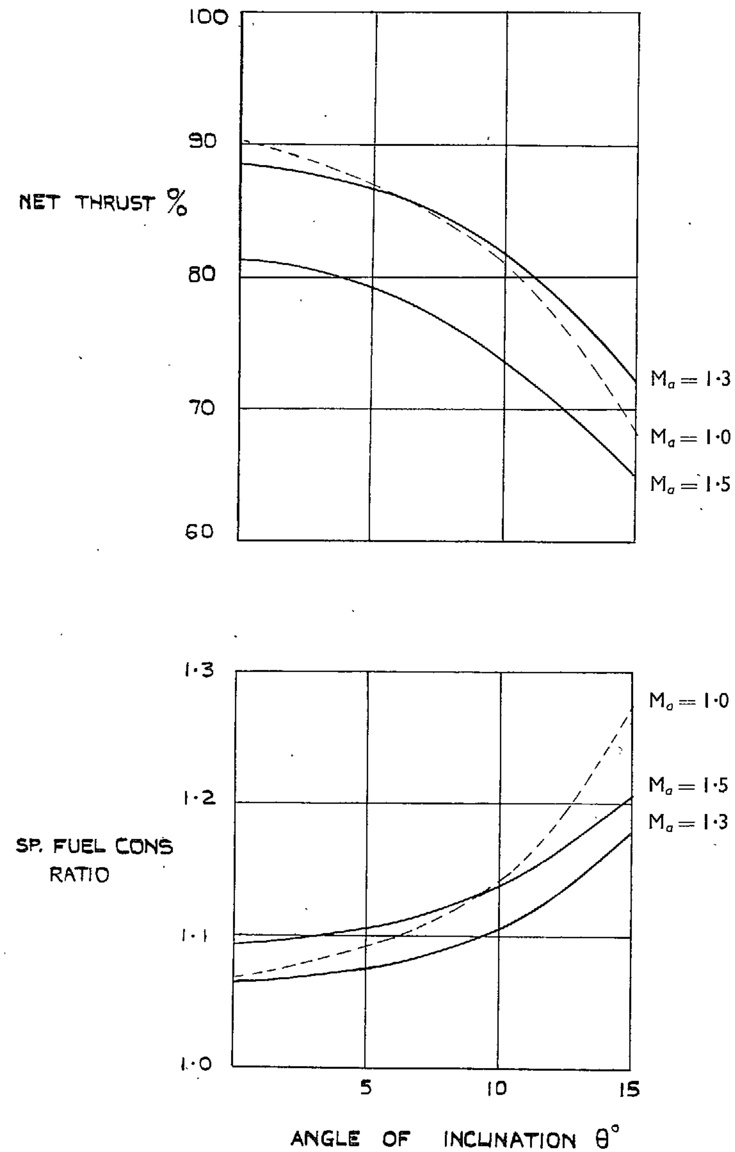

FIG. 10. Net thrust and specific fuel consumption for propulsive duct. (Relative to 100 per cent intake efficiency). Design mass flow 95 per cent of maximum mass flow at $\theta = 0$ deg.

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