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Schlieren Tests on some Conventional Turbine Cascades

By

J. A. DUNSBY

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COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR),
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Summary.—Schlieren tests on a series of conventional turbine cascades have shown that the variations in performance at high speed can be accounted for by shock-wave and boundary-layer interaction. The rise in loss coefficient sometimes encountered at outlet Mach numbers of 0·6 to 0·8 is shown to be due to the formation of a λ-shock series on the upper surface of the blade, the subsequent fall in loss coefficient and increase in deflection as the outlet Mach number rises to unity being caused by the formation of a shock system at outlet which forces the separated part of the boundary layer back on to the blade surface. It is shown that a λ-shock series may form on a boundary layer which is apparently turbulent. This has not been observed before.

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1. *Introduction.*—A recent report by Bridle (R. & M. 2697[1]) has given the results of tests on the performance of some typical conventional turbine cascades at high speeds, pointing out several peculiarities in the performance of these cascades. In particular it is noted that under more or less impulse conditions there are large variations in loss coefficient with change in Mach number. Theories have been advanced to cover these peculiarities, but, up to the present, little definite evidence has been offered to confirm or deny them.

An investigation has been made by Todd[2,3] on a cascade similar to one of those tested by Bridle, in which the shock-wave and boundary layer phenomena at outlet were visualised, by means of a schlieren apparatus, and an attempt was made to infer the conditions further upstream from these observations.

It was considered that a more detailed and systematic study of the shock-wave and boundary-layer formations on the complete blade surfaces would be of value. The present investigation was therefore made in which the latter are studied, by means of a schlieren apparatus, over the entire blade chord of each of the seven cascades originally tested by Bridle. An attempt is made to correlate the observed phenomena with the results obtained for the variation of loss coefficient ($\omega/P_{\mathrm{tot}\,1} - P_2$) and fluid outlet angle (α_2) with mean outlet Mach number $\bar{M}_{n2}$) in the original tests.

2. *Description of Rig.*—2.1. *Aerodynamic Equipment.*—The aerodynamic rig consists essentially of No. 3 High-Speed Cascade Tunnel, as used for the original tests (described in R. & M. 2697[1]), with the traversing gear removed. Since the completion of the original tests, the tunnel has been moved to a more permanent position and this has necessitated certain changes in the ducting between the tunnel and the compressor. Check traverses were made to ascertain whether the flow conditions in the tunnel had been changed. It was found that there is no measurable difference. A photograph of the rig is shown in Fig. 1.

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* N.G.T.E. Report R.56, received 24th January, 1950.

The cascades used for the schlieren tests were, as was stated earlier, the original series of seven tested on the tunnel, the blade profiles of which are shown in Fig. 2. The profiles are composed entirely of circular arcs and straight lines. Full details of the construction of the profiles may be found in R. & M. 2697[1].

In order to see the flow over the blade surfaces, it was necessary to mount three of the blades between optically flat windows in the cascade side plates. This was done by drilling holes in the glass and mounting the blades by pins as is usual with steel side plates.

The only measurements recorded during the taking of the schlieren photographs were the upstream pressure $P_{\text{tot}2}$ and downstream static, *i.e.*, barometric, P_a. From these a theoretical outlet Mach number $\bar{M}_{n2\text{th}}$ may be obtained which, from the results of the previous tests, may be related to any of the other variables.

2.2. *Optical Equipment.*—The optical rig is a schlieren apparatus of more or less conventional layout[4], a schematic diagram of which is shown in Fig. 1b. The type of apparatus used was determined principally by considerations of available space. Lenses are employed in place of the more usual mirrors in order to avoid the Z configuration necessary when concave mirrors are used in a system having parallel light in the working-section.

The lenses are fully corrected optically in the normal sense of the term, but for schlieren work, even this is not adequate and it is necessary to work with a practically monochromatic light source in order to avoid chromatic aberration. For visual purposes this is provided by a mercury vapour lamp and a filter, whilst for the high-speed photography a spark discharge between copper electrodes in air gives a sufficiently monochromatic source.

The knife edges in the system are fully rotatable and it is thus possible to obtain the plane of maximum schlieren resolution in any direction through the cascade. The majority of the testing was done with the knife edges perpendicular to the direction of inlet air flow, thus obtaining the best pictures of the boundary layer on the upper surface of the blades at outlet, as the average cascade gives about 90 deg fluid deflection. All illustrations in this report were obtained with the knife edges in this position.

3. *Development of Shock Formations with increasing Mach number in a Typical Cascade.*—The cascade taken as typical is No. 6 of the series. This is an impulse-type cascade with blade inlet and outlet angles of 35 deg and 40 deg respectively (N.B. these angles are the angles quoted in R. & M. 2697[1] and not backbone angles), which exhibits practically all of the phenomena noted in other cascades. Figs. 3, 4 and 5 show schlieren photographs obtained at various Mach numbers with this cascade at incidences of -15 deg, $+5$ deg and $+10$ deg respectively.

3.1. *At Design Incidence.*—Design incidence is taken as $+5$ deg, *i.e.*, an inlet angle of 40 deg, and the relevant schlieren photographs and performance curves are shown in Fig. 4.

In the low-speed region, there is a drop in loss coefficient as the mean outlet Mach number increases, up to a Mach number of about $0 \cdot 5$ at which point there is an apparent discontinuity in the curve and the loss rises with increase in Mach number until it reaches a value of about $0 \cdot 6$ when there is a second discontinuity and the loss coefficient falls as the Mach number increases until the Mach number $= 0 \cdot 7$. At the same time the fluid outlet angle increases with Mach number, the curve flattening out at Mach number $= 0 \cdot 6$ and the outlet angle remaining virtually constant until the Mach number $= 0 \cdot 7$.

The schlieren apparatus failed to reveal the presence of shock-waves or any other compressibility phenomena likely to affect the performance of the cascade in this region as suggested in R. & M. 2697[1], *see* Figs. 3a and 3b, which show two typical schlieren photographs. The cause of this variation must therefore be found in Reynolds number effects.

The form of the loss against Mach number curve is then seen to be similar to the curves of drag against Reynolds number which may be obtained for an isolated aerofoil at low Mach numbers[5]. The curve for the cascade, is then composed of (a) Mach number $= 0$ to $0 \cdot 5$, laminar boundary layer with laminar separation, (b) Mach number = $0\cdot5$ to $0\cdot6$, transition from laminar to turbulent boundary layer, and (c) Mach number = $0\cdot6$ to $0\cdot7$, turbulent boundary layer. The transition region is very small as compared with an isolated body, and will be checked by the china-clay technique.

It is of interest to note that the separation point of the boundary layer moves steadily towards the trailing edge with increasing Mach number thus causing an increase in outlet angle. This movement could in some cases be seen in the schlieren apparatus.

Above Mach number = $0\cdot7$, the loss increases rapidly with increase in Mach number, the curve flattening out at Mach number = $0\cdot8$ and then falling up to and presumably beyond an outlet Mach number of unity[6]. Whilst this is occurring the outlet angle increases steadily.

At an outlet Mach number of $0\cdot68$, the schlieren apparatus reveals a small disturbance on the upper surface of the blade which grows with increase in Mach number, Figs. 3c and 3d, until it is recognisable as a λ-shock series[7]. This shock formation, apart from the small loss due to the compression through it, increases both the thickness and turbulence of the boundary layer and thus delays separation so that the outlet angle is increased.

When the outlet Mach number reaches a value of $0\cdot77$, a single shock is formed on the upper surface of the blade towards the trailing edge. As the Mach number is increased still further, it moves downstream and spreads across the blade passage until it locates itself between the two trailing edges when further increase in Mach number causes a reflected shock system to be formed. This shock is seen to force the separated part of the boundary layer back on to the blade, Figs. 3e and 3f, thus both reducing the loss and increasing outlet angle.

After the trailing-edge shock system has formed, it is seen that the λ-shocks on the upper surface of the blade are still present and are not swept back to form the trailing-edge system as was suggested in Refs. 2 and 3. There is however a reduction in the number of λ-shocks in the series.

3.2. *At Other Incidences.*—Schlieren pictures for the cascade discussed in the preceding section at incidences of -15 deg and $+10$ deg are shown in Figs. 3 and 5 respectively. The sequence of events and form of the loss curve are similar to those at design incidence with the exception of the first rise in loss with increase in Mach number—between outlet Mach numbers of $0\cdot5$ and $0\cdot6$ at design incidence—which is ascribed to transition from a laminar to a turbulent boundary layer. This rise does not appear at negative incidence and is more pronounced at positive, occurring in this case between Mach numbers of $0\cdot35$ and $0\cdot5$.

As the incidence is increased at constant Mach number, the λ-shock series moves towards the leading edge. At these higher incidences the shock first appears at lower values of Mach number, *e.g.*, at an incidence of $+10$ deg it forms when the Mach number = $0\cdot56$ as compared with Mach number = $0\cdot68$ at an incidence of $+5$ deg. As the Mach number is further increased at incidence = $+10$ deg the shock series takes up a new form with a fairly strong shock inclined forward towards the leading edge (Fig. 5d). The schlieren photographs show evidence of strong secondary flow in the cascade which is now stalled.

As the incidence is reduced, the converse holds good. The λ-shock series moves towards the trailing edge and first occurs, at incidence = -15 deg, when the Mach number = $0\cdot71$. In this case the form of the λ-shocks is not so pronounced, the shocks tending to take the form of a series of single-limbed momentum shocks (Fig. 3d). At higher values of outlet Mach number, the shocks merely increase in size and do not change in form as at the higher value of incidence (*cf.* Fig. 3 with Fig. 5).

4. *Effect of Reaction on Shocks.*—By definition, in reaction-type blading the inlet velocity is considerably lower than the outlet velocity, hence shocks forming on the upper surface would be expected to be found further towards the trailing edge than on similar impulse blading.

Schlieren photographs for a reaction-type cascade are shown in Fig. 6 and, for blading resembling a nozzle, in Fig. 7, these cascades being No. 3 at zero incidence and No. 4 at an incidence of +5 deg respectively. It will be seen that the λ-shock series occurs well back on the blade in each case, in a position corresponding roughly to the throat of the blade passage. In both cases the shocks are very weak and occur at higher Mach numbers than on an impulse-type cascade, the values being 0·78 on cascade No. 3 (reaction) and 0·83 on No. 4 (nozzle). As the outlet Mach number is increased still further, the λ-shock series becomes combined with the trailing-edge shock systems.

The variation in performance with Mach number for these cascades is very much smaller than with an impulse-type cascade, due to the fact that, firstly the λ-shocks are of low intensity and secondly that the trailing-edge shocks form between the trailing edge of one blade and a point some distance upstream of the next, Figs. 6e and 6f, and 7e and 7f, and are unable to exert their full influence in reducing the separation of the boundary layer. Separation under low-speed conditions is not so marked as the flow is accelerating throughout almost the entire blade passage and the boundary layer is therefore less likely to separate.

Change in incidence makes very little difference to the form or position of the shock-wave systems or to the form of the loss against Mach number curve. There is however a slight tendency for the λ-shock series to move upstream towards the leading edge with increase in incidence and downstream with decrease.

In general, the shock formations and variation in performance of each of the remaining four cascades, may be said to be intermediate between those already described, the degree of similarity between any two given cascades being a function of the amount of reaction. Examples from each of these four cascades are shown in Figs. 8a, 8b, 8c and 8d.

5. *Some General Observations.*—Probably the most important of the shock formations observed in these tests is the trailing-edge system. It has been seen that this system is capable of reducing the high-speed losses very considerably, so much in fact that at unity outlet Mach number, the loss coefficient may have its minimum value. It is evident that the position of this shock system will have a major influence on its effects. For example, on cascade No. 6 at normal incidence, Fig. 3f, the shock forms from one trailing edge to a point very close to the trailing edge of the next. On cascade No. 4 however it forms between the trailing edge of one blade and a point some 20 per cent of the chord from the trailing edge of the next, Fig. 7f. Examination of the appropriate loss curves shows that in the case of cascade No. 6 the loss coefficient drops by nearly 10 per cent as the outlet Mach number rises from 0·8 to unity, whilst with No. 4 cascade the corresponding drop is almost negligible.

A point of considerable fundamental interest which arises from the tests is the formation of a λ-shock series on the upper surface of a blade. According to Ref. 7, a λ-shock series only forms on a laminar boundary layer, and, if the boundary layer is made turbulent either by increasing the Reynolds number or by other means, the λ-shocks are replaced by a single limbed momentum shock having a very small oblique component at its base. From the loss curves for the typical cascade, it has been deduced that at the time of the formation of the λ-shock series the boundary layer is turbulent, *see* section 3.1. Confirmation of the fact that the series may be formed on a turbulent boundary layer is provided by Fig. 8e which shows a λ-shock series on the boundary layer of a stalled blade. There can be no doubt that this is highly turbulent. It is thought that the difference between the shock formations noted here and those observed previously is accounted for by the difference in curvature of the surface on which they form.

A further point of interest arises from the schlieren photographs of the λ-shock series. It has been pointed out previously[7,8,9] that when a bifurcated or λ-shock is formed, there must be a vortex sheet separating the regions of flow above and below the point of intersection of the main and oblique shocks. This vortex sheet was observed in the schlieren apparatus in some instances, and an example may be seen in Fig. 8f. It is not possible however to detect separately the loss due to this vortex sheet in the detail traverse, which is made at a distance of one chord downstream from the trailing edge of the blade. The reason for this is, presumably, mixing with the main wake from the blade.

A feature was noted with stalled reaction-type blading and is illustrated by Figs. 8g and 8h, which show cascade No. 4 operating at high and low speed at an incidence of +35 deg. Despite the fact that the cascade is stalled in the normal sense of the term with separation at the leading edge, the separated boundary layer still follows the blade profile fairly closely, and the loss coefficient at this very high incidence is only of the order of three times its value at zero incidence.

6. *Conclusions.*—From the schlieren photographs presented in this report, it may be seen that marked shock phenomena are likely to be encountered in most turbine blades operating at or near normal design conditions. The variations in cascade performance previously noted in R. & M. 2697[1] and by others may be accounted for firstly by Reynolds number effects up to outlet Mach numbers of the order of 0·7 and above this by shock-wave and boundary-layer interaction.

The shock interaction may be advantageous as in the case of certain trailing-edge shock systems or detrimental as in the case of λ-shocks occurring on the upper surface of the blades. The marked change in fluid outlet angle at high speed may also be attributed to the shock formations.

From a fundamental point of view the existence of a λ-shock series on a boundary layer which has every indication of turbulence is contradictory to previous evidence. The large curvature of the blade surface, on which the series forms, may however be the governing parameter.

7. *Acknowledgment.*—The author wishes to thank Mr. A. J. Colbourn for his assistance in the photographic aspects of these tests.

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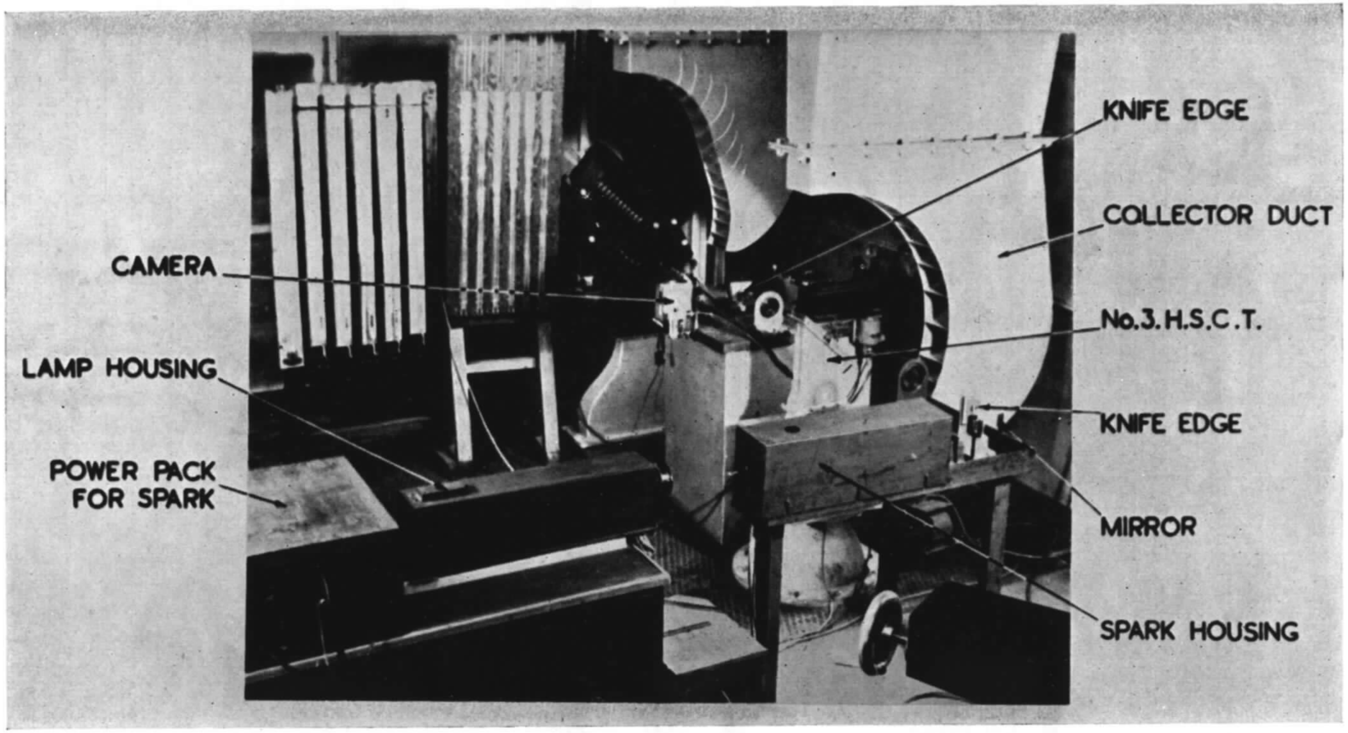


Fig. 1a. No. 3 High-speed cascade tunnel and schlieren apparatus.

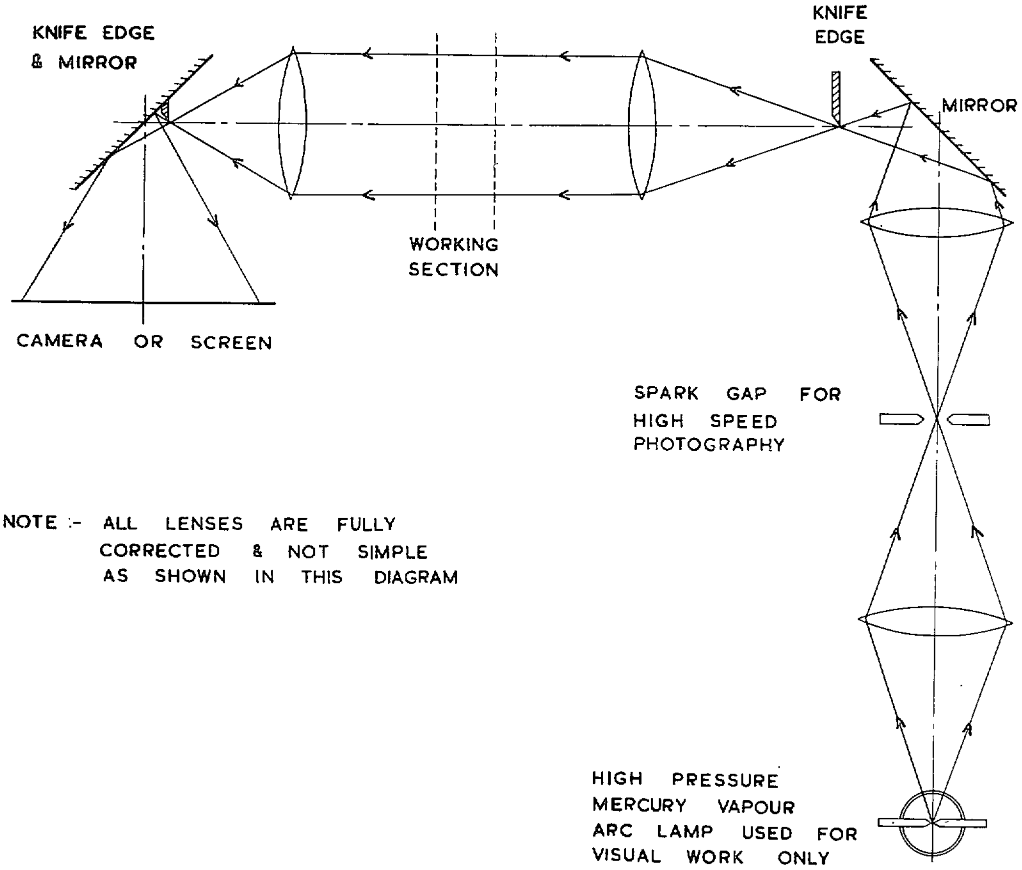


FIG. 1b. Schlieren apparatus as used on high-speed cascade tests.

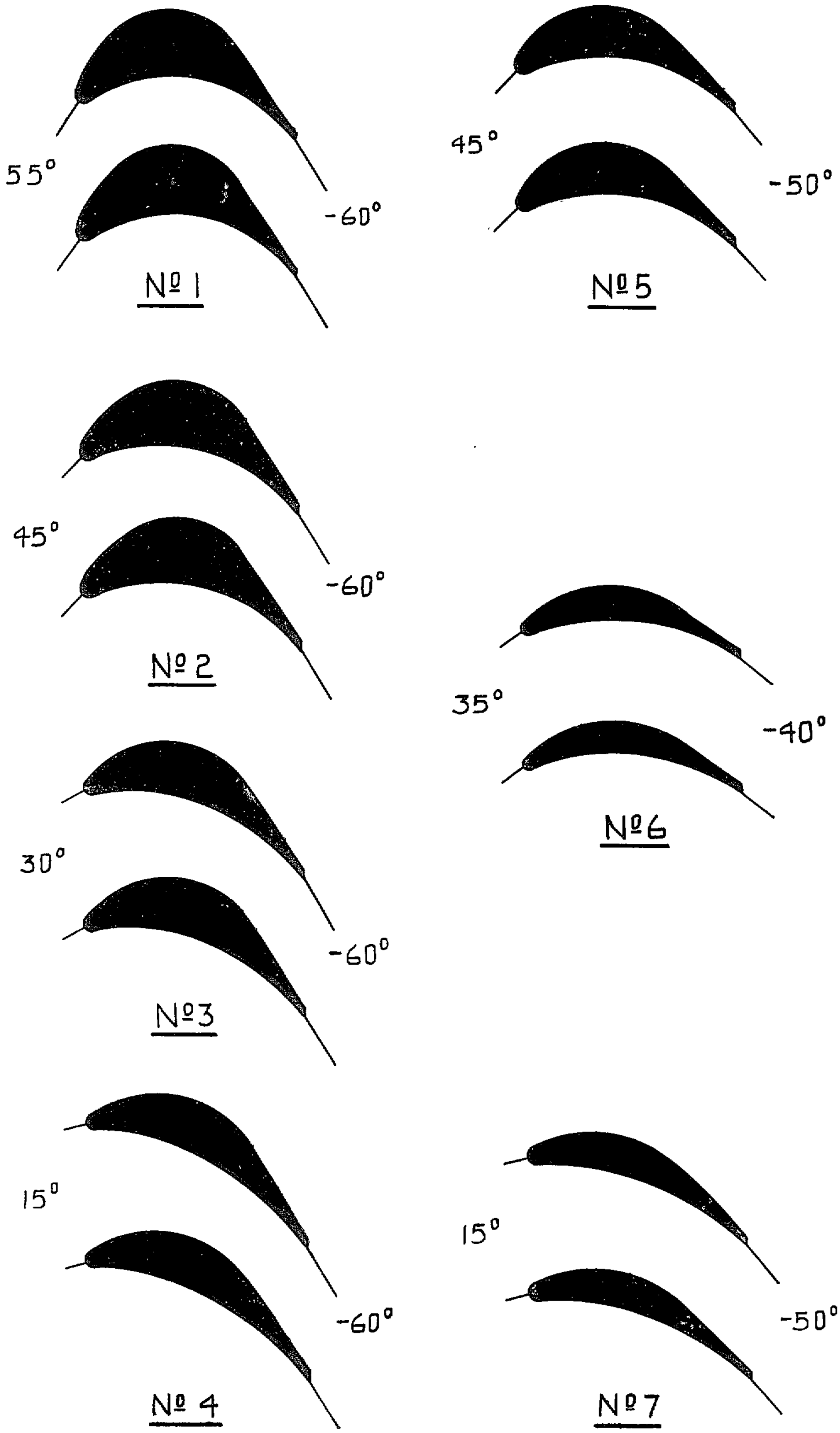
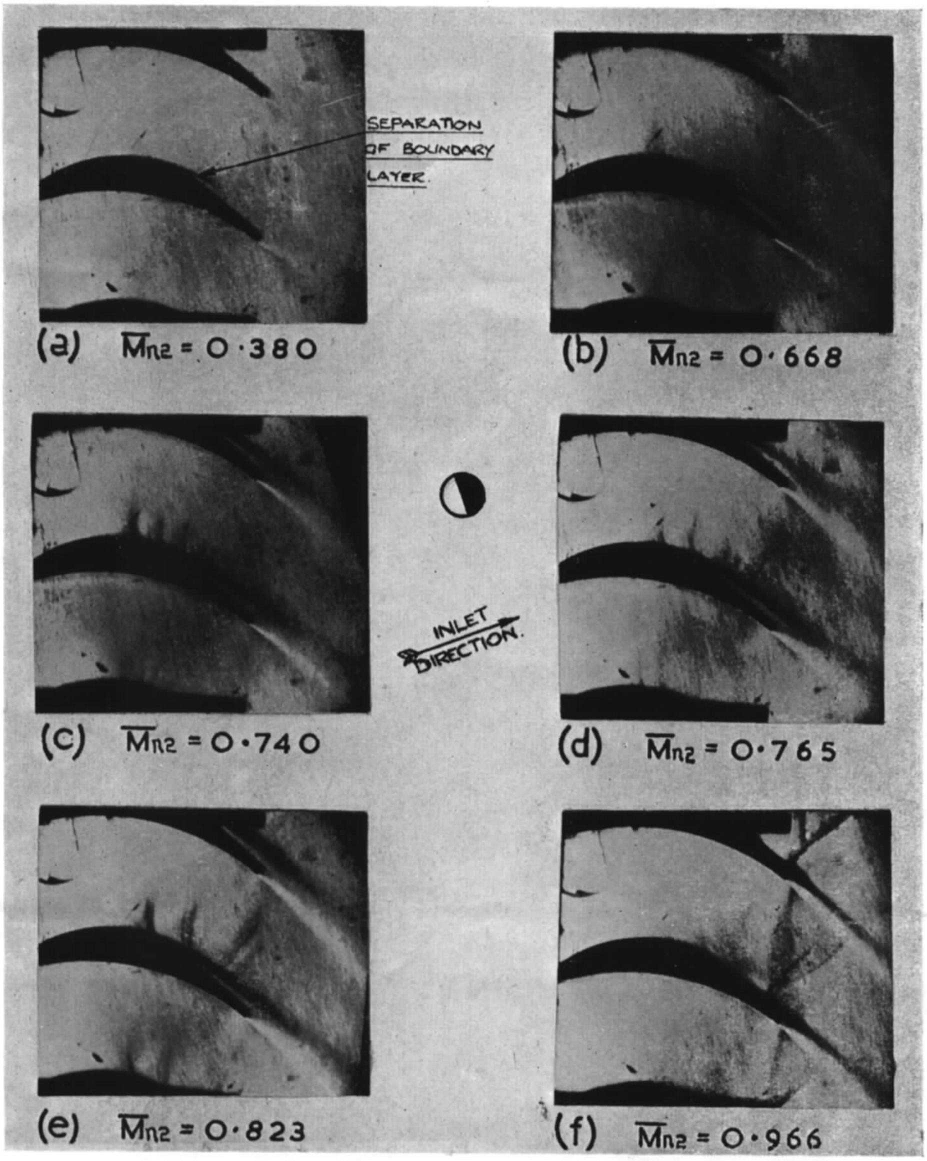


FIG. 2. Cascade details. Pitch/width = 0·C25. Values of design inlet angles and $\cos^{-1}$ (throat/pitch) as indicated.



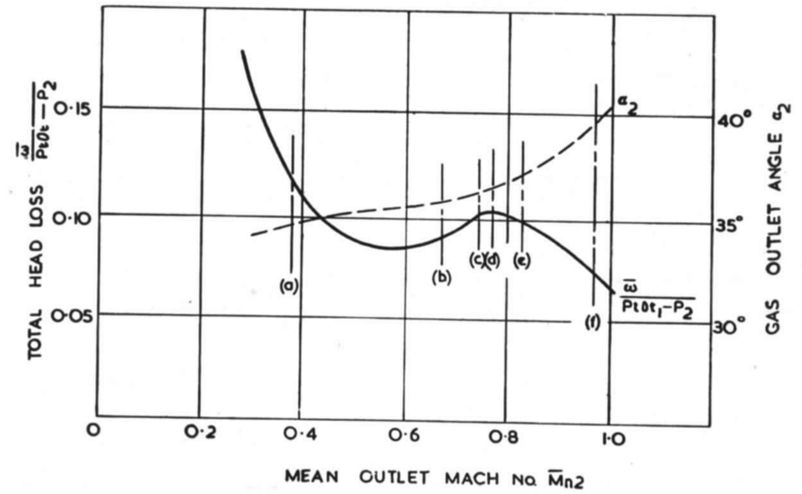


FIG. 3. Variation with $\overline{M}_{n2}$. Impulse cascade (No. 6) at negative incidence ($i = -15$ deg).

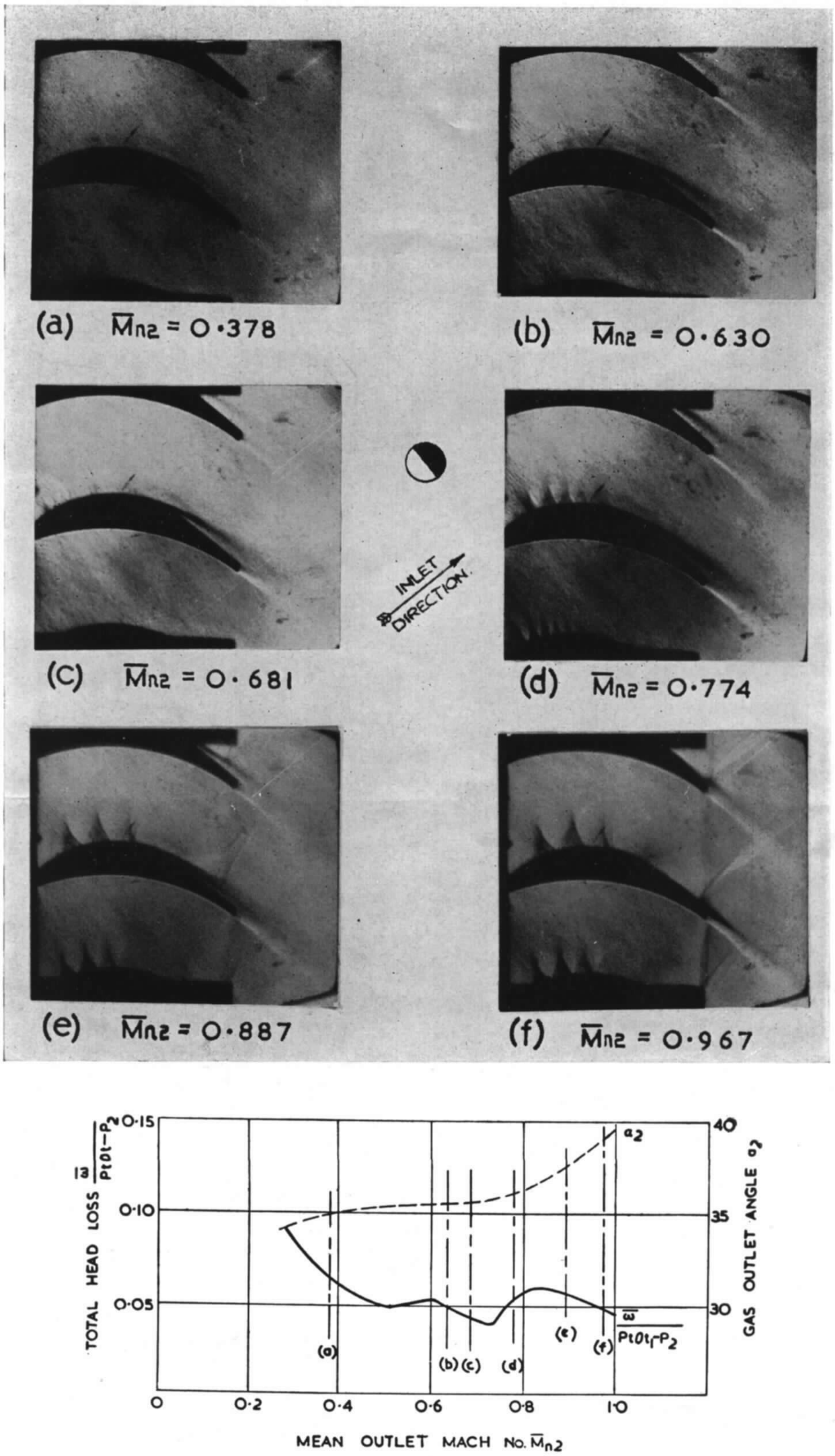


FIG. 4. Variation with $\bar{M}_{n2}$. Impulse cascade (No. 6) at normal incidence ($i = +5$ deg).

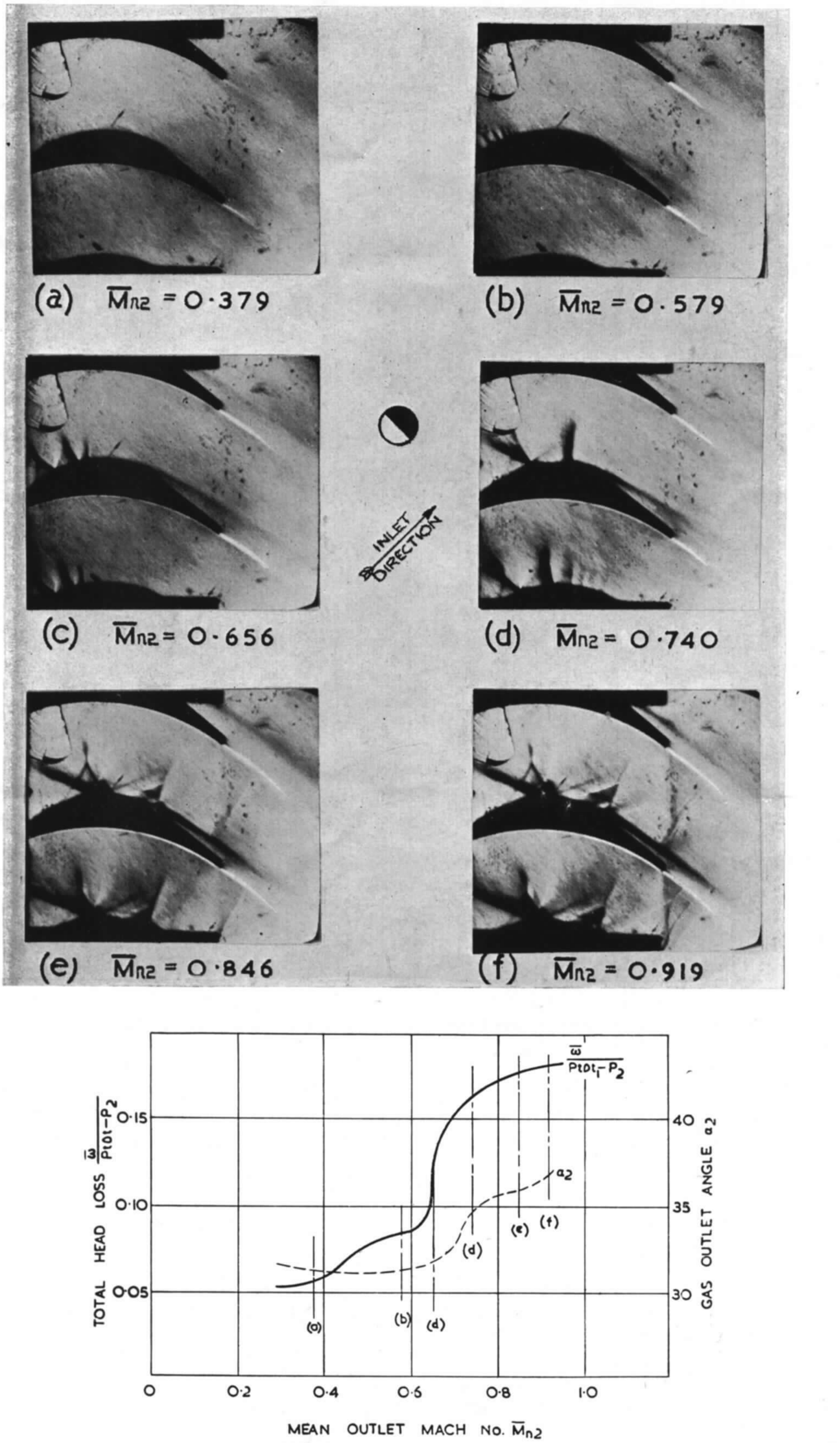


FIG. 5. Variation with $\bar{M}_{n2}$. Impulse cascade (No. 6) at positive incidence ($i = +10$ deg).

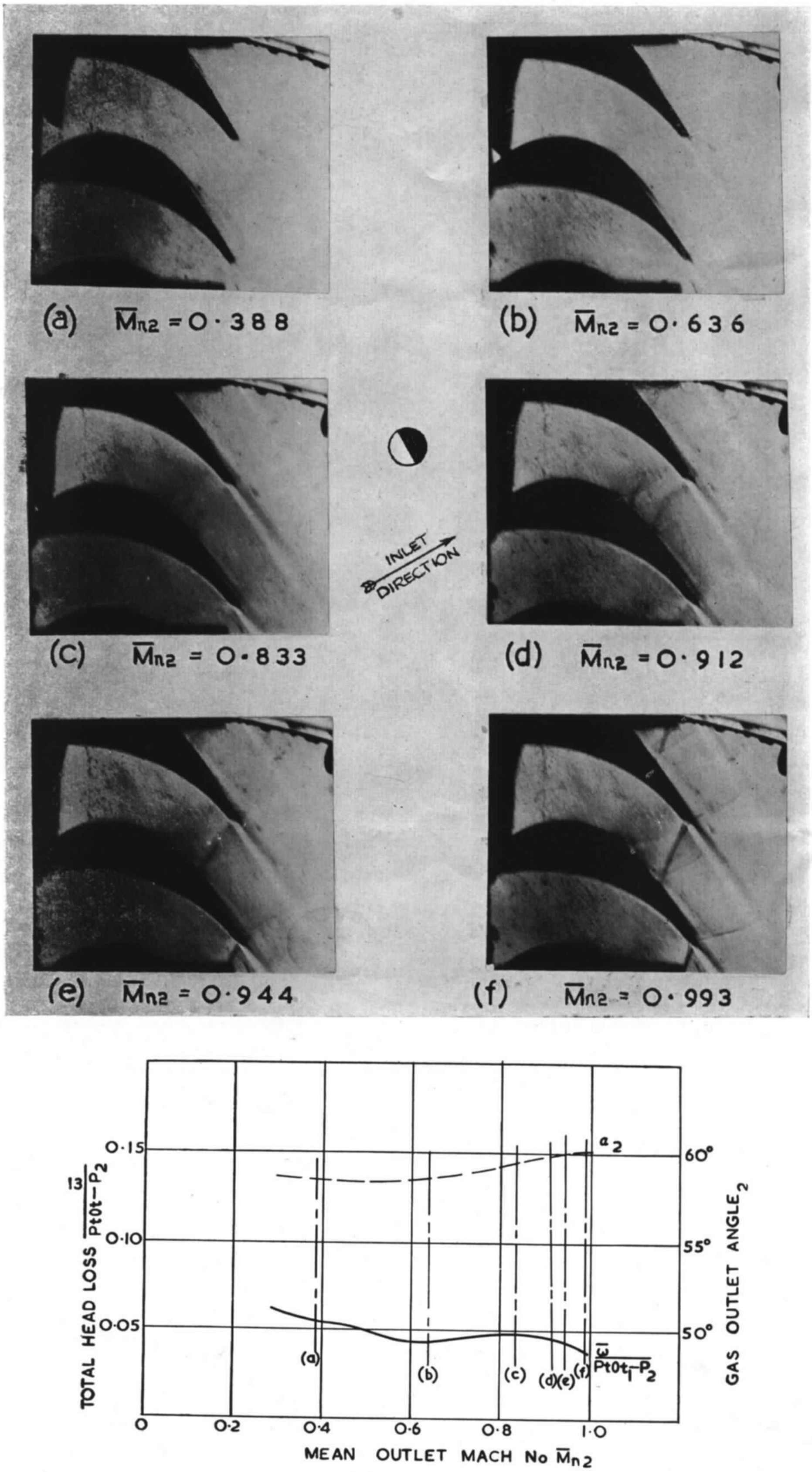


FIG. 6. Variation with $\bar{M}_{n2}$. Reaction cascade (No. 3) at normal incidence ($i = 0$ deg).

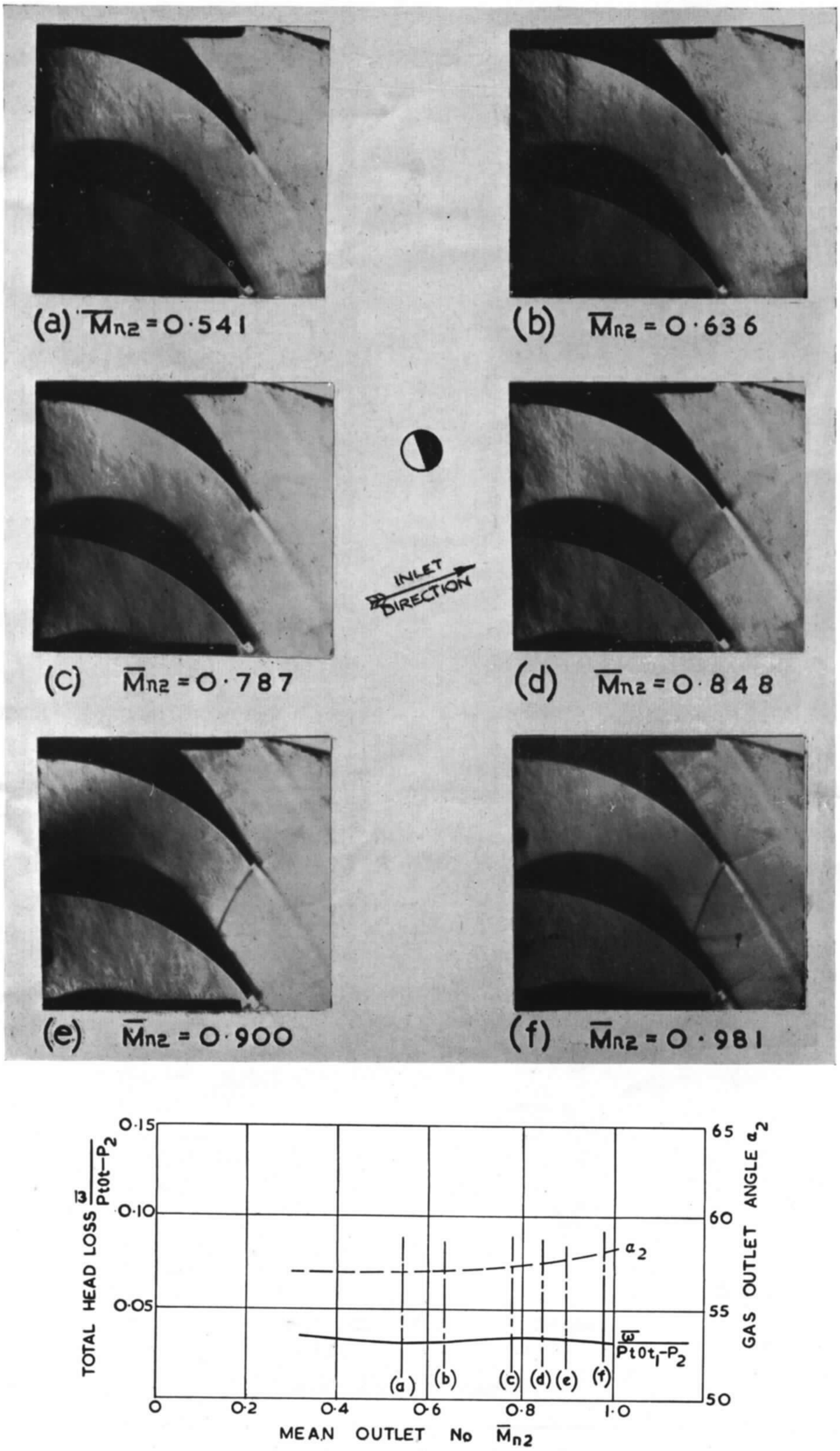


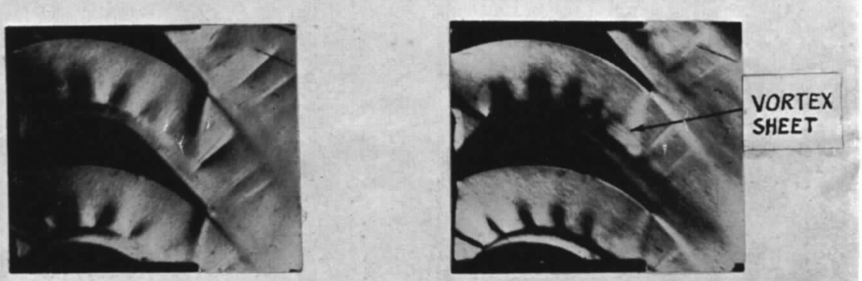
FIG. 7. Variation with $\bar{M}_{n2}$. Nozzle (No. 4) at normal incidence ($i = +5$ deg).

(a) CASCADE No. 1
$\alpha_1 = 60°$ $\overline{M}_{n2} = 0\cdot909$

(b) CASCADE No. 2
$\alpha_1 = 55°$ $\overline{M}_{n2} = 0\cdot922$

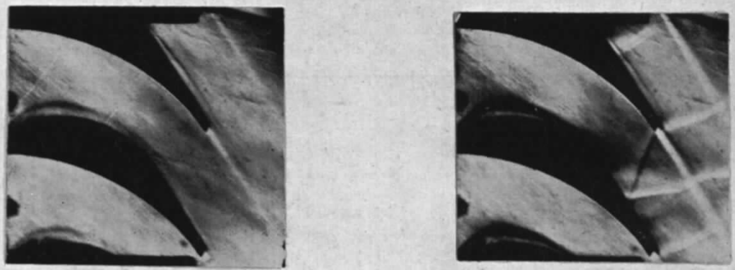
(c) CASCADE No. 5
$\alpha_1 = 40°$ $\overline{M}_{n2} = 0\cdot906$

(d) CASCADE No. 7
$\alpha_1 = 15°$ $\overline{M}_{n2} = 0\cdot907$



(e) λ SHOCK SERIES ON SEPARATED BOUNDARY LAYER
(CASCADE No. 5, $\alpha_1 = 55°$ $\overline{M}_{n2} = 0\cdot720$)

(f) VORTEX SHEET FROM λ SHOCKS
(CASCADE No. 5, $\alpha_1 = 55°$ $\overline{M}_{n2} = 0\cdot851$)



SEPARATED BOUNDARY LAYER FOLLOWING BLADE PROFILE

(g) CASCADE No. 4 $\alpha_1 = 50°$
$\overline{M}_{n2} = 0\cdot512$

(h) CASCADE No. 4 $\alpha_1 = 50°$
$\overline{M}_{n2} = 0\cdot938$

FIG. 8. Other examples of shock formations.

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