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# Note on the Time Required for the Achievement of Steady Flow Past a Slender Body in a Hypersonic Shock Tunnel

*By*

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# Note on the Time Required for the Achievement of Steady Flow Past a Slender Body in a Hypersonic Shock Tunnel

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SUMMARY

Observations of the heat transfer have been made to a two-dimensional flat plate held at zero incidence in a hypersonic shock tunnel operated at a flow Mach number of about 7.5. The results show that the time required for the heat transfer to become steady is much longer than the time predicted by simple considerations of the diffusion time through the boundary layer. Schlieren observations suggest that the discrepancy may arise because of Reynolds number changes associated with the disturbances formed during the nozzle starting process, which, it is suggested, requires further investigation.

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## 1. Introduction

A major uncertainty concerning the utility of hypersonic shock tunnels for aerodynamic testing arises from the brevity of the uniform test flow that they provide. It is, therefore, important on the one hand to investigate methods for increasing the flow duration, and, on the other, to examine the duration that is required for representative types of experiment. To enable the factors that influence the problem to be identified, it is convenient to consider an idealised situation in which they are assumed to be independent. For useful measurements to be made, we must then have:-

$$t_i < t_w - t_m, \qquad \ldots(1)$$

where $t_i$ is the response time of the measuring instrument,

$t_w$ is the duration of uniform free-stream flow at the working section, and

$t_m$ is the time required for the flow near the model under test to become steady once uniform free-stream conditions have been established.

The duration of uniform test flow is given by

$$t_w = t_o - t_n, \qquad \ldots(2)$$

where $t_o$ is the duration of uniform condition at the nozzle entry, and

$t_n$ is the loss of duration associated with the expansion process in the nozzle.

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We must recognise that, in practice, the situation will be more complex than that described by equations (1) and (2). As we shall see later, for example, the way in which the flow near the model achieves a steady state depends on the nozzle starting process, so that $t_m$ and $t_n$ are related. Also, with "equilibrium" contact surface operation[1], the flow in the nozzle, or past the model, may in some cases be effectively established before the pressure at the nozzle entry becomes steady.

A review of the current position of N.P.L. work on these factors is given in Ref. 2, which includes preliminary details of the times required for representative measurements. Here we should note that in many cases $t_i$ needs to be small compared with $(t_w-t_m)$, if only to indicate whether the flow past the model has become steady. Detailed investigations of the time $t_o$ are described in Ref. 3 for "straight-through" shock tunnels, and in Refs. 1 and 4 for "reflected-shock" tunnels. The loss of flow duration in the expansion nozzle is discussed in Refs. 3 and 5. The present note is concerned with the preliminary results of current work on the time $t_m$ required for the flow past the model to become steady.

## 2. Observations of the Times Required for the Establishment of Steady Flow Past Models

For the flow near the stagnation point of a bluff body, the available evidence suggests that steady conditions are achieved rapidly, and recent N.P.L. work has accordingly concentrated on flows past slender bodies, or involving boundary-layer separation. The work has been done at a free-stream Mach number of about 7.5, in a small shock tunnel fitted with a 3 inch diameter driving tube and an 8 inch diameter working section. The maximum pressure in the driving tube is limited to 2000 lb/sq in., and, to avoid non-equilibrium effects in the expansion nozzle, the experiments were made at a stagnation temperature (2400°K, corresponding to a shock Mach number of 4.1) that was sufficiently low for high-temperature real-gas effects to be small. The shock tunnel was operated by the reflected-shock technique, and measurements[1] of the stagnation pressure at the nozzle entry showed that it remained substantially constant for about 7 milliseconds.

A relatively simple quantity to determine in a shock tunnel is the instantaneous heat-transfer rate, as measured by a thin-film resistance thermometer attached to the surface of the model under test. The variation of heat transfer with time during the flow-establishment process has, accordingly, been used to provide data on how long the flow requires to become steady. The resistance thermometers were located at the distances, x, from the leading edge of a flat plate at zero incidence indicated in Table 1.

Table 1

Results for a Flat Plate at Zero Incidence

| Distance from leading edge<br>x inches | Time for heat transfer to become steady<br>t microseconds | $\frac{ut}{x}$ |
|---|---|---|
| 0.39 | 680 | 140 |
| 0.54 | 700 | 110 |
| 1.30 | 1200 | 80 |
| 2.20 | 1800 | 70 |

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The signal from the resistence thermometer located at $x = 2.20$ in. is reproduced in Fig. 1, which also includes the derived variation of instantaneous heat-transfer rate with time. It is inferred from the latter that the heat transfer takes roughly 1800 microseconds to become steady*, and this value, and the corresponding values for the other measuring stations are included in Table 1, together with the values of the non-dimensional parameter $ut/x$. Here, $u$ denotes the steady value of the velocity of the test stream after the flow in the working section is established. It is clear from Fig. 1, that considerable errors are possible in the estimation of the time required for steady heat transfer, and the values listed in Table 1 should be regarded only as giving an order of magnitude result.

If the initial shock that passes the model is followed by a uniform stream, and it is assumed that the time required for the achievement of steady conditions is related to the diffusion time through the boundary layer, the time would[6] be approximately $\frac{\delta^2}{\nu} \approx \frac{x}{u}$. It would then be anticipated that the non-dimensional parameter $ut/x$ would be of order unity, whereas the present experiment indicates values perhaps two orders of magnitude greater.

The reason for this discrepancy is to be found in the schlieren photographs of the starting process reproduced in Fig. 2. If the simple starting process discussed above was realized, the boundary layer might be expected to have zero thickness at the leading edge and at the shock, and to grow towards its steady thickness as sketched in Fig. 3. In practice, the schlieren photographs suggest that the boundary layer is initially very thick, or separated, and that it becomes thinner as steady conditions are approached. It is thought that this occurs largely because of the Reynolds number change that takes place during the starting process. Thus, for the large initial pressure ratio across the nozzle diaphragm used in the present investigation, the initial shock that passes through the nozzle will be followed by a strong expansion wave. As the shock and expansion wave pass along the flat plate, the pressure will change as sketched in Fig. 4, and there will be a marked increase of Reynolds number.

For the flat plate, it is, therefore, suggested that the flow-establishment process is dominated by the changes that occur during the starting flow in the expansion nozzle, and that the time scale is determined largely by that of the nozzle starting process. For the separated flow up a step, a different flow-establishment process is observed, as illustrated in the schlieren photographs of Fig. 5. Here the separation point, and its associated shock wave, are seen to move upstream to their steady position. It is difficult to explain this in terms of the effects of changes of Reynolds number, although the boundary layer downstream of the step is seen to become thinner as the starting process proceeds. It is possible that the velocity of upstream propagation of the disturbance reflected from the step when it is struck by the initial shock plays an important rôle.

## 3. Concluding Remarks

The object of the present note is to indicate that the time required for the boundary-layer on a slender body to become steady during shock-tunnel testing may be relatively long, and appears to be determined

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*The times quoted are measured from the instant when the initial shock that passes through the nozzle meets the leading edge of the plate. To the present order of accuracy, this is acceptable, because the shock takes only 30 microseconds to cover the length of plate containing the heat-transfer gauges.

by the disturbances formed during the nozzle starting process rather than by delays in the development of the boundary layer itself. It appears, therefore, that detailed investigations of the nozzle starting process are required, with special reference to the effects of the initial pressure ratio across the nozzle diaphragm.

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List of Symbols

| | |
|---|---|
| x | distance from leading edge |
| u | free-stream velocity |
| $\delta$ | boundary-layer thickness |
| $\nu$ | kinematic viscosity |

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|---|---|---|
| 1 | D. W. Holder and D. L. Schultz | On the flow in a reflected-shock tunnel. A.R.C. 22,152 August, 1960. |
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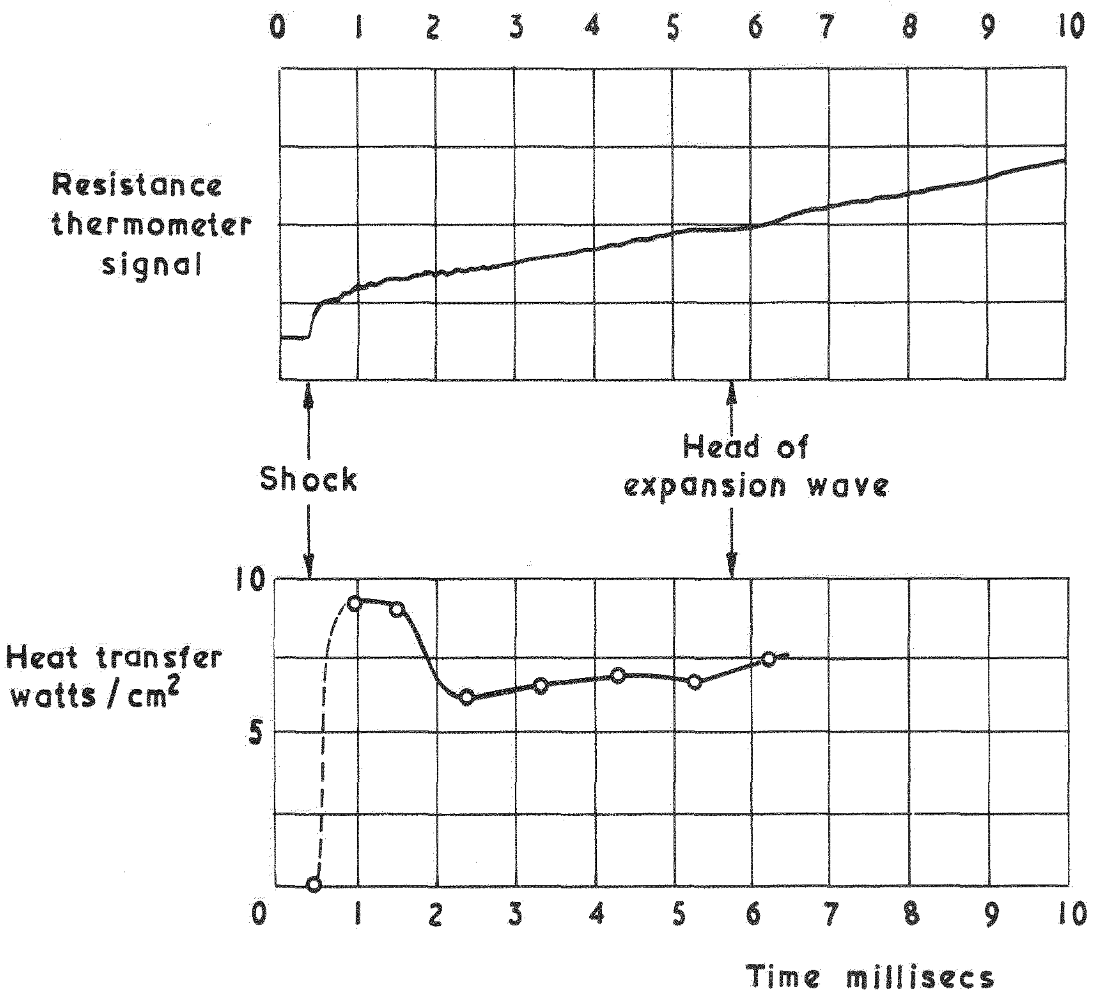
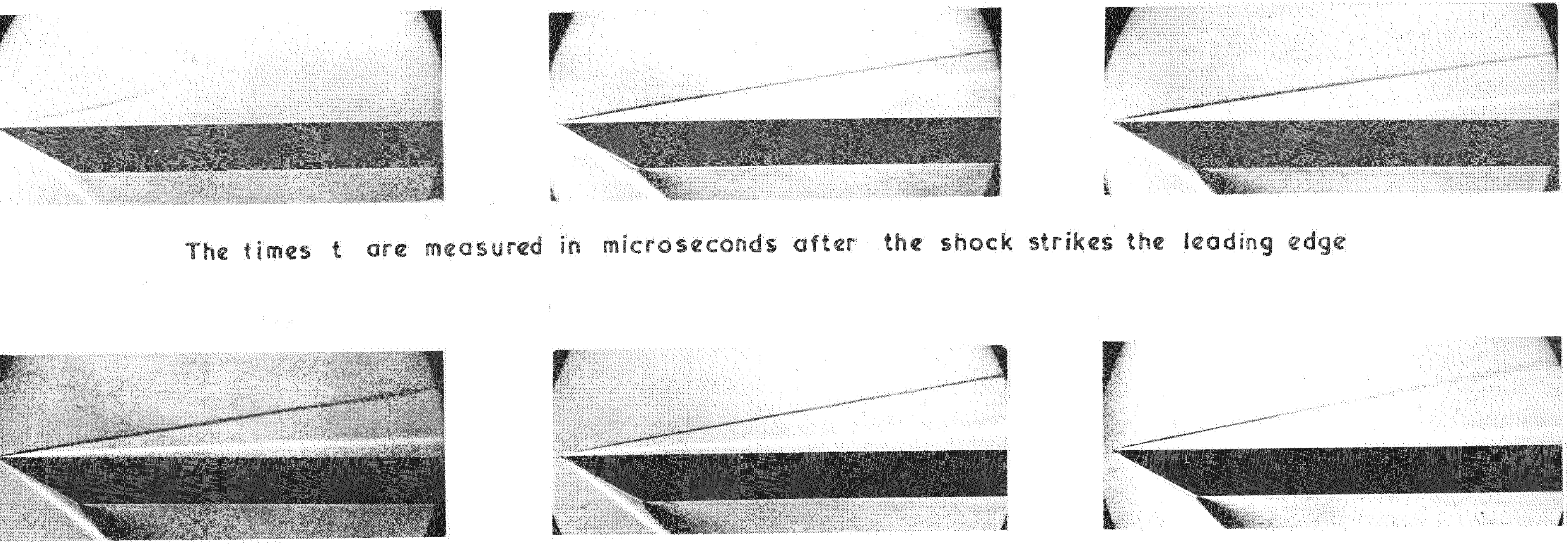
FIG. 1




Variation with time of the heat transfer to a flat plate

x = 2·20 inches



t = 405 t = 462 t = 525

The times t are measured in microseconds after the shock strikes the leading edge

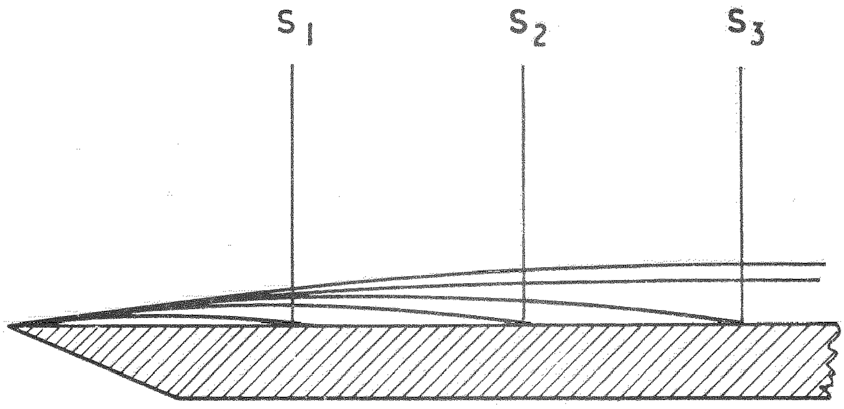
t = 1000 t = 4000 t = 6000

Schlieren photographs illustrating the establishment of the boundary layer on a flat plate

FIG. 2.

FIGS. 3 & 4

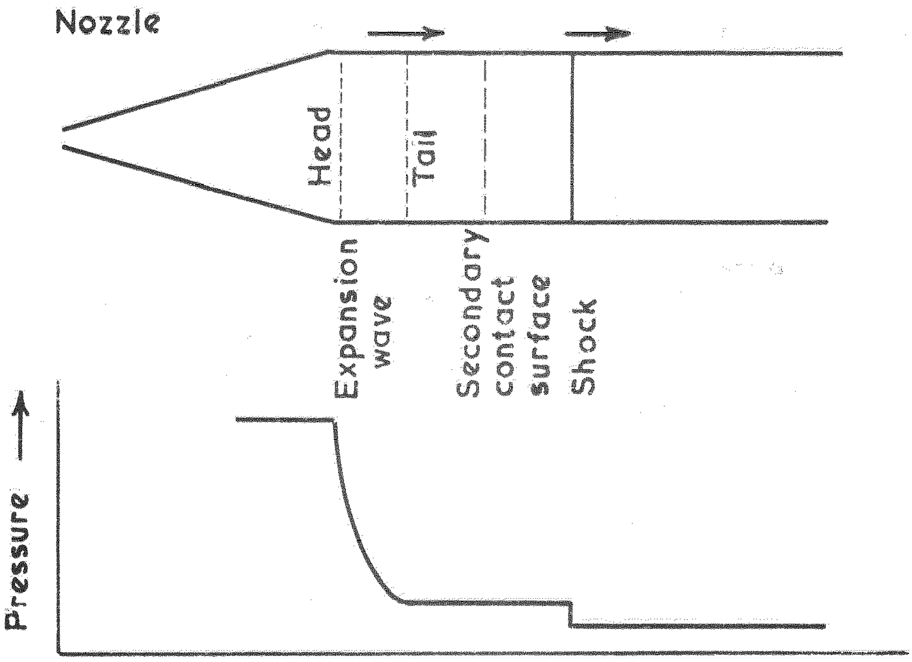
FIG. 3




$S_1$, $S_2$ and $S_3$ are instantaneous shock positions

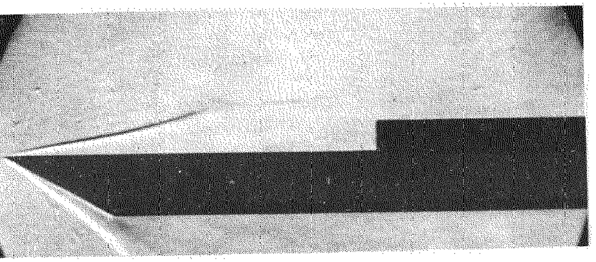
Sketch of boundary layer development as a shock followed by a uniform stream moves along the surface of a flat plate

FIG. 4

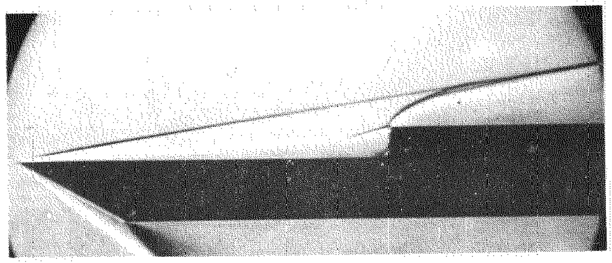



Sketch of shock and expansion wave formed during nozzle starting process and the corresponding pressure changes.

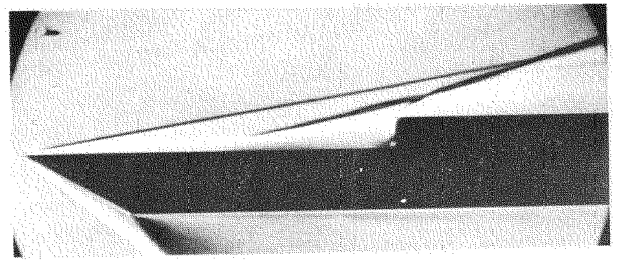
t = 410



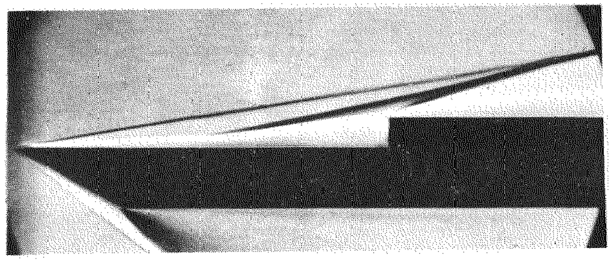
t = 500



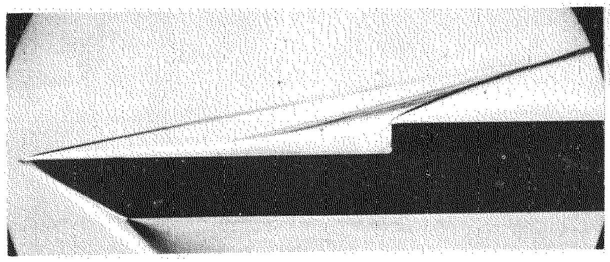
t = 575



The times t are measured in microseconds after the shock strikes the leading edge



t = 1000



t = 8000

FIG. 5

Schlieren photographs illustrating the establishment of the separated flow up a step

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