Laminar Heat Transfer to a Two-Dimensional Backward Facing Step from the High-Enthalpy Supersonic Flow in the Shock Tube

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Heat-transfer rates are measured over a two-dimensional backward facing step in a laminar supersonic flow in the shock tube The shock Mach number ranges from 4 to 10 The corresponding flow Mach numbers are approximately 1 5 to 2 5 and the Reynolds numbers are varied between 2 × 10³ to 2 × 10⁵ Local heat-transfer rates are found to vary with distance behind the step and to depend on the ratio of the boundary-layer thickness at separation to step height This ratio is represented by the parameter $L/hRe_L^{1/2}$ When $L/hRe_L^{1/2}$ is larger than about 0 067 (relatively thick incoming boundary layers) the local heat-transfer rate is found to increase gradually through the reattachment zone With relatively thin incoming boundary layers, $L/hRe_L^{1/2}$ less than 0 067, a sharp peak is found at reattachment This peak value increases with the decrease of the incoming boundary-layer thickness reaching about 7 times the laminar flat-plate value at $L/hRe_L^{1/2}$ = 0 02 The average heat-transfer rate to this separated region is found also to increase with decreasing values of the incoming boundary-layer thickness rising to values higher than laminar flat-plate heat transfer for $L/hRe_L^{1/2}$ values below about 0 07

Nomenclature

h = step height
H = enthalpy
L = flat-plate length ahead of step
M = Mach number
M_s = shock Mach number
Nu = Nusselt number
p = pressure
Pr = Prandtl number
Re = Reynolds number
q = heat-transfer rate
t = time
x = length coordinate along model axis
Δx = distance behind the step
Δx_h = distance between step and beginning of reattachment
Δx = distance between step and end of reattachment
δ = viscous layer thickness

Subscripts

e = external freestream conditions
f p = flat-plate conditions
L = conditions based on length of flat plate ahead of step
x = local condition
s = separation point conditions
w = wall conditions
s = external stagnation conditions

I Introduction

FLOW separation in supersonic and hypersonic flows is known to alter the heat transfer at and beyond the separation region The low velocity in the "dead air" region is expected to cause relatively low heat-transfer rates in the mixing zone At the reattachment zone the heat-transfer rates may either increase gradually to their attached flow values or peak to comparatively large values The average heat-transfer rate in a laminar separated region was calculated by Chapman[1] to be 0 6 of the laminar attached flow value This analysis evaluated the heat transfer only in the mixing zone excluding the contribution of the heat transfer at reattachment The heat-transfer measurements of Larson[2] in a laminar mixing zone of the flow over a cavity agree well with this value (again excluding the reattachment zone contribution) Measurement of heat-transfer rates at and near the reattachment zone do show conditions when very high heat-transfer rates are obtained even when the reattachment is completely laminar Recent measurements of such conditions are reported in Refs 3 and 4; indications of such an effect can also be seen in the data of Ref 2 An extension of Chapman's analysis[2] to the reattachment zone is presented by Chung and Viegas in Ref 5 This calculation shows that heat-transfer rates averaged over the reattachment zone may be up to 4 or 5 times the average attached laminar flat-plate heat-transfer rate It can be seen that the large reduction in heat transfer to the mixing zone may be overshadowed by the high heat-transfer rates at the reattachment zone, so that a new increase in heat transfer because of local separation may be detected instead of the desired decrease of the aerodynamic heating

In the present investigation local heat-transfer rates are measured in the separated region behind a backward facing step in the shock tube Heat-transfer rates are measured both in the mixing zone and in the reattachment zone The variation of the local heat-transfer rates with Reynolds number is measured when the flow Mach number is 1 5–2 5 while H/H_w is varied between the values of 3 to 50 Previous measurements of pressure distribution of laminar flow over a backward facing step in a wind tunnel at similar supersonic Mach numbers are reported in Ref 6 The measurements are used to evaluate the extent of the various separated flow regimes as shown in Fig 1 It is also shown in Ref 6 that the flow parameters can be correlated by the nondimensional parameter $L/hRe_L^{1/2}$ This parameter is a measure of the ratio of the boundary-layer thickness at separation to step height $L/hRe_L^{1/2} \sim \delta/h$ The wind-tunnel measurements covered a range of $L/hRe_L^{1/2}$ between 0 02 to 0 1 This variation was obtained using four different models because of the limited Reynolds number range of the wind tunnel The corresponding range has been covered in the shock tube using a single model with a fixed step height and varying the flow Reynolds number by a factor of about 100 Such a large variation in flow properties in the shock tube is possible by operating the low pressure section with initial pressures vary-

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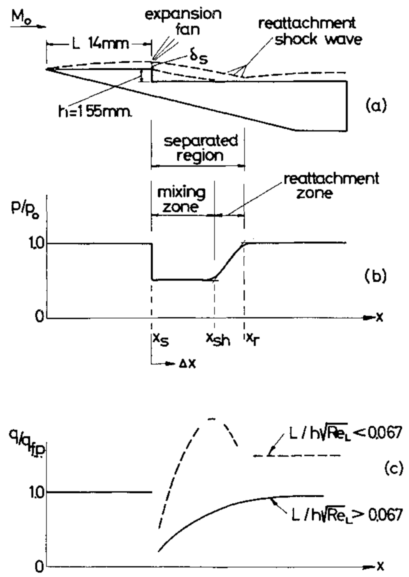


Fig 1 Laminar flow over a backward facing step: a) physical flow field; b) schematic pressure distribution; c) schematic heat-transfer distribution

ing from 0 35 mm Hg abs to 50 mm Hg abs while using moderate pressures (few hundred psi) or hydrogen or air driver gases Of course the conditions of the wind-tunnel measurements are not exactly comparable to the shock-tube conditions, because of the highly different stagnation enthalpy in the shock tube However, one may draw some qualitative conclusions from a comparison of both sets of data

Measurements in separated flows in the shock tube require determination that duration of available flow is larger than the time required for establishment of steady flow over the model Previous measurements of separated flows in shock tubes[7 8] indicated that such flows are established within 50 to 100 μsec The present tests do concur generally with these results but in addition indicate a strong effect of shock Mach number on this starting time

II Experimental Apparatus

A Shock Tube and Its Instrumentation

The shock tube used in this investigation consists of a cylindrical compression chamber 1 5 m long and a square low-pressure tube of 75 mm × 75 mm cross section, 7 m long The low-pressure tube is evacuated to pressure of 0 35 mm Hg abs High-pressure bottled hydrogen or air are used as driver gases in the compression chamber

Shock-wave speed is determined by measurement of the time of travel of the shock wave between two thin platinium film gages mounted a known distance apart on the shock-tube wall The output of the gages is fed through pulse amplifiers into a counter with a 1 μsec resolution

The local heat-transfer rate is measured by thin platinium films sputtered on pyrex glass backing material The details

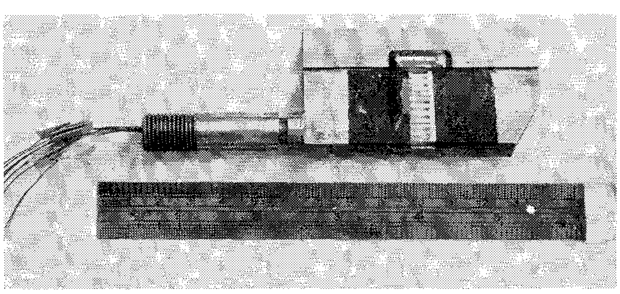


Fig 2 Backward facing step model for heat-transfer measurements in the shock tube

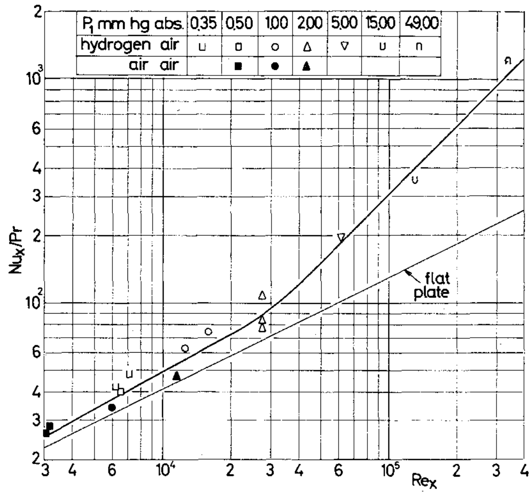


Fig 3 Nu_xPr as a function of Re_x at gage 1

of manufacturing and of the operation of these gages are described in Ref 9 The output of the films is fed into a 535 Tektronix oscilloscope with a 121 Tektronix preamplifier The oscilloscope trace is recorded by a Polaroid camera Details of the experimental apparatus are described in Ref 10

B Backward Facing Step Model for Heat-Transfer Studies

The model for heat-transfer measurements is a steel plate having a sharp leading edge into which a step of height h = 1 55 mm is machined 14 mm behind the leading edge The lower surface is machined to form the plate into a sharp wedge with an initial opening angle, at the leading edge, of 9° At the plate center, ahead and behind the step, a groove is machined for insertion of the pyrex glass elements on which the thin platinium films are sputtered The gage positions are at x/L = 0 7, 1 11, 1 3, 1 48, 1 7, and 2 08 The model is shown in Fig 2 The model spans the shock-tube test section with its surface aligned parallel with the tube axis for flow alignment

III Uniformity of Flow Conditions in the Shock-Tube Tests

Two disturbing effects may be present in the shock-tube measurements These may be due to non-two-dimensionality of the flow over the backward facing step model and due

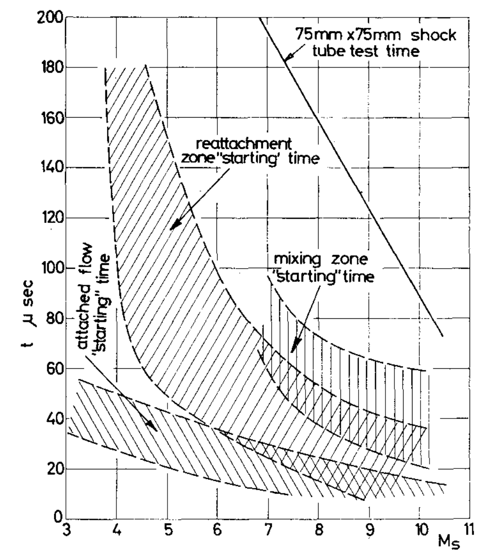


Fig 4 Nu_x/Pr as a function of Re_x at gage 2

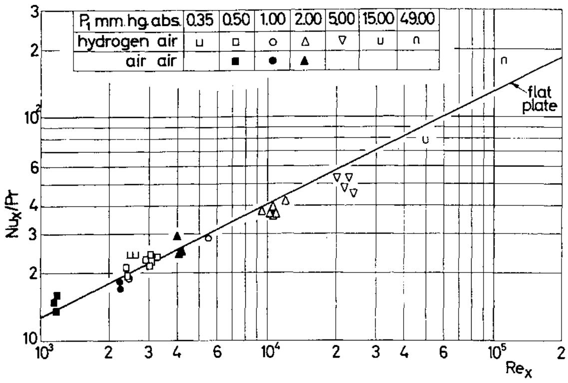


Fig 5 Nu_x/Pr as a function of Re_x at gage 3

to nonsteadiness of the flow in the separation region because of insufficient time for establishment of the separated flow

The two-dimensionality of the flow over the model can be ascertained from previous measurements on a similar model configuration in a wind tunnel reported in Ref 6 Furthermore, these shock-tube measurements are obtained by consecutive shock-tube runs The reproducibility of the results with acceptable experimental scatter indicated in Figs 3 to 8 shows reproducible flow conditions It is shown that when deviations from two-dimensional flow conditions exist, large unexplained scatter is generally found in the data

The heat transfer in the flow in the shock tube must reach steady conditions before the termination of the uniform hot flow In the present shock tube, uniform flow duration varies between about 300 μsec at shock Mach number of 4 to about 90 μsec at shock Mach number of 10 Previous shock-tube investigations showed that in the case of attached flows, steady flow conditions are established within 10 to 50 μsec [9] The few measurements of flow in separated regions in shock tubes[7, 8] indicated the corresponding flow duration to be of the order of 100 μsec

The present measurements indicate that the time of establishment of steady flow conditions at and downstream of reattachment (gages 4, 6, and 8) is about equal to the time of establishment of attached flow for shock Mach numbers above about 6, whereas the heat-transfer rates measured inside the separated region (gages 2 and 3) reach steady values after a longer time The results also show that this establishment time decreases considerably with increasing shock Mach number The results of the measured duration for establishment of steady heat-transfer rate at the various positions of the gages are summarized in Fig 9 This duration is determined by the time for establishment of $t^{1/2}$ variation of gage output The determination of this duration is not a very exact measurement; however, it does serve as an indication for the duration of the time of establishment of steady heat-transfer conditions The output of the gages at various shock-

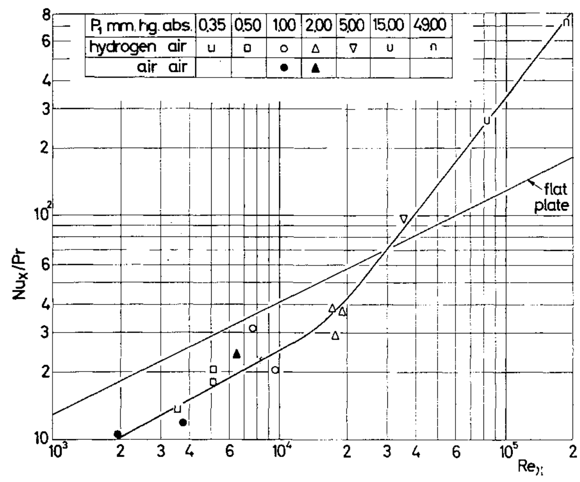


Fig 7 Nu_x/Pr as a function of Re_x at gage 6

tube operating conditions are shown in Figs 10a–10c Most of the gage responses are fairly regular, indicating relatively short starting times, except for gage 2 which is always within the mixing zone and does not reach a steady value at shock Mach numbers between 4 and 5, even after 250 to 300 μsec of available hot flow at initial pressures below 15 mm Hg abs At these conditions the gage output is like a step function in surface temperature (Fig 10a) The step-function response of this gage at these conditions is similar to the response of the thin film gage on the shock-tube wall and also to the response of such a gage subjected to pure heat conduction (e g , at the end wall of a shock tube after reflection of the shock wave) This gage response may be explained by a "trapped" hot gas in the vicinity of the step which is then mixed with the external flow until steady aerodynamic and heat-transfer conditions are reached at this position In tests with initial pressures above 15 mm Hg abs with shock Mach numbers of about 4 5 to 6, the starting times on gage 2 are reduced to about 50 μsec (Fig 10b) At higher Mach numbers ($7 < M < 10$) the steady conditions are reached within 20–60 μsec with initial pressures above 0 35 mm Hg abs on practically all gages (Fig 10c) It may be concluded that there is a range of shock-tube operating conditions where steady heat-transfer rates can be obtained in the laminar separated flow over the backward facing step model used in the present investigation

IV Discussion of Results: Heat-Transfer Measurements

The heat-transfer rates are obtained from the output of the gages, some of which are shown in Figs 10a–10c The local

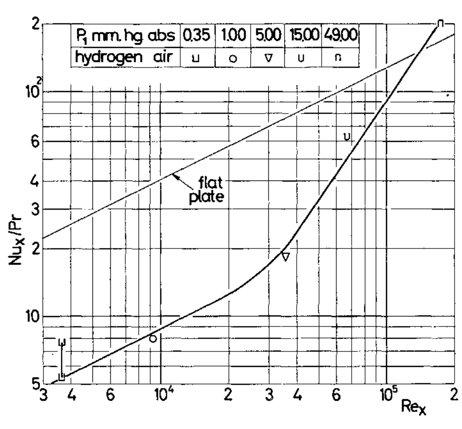


Fig 6 Nu_x/Pr as a function of Re_x at gage 4

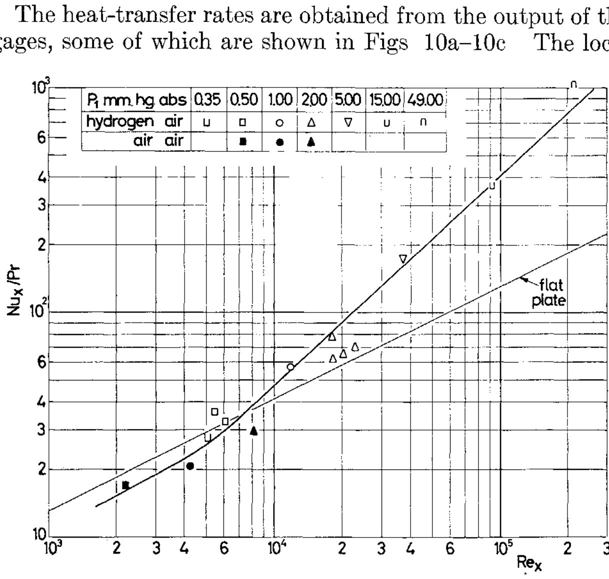


Fig 8 Nu_x/Pr as a function of Re_x at gage 8

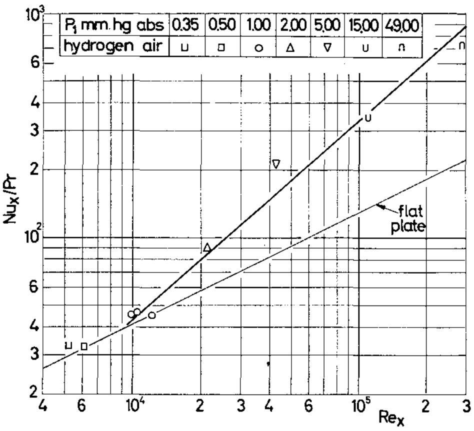


Fig 9 Time of establishment of steady flow in various flow regions in the shock tube

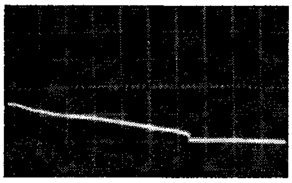
heat-transfer rate expressed as the local Nusselt number Nu_x is plotted as a function of the local Reynolds number Re_x in Figs 3–8 Both the Nusselt number and the Reynolds number are evaluated at external freestream flow conditions (i e., using values of u , ρ , μ , k , H) These measurements can be compared to attached laminar heat-transfer rate over a flat plate given by

$$Nu_x = 0\ 33 Pr^{1/3} Re_x^{1/2} \qquad (1)$$

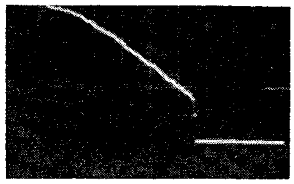
and measured in these tests by gage 1 (Fig 3)

It is interesting to note that this correlation of local Nusselt number with local Reynolds number disregarding the large variation of shock Mach number ($4 < M < 10$) does not introduce undue scatter into the data This may be taken to indicate that this variation of the ratio of stagnation to wall enthalpies ($3 < H_s/H_w < 50$) does not affect the local heat-transfer rate correlation when proper local conditions are used

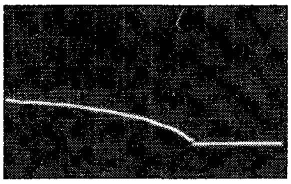
The ratio of local heat-transfer rate to the attached laminar flat-plate heat-transfer rate $q/q_{f\ p}$ is evaluated as a function of Reynolds number based on length of flat plate ahead of the step Re_L and presented in Fig 11 It can be seen that for Re_L up to about 10^4 the heat-transfer rate increase is gradual, whereas at higher Reynolds numbers the heat-transfer rate in



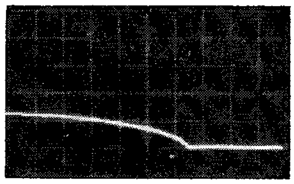
Gage no 1 M = 4 5 P_1 = 49 0 mm Hg abs Sweep = 50 μsec/div



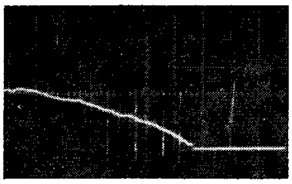
Gage no 2 M = 4 9 P_1 = 49 0 mm Hg abs Sweep = 50 μsec/div



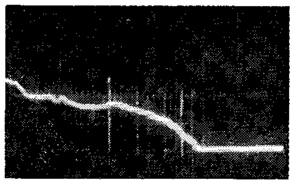
Gage no 3 M_s = 4 57 P_1 = 49 0 mm Hg abs Sweep = 50 μsec/div



Gage no 4 M = 4 5 P_1 = 49 0 mm Hg abs Sweep = 50 μsec/div

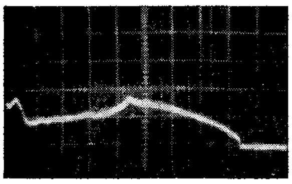


Gage no 6 M_s = 5 39 P_1 = 49 0 mm Hg abs Sweep = 50 μsec/div

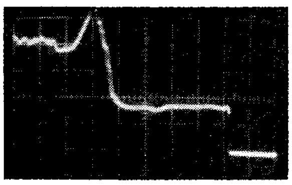


Gage no 8 M_s = 5 29 P_1 = 49 0 mm Hg abs Sweep = 50 μsec/div

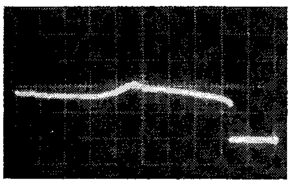
Fig 10b Gages output over a backward facing step in the shock tube at M_s = 4 5 and p_1 = 49 0 mm Hg abs



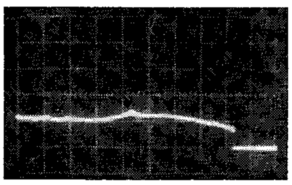
Gage no 1 M = 4 46 P_1 = 1 0 mm Hg abs Sweep = 100 μsec/div



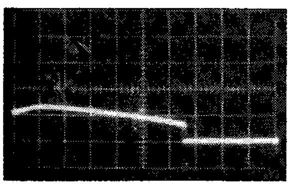
Gage no 2 M = 4 22 P_1 = 2 0 mm Hg abs Sweep = 100 μsec/div



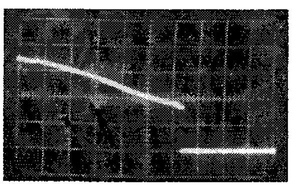
Gage no 3 M = 4 48 P_1 = 1 0 mm Hg abs Sweep = 100 μsec/div



Gage no 4 M = 4 46 P_1 = 1 0 mm Hg abs Sweep = 100 μsec/div

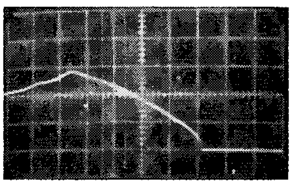


Gage no 6 M = 4 67 P_1 = 0 5 mm Hg abs Sweep = 50 μsec/div

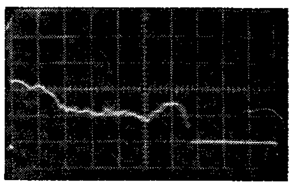


Gage no 8 M = 4 46 P_1 = 1 0 mm Hg abs Sweep = 50 μsec/div

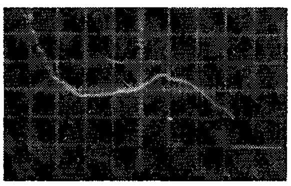
Fig 10a Gages output over a backward facing step in the shock tube at M_s = 4 4 and p_1 = 1 0 mm Hg abs



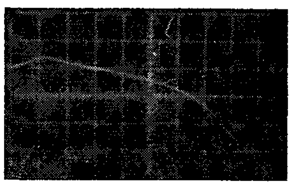
Gage no 1 M = 7 63 P_1 = 1 0 mm Hg abs Sweep = 20 μsec/div



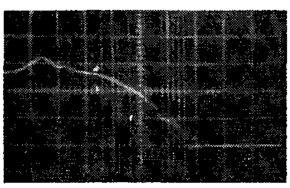
Gage no 2 M_s = 7 70 P_1 = 1 0 mm Hg abs Sweep = 20 μsec/div



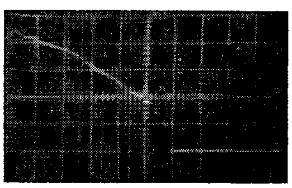
Gage no 3 M_s = 8 52 P_1 = 2 0 mm Hg abs Sweep = 50 μsec/div



Gage no 4 M_s = 9 24 P_1 = 0 5 mm Hg abs Sweep = 10 μsec/div



Gage no 6 M = 7 91 P_1 = 1 0 mm Hg abs Sweep = 20 μsec/div



Gage no 8 M = 7 98 P_1 = 1 0 mm Hg abs Sweep = 20 μsec/div

Fig 10c Gages output over a backward facing step in the shock tube at M_s = 8 0 and p_1 = 1 0 mm Hg abs

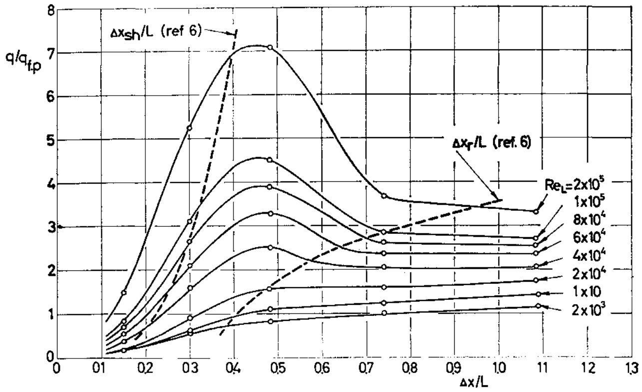


Fig 11 Local heat-transfer rate in the separated region as a function of $hRe_L^{1/2}/L$

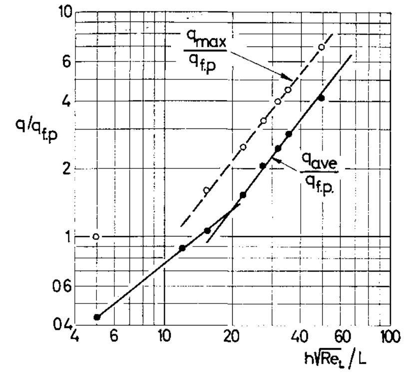


Fig 12 Maximum and average heat-transfer rates in the separated region as a function of $hRe_L^{1/2}/L$

the reattachment zone is increased to a peak up to 7 times the flat-plate value at $Re_L = 2 \times 10^5$ After reattachment, the heat rate is again reduced to an equilibrium value that is higher than the corresponding undisturbed attached flat-plat flow value The limits of the reattachment zone as measured in the wind tunnel[6] at corresponding values of the parameter $hRe_L^{1/2}/L$ are also indicated on Fig 11 The extent of various zones in the separation region which were measured in the wind tunnel[6] do correspond to the variation of the heat-transfer distribution measured in the shock tube at much larger ratios of stagnation to wall enthalpies This fact indicates that the flow field and the heat-transfer rates are not radically affected by the large variation of stagnation to wall enthalpies, at least in the range of parameters used in this investigation, i e , $3 < H_s/H_w < 50$

The rising portion of the heat-transfer rate distribution shown in Fig 11 (i e , $\Delta x/L$ less than about 0 4), can be correlated by a single relation for $hRe_L^{1/2}/L$ values above about 15 ‡ This relation follows the measured heat-transfer rates within about ±10%:

$$q_x = 0\ 22(hRe_L^{1/2}/L)^{1\ 3}(\Delta x/L)^{1\ 7} \qquad hRe_L^{1/2}/L > 15; \quad \Delta x/L < 0\ 4 \qquad (2)$$

The value of maximum heat-transfer rate measured in the reattachment zone can be correlated by the parameter $hRe_L^{1/2}/L$ as shown in Fig 12 The average heat-transfer rate is evaluated from the local heat-transfer rate distribution up to the end of the reattachment zone and is also shown in Fig 12 For $hRe_L^{1/2}/L$ values above about 15 one finds the relations

$$q_{m\ x} = 0\ 0465(hRe_L^{1/2}/L)^{1\ 30}q_{f\ p} \qquad hRe_L^{1/2}/L > 15 \qquad (3)$$

and

$$q_{\ v} = 0\ 02(hRe_L^{1/2}/L)^{1\ 30}q_{f\ p} \qquad hRe_L^{1/2}/L > 15 \qquad (4)$$

For $hRe_L^{1/2}/L$ values up to 15 the maximum heat-transfer rate is very close to the local flat-plate value, their ratio varying between 1 at $hRe_L^{1/2}/L = 5$ to 1 5 at $hRe_L^{1/2}/L = 15$ The average heat-transfer rate is then

$$q_{ave} = 0\ 125(hRe_L^{1/2}/L)^{0\ 8}q_{f\ p} \qquad hRe_L^{1/2}/L > 15 \qquad (5)$$

So, for $hRe_L^{1/2}/L$ above about 14 the average laminar heat transfer is found to be higher than the average laminar heat transfer to a flat plate

The measurements indicate that the heat-transfer rate distribution is dependent on the relative thickness of the boundary layer at separation and the step height When the incoming boundary-layer thickness is comparable to the step height, i e , small values of $hRe_L^{1/2}/L$, the heat-transfer distribution is smooth and the reattachment is gradual When the incoming boundary layer is thin, i e , large values of $hRe_L^{1/2}/L$, the pressure rise at reattachment is quite abrupt[5] resulting in high local velocity gradients and high heat-transfer rates The peak value of the heat-transfer rate is found to increase with increased values of $hRe_L^{1/2}/L$ In the case of the relatively thin incoming boundary layer, the mixing and reattachment zones become fairly long so that eventually effects of transition may also be present

‡ The correlation of the heat-transfer data as a function of x/L was suggested by Max Scherberg of the Aeronautical Research Laboratories U S Air Force

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