JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 25, No. 3, July–September 2011

Measurement of Heat Transfer Rate on Backward-Facing Steps at Hypersonic Mach Number

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DOI: 10.2514/1.47101

Two backward-facing models with step heights of 2 and 3 mm are used to measure the convective surface heat transfer rates by using platinum thin-film gauges, deposited on Macor inserts. Heat transfer rates have been theoretically calculated along the flat plate portion of a model using the Eckert reference temperature method. The experimentally determined surface heat transfer rate distributions are compared with theoretical and numerical estimations. Experimental heat flux distribution over a flat plate model showed good agreement with the reference temperature method at stagnation enthalpy range of 0.8–2 MJ/kg. Theoretical analysis has been used for downstream of a backward-facing step using Gai's nondimensional analysis. It has been found from the present study that approximately 10 and 8 step heights are required for the flow to reattach for 2 and 3 mm step height backward-facing step models, respectively, at a nominal Mach number of 7.6.

Nomenclature

C_f	=	skin friction coefficient
C_p	=	specific heat of fluid at constant pressure, J/kg-K
C^*	=	$\frac{\rho^* \mu^*}{\rho_\infty \mu_\infty}$, Chapman–Rubesin parameter
H_0	=	stagnation enthalpy, MJ/kg
h	=	step height
h_w	=	wall enthalpy, kJ/kg
h_x	=	local unit thermal conductance (heat transfer coefficient), W/m^2-k
k	=	thermal conductivity of fluid, W/m-k
L	=	flat plate length upstream of the step, m
M_∞	=	freestream Mach number
P_0	=	stagnation pressure, kPa
P_r	=	Prandtl number (0.71 for air)
$\dot{q}$	=	convective heat transfer rate per unit area (heat flux)
Re	=	Reynolds number
St	=	Stanton number
$St_{\text{expt.}}/St_{\text{fp}}$	=	normalized Stanton number
St_{fp}	=	Stanton number for a flat plate condition
T	=	absolute temperature, K
T^*	=	reference temperature, K
T_0	=	stagnation temperature, K
T_{aw}	=	adiabatic reference temperature, K
T_w	=	wall temperature, K
U_∞	=	freestream velocity, m/s
u_e	=	velocity at the edge of the boundary layer, m/s
$\bar{V}_\infty$	=	hypersonic viscous interaction parameter
x	=	distance along the flat plate from leading edge, m
x'	=	distance from downstream of the step, m
Γ	=	ratio of specific heats at constant pressure and volume
r	=	temperature recovery factor

Received 9 September 2009; revision received 21 December 2010; accepted for publication 10 January 2011.

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I. Introduction

WHEN the adverse pressure gradient induced in the flow is large enough and if the oncoming flow is not able to surmount the huge pressure hill it usually separates from the surface. For example, the interaction between the shock wave and boundary layer can produce a region of separated flow. The phenomenon may also occur at the upstream facing corner formed by a deflected control surface on a hypersonic reentry vehicle, where the length of separation has implication on control effectiveness. Separation can also occur when a shock wave generated internally in a hypersonic air breathing propulsion system impinges on the boundary layer, as seen in the case of a scramjet combustor. The separation length is a very important parameter that influences the scramjet engine performance. In hypersonic flight corridors the flow separation plays a major role in dictating the vehicle aerodynamics since the inherent gasdynamic flow features of the separated flowfield are quite complex. For example, if we want to understand the separated flow behind reentry-type vehicles flying at hypervelocities, detailed knowledge of surface heat transfer, skin friction and static pressure field are necessary. One of the major implications of flow separation is the adverse effect on the overall aerodynamic drag characteristics of the vehicle. In the hypersonic flight regime, the drag induced by the bow shock contributes a significant portion of the overall drag of the vehicle. However, the situation changes quickly in the presence of separation and subsequent flow reattachment on the body. The skin friction drag in scramjet combustors can sometimes be as high as 30% of the total drag of the vehicle. Hence, proper understanding of flow separation is essential in any hypersonic mission, especially for design of vehicle control laws and aerothermodynamics. Knowledge of surface heat transfer rates and skin friction coefficient is essential for characterizing any hypersonic separated flowfield that is dominated by viscous interactions.

Computational fluid dynamic (CFD) codes are increasingly being used to understand complex hypersonic separated flow features around bodies. However, considerable differences on some of the basic features such as location of separation and reattachment points still persists between both experiments and CFD results even in case of hypersonic laminar flows. A reliable experimental database of laminar separated flows is necessary for validating some of the CFD codes that are used in the study of hypersonic aerothermodynamics. Before identifying precise objectives of this study a brief review of relevant literature available on hypersonic separated flows is presented. This literature review is focused on both experimental heat transfer and the CFD studies that have been carried out in separated hypersonic flow domain.

The rearward-facing step represents a simple flow geometry that can be used to study hypersonic separated flow and shock-wave/boundary-layer interactions. The flow of a thin boundary layer over a backward-facing step involves perturbation of a boundary layer into a mixing layer and the conversion of attached mixing layer back to a boundary layer [1]. As a result of these perturbations, the flow behind the backward-facing step becomes complicated and flow may also become turbulent. A schematic diagram of the viscous flow feature on backward-facing step model is shown in Fig. 1. The point at which the boundary-layer flow is parallel to the model surface is termed as the neck region, and in this region thickness of the boundary layer will be thin. After separation, the flow starts accelerating away from the recirculation zone near the step. This acceleration of the flow is facilitated by a number of recompression waves that eventually coalesce to form a reattachment shock wave away from the boundary layer. Between the points of separation and reattachment, a recirculating region of slower moving fluid is formed. The solid line between separation and reattachment, shown in Fig. 1, represents the zero u-velocity line which delineates between the forward and reverse flow regions. The dashed line separates the recirculating flow at base of the step from the flow that continues downstream [2].

Figure 2 (reproduced verbatim from [2] with the author's permission) shows the type of distribution of heat flux and pressure that occurs downstream of a rearward-facing step. The heat fluxes downstream of the step q are normalized by the flat plate heat fluxes q_{fp} that would exist at that location in absence of a step. Similarly, the surface pressure p is normalized by the flat plate surface pressure p_{fp} that would exist at that location in absence of step. The distance downstream of the step x' is normalized by the step height h. The heat flux can vary from zero to the initial flat plate value (curve 1 in Fig. 2) to a situation where an overshoot in heat flux occurs and the overshoot phenomena can be seen in curve 2 of Fig. 2. The overshoot value is many times the value of equivalent flat plate. The maximum heat flux occurs at reattachment point due to stagnation flow along the dividing streamline. The pressure remains almost constant in the separated region and as a result the recirculating flow moves with a very low velocity compared with the freestream velocity, while surface pressure increases to the value that would exist in absence of the step through the reattachment region. While most of the gas

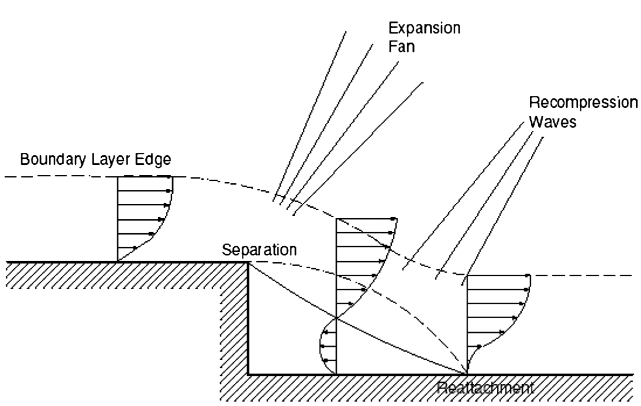


Fig. 1 Schematic diagram of the classical gas dynamic viscous flow features over a rearward-facing step exposed to hypersonic flow.

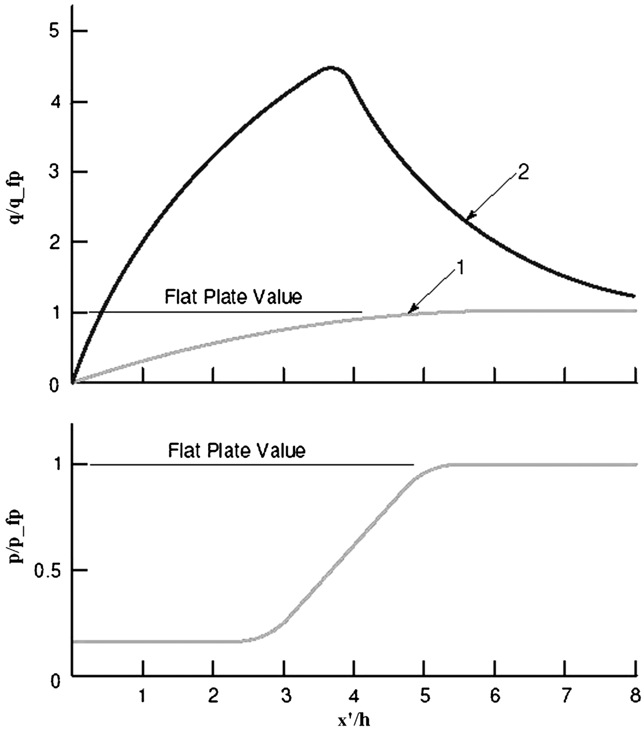


Fig. 2 Typical distribution of heat flux and pressure expected downstream of a backward-facing step [reproduced with author's permission Hayne [2], 2004].

dynamic flow features around a backward-facing step model exposed to hypersonic flow are well known in the open literature, variation of surface convective heat transfer rates for moderate enthalpy levels are not reported. The exact method by which the surface convective heat transfer rate reaches the flat plate values at moderate stagnation enthalpy levels is still not clear. There is a scarcity of backward-facing step experimental data in the separated flow at these low enthalpy levels in the open literature. Hayne [2] carried out experiments on rear ward facing step at very high stagnation enthalpies above >50 MJ/kg. Experimentally validating the functional relation for the heat transfer distribution downstream of the step at lower enthalpy levels using nondimensional analysis developed by Gai et al. [3] is one of the primary focuses of the present work.

Gai et al. [3] suggest that surface heating rates after separation reach the flat plate value in a smooth fashion and there are no sudden spikes as suggested by Rom and Seginer [4]. Laminar heat transfer measurements were made in a shock tube [4] over a two-dimensional backward-facing step flat plate behind a sharp leading edge. However, in stagnation enthalpy range of 0.8–2 MJ/kg and nominal Mach number of 8, there is no experimental data to verify the variation of surface heating rates on a backward-facing step after the flow separation from the flat plate portion of the model. The separated flow around a backward-facing step can be termed as a typical 2-d flowfield and hence, characterizing the flowfield around this type of configuration will be very useful to get further insight into 2-d hypersonic flow separation at moderate stagnation enthalpy. Chapman [5] carried out the theoretical analysis of base pressure distribution on backward-facing step by assuming the flow to be inviscid with separation occurring at the corner. He concluded from dimensional analysis that the pressure ratio, is a function of flow Mach number, step height, and boundary-layer thickness at the step for 90° corners, which can be written as:

$$\frac{P_b}{P_\infty} = F\left(M_\infty, \frac{\delta_L}{h}\right) \tag{1}$$

For a backward-facing step, the ratio of boundary-layer thickness to step height, assuming laminar flow over the backward-facing step model, can be written as:

$$\frac{\delta_L}{h} \approx \frac{L}{h\sqrt{Re_L}} \tag{2}$$

Substituting Eq. (2) in Eq. (1), we get:

$$\frac{P_b}{P_\infty} = F\left(M_\infty, \frac{L}{h\sqrt{Re_L}}\right) \tag{3}$$

Chapman [5] also showed that $\frac{L}{h\sqrt{Re_L}}$ is an important parameter for correlating a base pressure for experimental model. His analysis of heat transfer in the regions of separated flow indicate that separation of a laminar boundary layer reduces the average heat transfer rate, while separation of the turbulent boundary layer can either increase or decrease from the average heat transfer, depending on the flow Mach number. Rom and Victor [6] have shown that the length of separation region is a function of $\frac{L}{h\sqrt{Re_L}}$, but was independent of flow Mach number. Rom and Seginer [7] carried out the heat transfer measurements on backward-facing step at low supersonic flow Mach numbers (i.e., 1.5 to 2.5) in a shock tube. Rom and Victor [6] and Rom and Seginer [7] correlated the local heat flux with the parameter $\frac{L}{h\sqrt{Re_L}}$. When $\frac{L}{h\sqrt{Re_L}} > 0.067$, the boundary layer is thick at the step and the local heat flux increases gradually through the reattachment zone to the level that would be attained for a laminar flat plate in absence of a step. For values of $\frac{L}{h\sqrt{Re_L}} < 0.067$, the boundary layer is thin at the step and as a result the local heat flux significantly increases above the equivalent attached laminar flat plate level near the reattachment zone. Rom and Seginer [7] suggested the delineating value of 0.067 for the parameter $\frac{L}{h\sqrt{Re_L}}$ for hypersonic flow over the rearward-facing step and below which peak heat flux of 0.03 [8] was recorded. A similar study (without considering the Mach number effect) was also carried out by Rom and Seginer [7] and found that the delineating value is 0.067. The difference between Rom and Seginer [7] and Wada and Inoue [8] is most likely due to the effect of Mach number. In the present investigation, we have not used the parameter ($\frac{L}{h\sqrt{Re_L}}$), however, it has been used extensively by Rom and Seginer [7] and Wada and Inoue [8] in their experimental results.

Gai et al. [9] measured the heat flux for a backward-facing step in a dissociated, laminar, high enthalpy flow. For a given L/h and step height h, Gai et al. found that the effect of increasing the value of $\frac{L}{h\sqrt{Re_L}}$ resulted in shifting peak heat flux, which happens further downstream of the step, due to decrease in Re_L. They also found that increasing the value of parameter $\frac{L}{h\sqrt{Re_L}}$ by changing the ratio of L/h was not the same as increasing $\frac{L}{h\sqrt{Re_L}}$ through a change in Re_L. Thus, Gai et al. [9] found that $\frac{L}{h\sqrt{Re_L}}$ was an important parameter to measure the heat flux for a rear ward facing step (downstream) configuration.

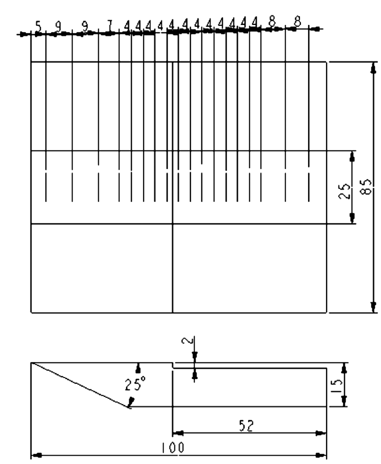
Gai et al. [3] carried out the heat transfer experiments on backward-facing step models of 2 and 3 mm step height at very high enthalpies of 20 MJ/kg in an expansion tube facility in hypervelocity flow regime. Their results showed a gradual rise from the rear of the step to a plateau several step heights downstream. Despite the large number of experimental and theoretical investigation of laminar flowfield over the rearward-facing step, no investigation has yet managed to conclusively determine the parameters that quantitatively influence heat flux and pressure downstream of the step. However, it appears that $\frac{L}{h\sqrt{Re_L}}$ is an important parameter for correlating different experimental data points in laminar hypersonic flow over rearward-facing step flow, not only a parameter which influences heat flux downstream of the step. The theory of Gai et al. [3] has not been experimentally verified in the moderate stagnation enthalpy range (0.8–2 MK/kg) in shock tunnels. In this backdrop the objectives of the present study are given in the next section.

II. Objectives

The objectives of the present experimental studies on backward-facing step models are: measurement of the surface convective heat transfer rates at Mach 7.6, comparison of experimentally measured surface heat transfer rates with theoretical and numerically simulated results, identification of reattachment point location from the heat transfer rate measurements, determining suitable correlating parameters for characterization of flow downstream of the backward-facing step models, and generating an experimental database of surface heat transfer rates at lower enthalpies (2 MJ/kg) in the hypersonic separated flow regime.

III. Test Models

A backward-facing step configuration was chosen because of its relatively simplicity, which facilitates both the experiment and computations. Two backward-facing models, with step heights of 2 and 3 mm, are chosen for the present investigation. The test models are manufactured using lightweight duralumin material. The leading edge is beveled to an angle of 25° on bottom side of the plate. The schematic diagram and photograph of the 2 mm step height backward-facing step model along with the platinum thin-film gauges is shown in Fig. 3. The 2 mm step height model is 100 mm in total length. The length of upstream flat plate portion is 48 mm and the model is 85 mm wide. Eighteen platinum thin-film gauges have been used for the first configuration to measure the surface convective heat transfer rates along the entire length of the model. In upstream flat plate portion, eight platinum gauges are deposited and remaining gauges are deposited on downstream portion of the step. The second model (3 mm step height and not shown here) is 122 mm long with an upstream flat plate length of 72 mm and width of 60 mm. Because the second model is slightly longer when compared with first configuration, 23 platinum thin-film heat transfer gauges are used here to measure the heat transfer rates. In the upstream flat plate portion, 12 platinum gauges are deposited and the remaining gauges are deposited on the downstream portion of the step. For both the configurations, the same ratio of upstream flat plate length to step height (24) has been maintained. The heat transfer gauges are staggered in such a fashion that measurement locations can be increased in the vicinity of the step and at reattachment region.



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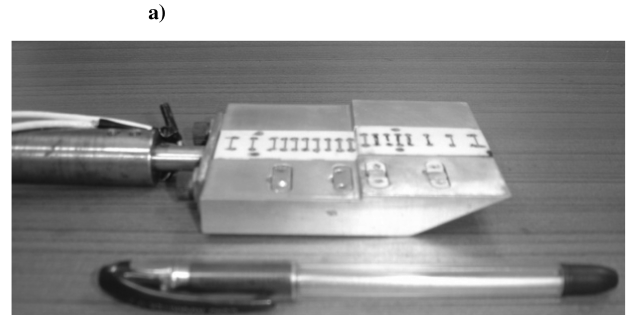


b)

Fig. 3 Schematic diagram and photograph of the 2 mm step height backward-facing step model along with heat transfer gauge locations (all dimensions are in millimeters).

IV. Platinum Thin-Film Gauge Preparation

A. Thin-Film Gauge Preparation

Extreme care has been taken to have a smooth surface finish on the model, as any irregularities on the surface or surface roughness will induce the effect of laminar to turbulent transition. The test model has a provision for inserting the detachable Macor inserts (18 mm width and 5 mm thickness) with platinum thin films over the surface. Precision holes of about 1.5 mm diameters have been drilled along the length of the strip for electrical connections. Suitable counter sunk threaded screws are used to rigidly fasten the macor strips in their slots. Macor is a good insulator with low thermal conductivity and as a result during shock-tunnel testing we can assume that heat conduction is only through the film and no heat is conducted through the metallic model. This enables us to come up with a one-dimensional heat conduction model formulation for measurement of surface convective heat flux in short duration facilities where the typical test time is $\sim$1 ms. In this present study, platinum is deposited on a ceramic glass substrate (Macor) and detailed procedure of coating is briefly given by Saravanan [10]. The sputtered platinum thin-film gauge is a passive sensor and hence thin-film gauge is energized using a constant current power source of 20 mA. The constant current has been kept at a lower current (20 mA) so that the self ohmic heating of the gauge is minimized. The gauges are energized just before the test and switched-off immediately after the test. The resistance of a platinum thin-film sensor is very sensitive to temperature. This would result in a change in the voltage of the circuitry. This change in the voltage across the gauge with respect to time is the temperature time history at the gauge location on the model surface. The use of thin-film gauges for heat transfer measurements in short duration facilities is well established by Schultz and Jones [11]. The thin film works like a resistance thermometer, a detailed analysis of these gauges was reported by Vidal [12]. In addition, we have monitored the gauge resistance after each test and it has been found that the durability of the thin-film gauges is very good for the tested stagnation enthalpy.

B. Calibration of Platinum Thin-Film Gauge

The platinum thin-film gauges have to be calibrated to get the convective heat transfer rate and hence, in the present study, calibration is carried out from atmospheric temperature to 100°C in steps of 5°C. The calibration procedure to obtain temperature coefficient of resistance for the gauge, α is presented in detail by Saravanan et al. [13]. The typical value of α is estimated for the sputtered gauges and found to be 0.0028. The calibration procedure for obtaining the value of gauge backing material property β is presented in detail by Srinivasa [14]. The value of β for Macor is determined as $2,200$ W-s$^{0.5}$/(m^{2}K), and the same value has been used in the present study.

V. Numerical Study

Before the experimental study an illustrative numerical investigation was carried out to understand the hypersonic flow features in a backward-facing geometry. The simulations were performed for the hypersonic flow conditions that the backward-facing step model will experience in the hypersonic shock tunnel. The chosen mesh is hybrid with both triangular prisms (structured mesh) near the model surface and tetrahedron mesh (unstructured mesh) for the remaining flow domain. In the subsequent runs, the number of grid points has been increased to study grid independent analysis and simulations are once again carried out to check variations in the heat transfer rate. Finally, a total number of around 0.825 million nodes (grid points) is used in the present study. Initially an upwind differencing scheme (first-order accurate) was used for computations with a local time scale factor of 0.9 for better convergence and physical time scale option are selected for the continuity equation. Simulations were then carried out with a high resolution second order accurate scheme. The target rms residuals have been set to terminate the simulation at 1.0×10^{-5}. Approximately 2000 iterations (time steps) have been used for the convergence. Approximately 17 hours of CPU time is required for the simulation on an Intel Pentium 4, 1.4 GHz processor. The program is run on a Windows XP platform. The CFD simulation using ANSYS-CFX 5.7 [15] flow is limited to obtain surface convective heat transfer rate over backward-facing step. This CFD package is capable of handling both incompressible and compressible flow problems in almost all the flow domains. It is a complete Navier–Stokes solver, which also incorporates well-established turbulent flow models [15].

VI. Heat Transfer Measurements

A. Flat Plate Heat Transfer Rates in the Hypersonic Flow Regime

A reference temperature empirical method was initially proposed for estimating the surface heating rates for compressible flows by Eckert [16], and this was latter validated theoretically by Dorrance [17]. These two are well-known heat transfer correlations, which are briefly discussed here.

Using Blasius theory, the local skin friction coefficient for laminar boundary-layer flow over a flat plate is:

$$C_f = \frac{0.664}{\sqrt{Re_x^*}} \tag{4}$$

Using the Reynolds analogy, the Stanton number can be written as:

$$St = \frac{0.332}{\sqrt{Re_x^*}} \sqrt{C^*} \{Pr^*\}^{-2/3} \tag{5}$$

C^* and Pr^* are evaluated at reference temperature T^*. T^* can be calculated by:

$$\frac{T^*}{T_e} \approx 0.5 + 0.039 M_e^2 + 0.5 \frac{T_w}{T_e} \tag{6}$$

It can also be calculated by using the Young–Jannsen reference temperature formulae which can be written as:

$$\frac{T^*}{T_e} = 1.28 + 0.023 M_e^2 + 0.58 \left(\frac{T_w}{T_e} - 1 \right) \tag{7}$$

where the Chapman–Rubesin factor C^* is defined as:

$$C^* = \frac{\rho^* u^*}{\rho_e u_e} \approx \left(\frac{T^*}{T_e} \right)^{-1/3} \tag{8}$$

The experimentally calculated Stanton number can be expressed as:

$$St = \frac{q_w}{\rho_e u_e c_p [T_r - T_w]} \tag{9}$$

where, the recovery temperature T_r is defined as:

$$T_r = T_e + r \left(\frac{u^2}{2C_p} \right) \tag{10}$$

where $r = \sqrt{p_r^*}$ for laminar flow.

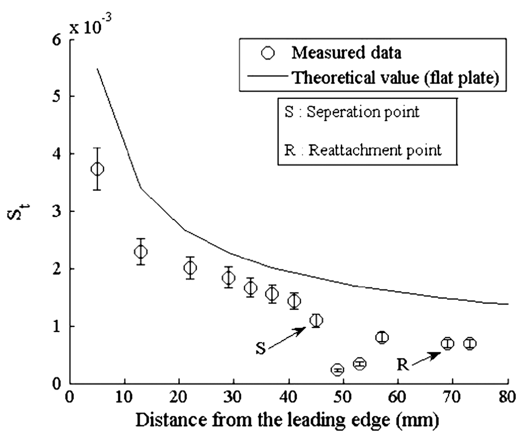
The surface heating rate measurements are carried out in the IISc hypersonic shock tunnel HST2 [18] and the experiments are repeated on an average three to 5 times for a given test condition (freestream condition is given in Table 1) and model configuration to evaluate the repeatability of the measurements. The shock-tube portion of HST2

Table 1 Experimental conditions in the IISc hypersonic shock tunnel HST2

H_0, MJ/kg ($\pm$10%)	P_0, MPa ($\pm$8%)	T_0, K ($\pm$10%)	P_∞, kPa ($\pm$5%)	T_∞, K ($\pm$9%)	U_∞, m/s ($\pm$4%)	M_∞ ($\pm$2%)	Re, per m ($\pm$16%)
2.379	1.76	2367	0.257	189	2094	7.6	7.764×10^5

consists of a 50-mm inner-diameter stainless-steel driver and driven sections separated by a metal diaphragm. For the present investigation, air has been chosen as the test gas and the helium as the driver gas. Pico CoulomB (PCB) pressure transducers mounted toward the end of the driven section monitor the shock-wave velocity. The pressure jump across the shock wave is measured using a pressure transducer (PCB; Piezotronics, Inc., USA) located at the end of the driven section. The wind-tunnel portion of the HST2 is composed of a truncated conical nozzle terminating into a 30×30 cm size test section. The tunnel is capable of producing a reservoir enthalpy of up to 5 MJ/kg and has an effective test time of about 1.2 ms. A high-speed data acquisition system has been procured from National Instruments Pvt. Ltd., for recording and processing of the data from the tunnel. The results from three runs are considered for the analysis as they showed small deviations. Comparison of the experimental Stanton number with theoretical estimation for a backward-facing step model is shown in Fig. 4. The maximum Stanton number occurs at a distance of 5 mm from the leading edge for both the configurations. It has been found that the measured values match well with the theoretical estimation. However, very close to the leading edge, in the vicinity of separation and reattachment points, the measured values deviated from the estimation for both configurations. It is interesting to note that the percentage of deviation is less for 3 mm step height (25–33%) compared with 2 mm step (29–47%) configuration. In general, as the step height h is increased, the length of the recirculation region also increases. In the case of 2 mm configuration, the recirculation region is not clearly observed, compared with 3 mm step height as shown in Fig. 4.

The experimentally derived Stanton number is compared with both the numerical simulation and theoretical estimation for the



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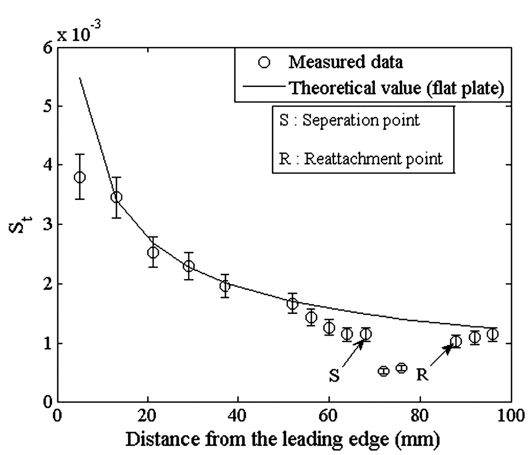

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Fig. 4 Comparison of experimental Stanton number with theoretical estimation of a flat plate on backward-facing step: a) 2 mm step height and b) 3 mm step height at Mach 7.6.

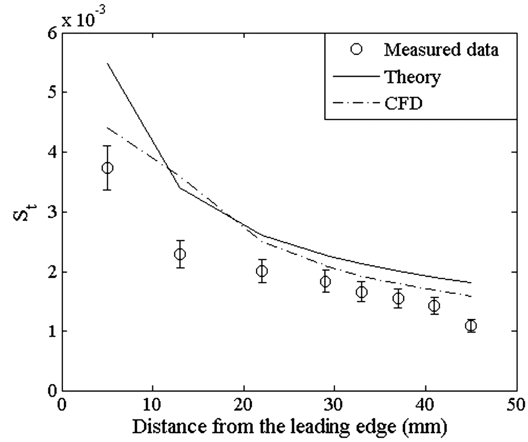

Fig. 5 Comparison of Stanton number for an upstream flat plate of the backward-facing step (2 mm step height) flying at Mach 7.6.

upstream flat plate portion of the 2 and 3 mm step height backward-facing models as shown in Figs. 5 and 6. The agreement between the measured value, theory and numerical simulation is quite satisfactory. The error bar on Stanton number is also shown in the same plot and found to be $\pm 8.5\%$. However, in the case of 3 mm backward-facing model, the computational results underpredict the experimental values. One possible explanation is the existence of transitional effects in the wall boundary layer of the flow, which are not taken into account in the simulations. At the leading edge of a flat plate, the measured Stanton number for both configurations deviates from the numerical simulation which may be due to leading-edge effects. Beyond the leading edge, the experimentally measured surface heat transfer rates match well with simulation results and with the Eckert reference temperature method. The flow recirculation region downstream of the step is clearly captured in the numerical simulation and is shown in Fig. 7. The mean velocity field clearly shows that a recirculation region is found behind the step. In the backward-facing step, the mean longitudinal velocity component changes slightly after $\theta = 90$ degree and secondary flow never achieves fully developed state.

B. Heat Transfer Rates at Downstream of the Step

Gai et al. [9] developed the heat flux functional relation based on Chapman's [19] separated flow analogy to determine the functional dependence of heat flux downstream of rearward-facing step model. The similarity correlations for the backward-facing step using hypersonic small disturbance theory originally developed by Gai et al. is described below for the hypersonic flow without dissociation. Assuming that step is orthogonal to the flat plate surface and to determine what parameters are matched for similarity to get Stanton

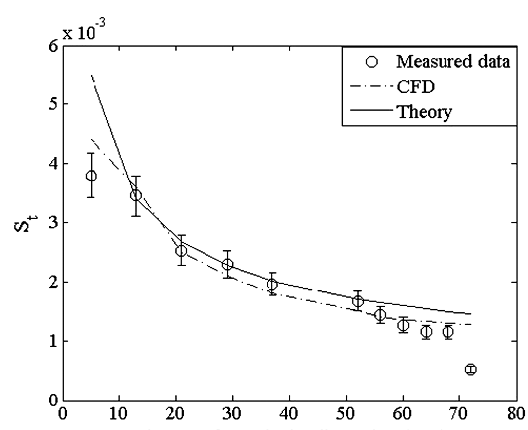

Fig. 6 Comparison of Stanton number for an upstream flat plate of the backward-facing step (3 mm step height) flying at Mach 7.6.

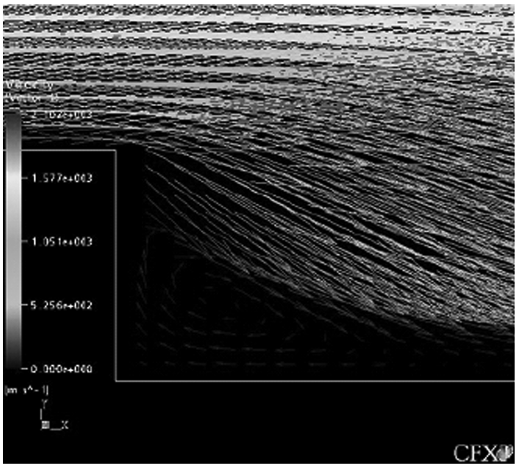

Fig. 7 Numerical simulation of velocity vector plot in the recirculated region on the backward-facing step (2 mm step height) model.

number distributions downstream of a backward-facing step model, we can write:

$$St\left(\frac{x^i}{h}\right) = f\left[M_\infty, Pr, \gamma, \alpha, Re_L, \frac{T_w}{T_0}, \frac{\delta_L}{h}, \frac{\delta_L}{r_d}\right] \tag{11}$$

For a given fluid medium and level of dissociation in the freestream, Pr, γ, α may be assumed constant, giving

$$St\left(\frac{x^i}{h}\right) = f\left[M_\infty, Re_L, \frac{T_w}{T_0}, \frac{\delta_L}{h}, \frac{\delta_L}{r_d}\right] \tag{12}$$

For experiments in shock tunnel and other similar flow facilities, $T_w/T_0 \ll 1$ and hence Eq. (12) becomes

$$St\left(\frac{x^i}{h}\right) = f\left[M_\infty, Re_L, \frac{\delta_L}{h}, \frac{\delta_L}{r_d}\right] \tag{13}$$

For a laminar boundary-layer flow, $\frac{\delta_L}{h} \sim \frac{L}{h\sqrt{Re_L}}$.

Therefore, the boundary-layer thickness at the step is estimated by using the relation proposed by Mallison et al. [20]. The flat plate boundary-layer thickness can then be written as:

$$\delta_L = \frac{1.721L}{\sqrt{Re_L}}\left\{2.397 + \frac{T_W}{T_\infty} + 0.193\sqrt{Pr}[\gamma - 1]M_\infty^2\right\} \tag{14}$$

Thickness of the boundary layer (3.54 mm) is comparable to step height (3 mm)

$$St\left(\frac{x^i}{h}\right) = f\left[M_\infty, Re_L, \frac{L}{h\sqrt{Re_L}}, \frac{\delta_L}{r_d}\right] \tag{15}$$

where $\frac{\delta_L}{r_d}$ can be considered to be a Damkholar number Ω, equivalent to rate of diffusion time in the boundary layer τ_d, divided by the time of recombination of species in the boundary layer τ_y. Neglecting the effect of dissociation gives

$$St\left(\frac{x^i}{h}\right) = f\left[M_\infty, Re_L, \frac{L}{h\sqrt{Re_L}}\right] \tag{16}$$

For complete similarity at the step, $\frac{L}{h\sqrt{Re_L}}$ should be matched. For high Mach numbers and low Reynolds numbers, such as those encountered by space craft, the viscous interaction parameter is appropriate to combine the effects of both Mach and Reynolds numbers.

Assuming such similarity holds good in the present flow situation of high enthalpy flow over a rearward-facing step, then the viscous interaction parameter $\bar{V}_\infty^* = M_\infty^* \sqrt{C^*}/Re$ and the well-known hypersonic small disturbance parameter [$M_\infty \tau$, where ($\tau = \frac{h}{L}$)] can be written as

$$St\left[\frac{x^i}{h}\right] = f\left[\frac{V_\infty^*}{M_\infty \tau}\right] \tag{17}$$

Therefore, for hypervelocity flows, the heat transfer behind a small step is dependent on the parameters of viscous interaction and the hypersonic small disturbance. Under these assumptions, the heat transfer behind a rearward-facing step (where $\tau \ll 1$) is a function of $\frac{V_\infty^*}{M_\infty \tau}$ for low to moderate Reynolds numbers. This is identical to Chapman parameter $\frac{L}{h\sqrt{Re_L}}$ in moderate to high supersonic Mach number flows. If the viscous interaction parameter is matched between different data sets, then the type of distribution and the level of heat transfer should also match. The measured Stanton number is normalized with the Stanton number of a flat plate configuration at the same location. The normalized Stanton number ($\frac{St_{\text{expt}}}{St_{\text{fp}}}$) is plotted in downstream of the step for both the configurations as shown in Figs. 8 and 9. The x-axis denotes the ratio of distance downstream of the step to the step height $\frac{x'}{h}$. From the above figures, we found that the measured heating rate is dropped substantially in the vicinity of the step, which is an indication of flow separation from corner of the step. It is well known that the flow separates from the corner for the backward-facing step model with 90° corners. In downstream of the step, reattachment of the flow occurs and as a result an increase in heat transfer rate is seen. In the separated flow, the heat transfer rate is $0.4\ \text{W/cm}^2$ immediately after the step. The Stanton number decreases exponentially until the separation point up to the step and then almost remains constant in the region of separated flow and then reaches the flat plate value smoothly at the reattachment region. The flow takes about 10 and 8 step heights to reattach in case of backward-facing step model for 2 and 3 mm step heights, respectively.

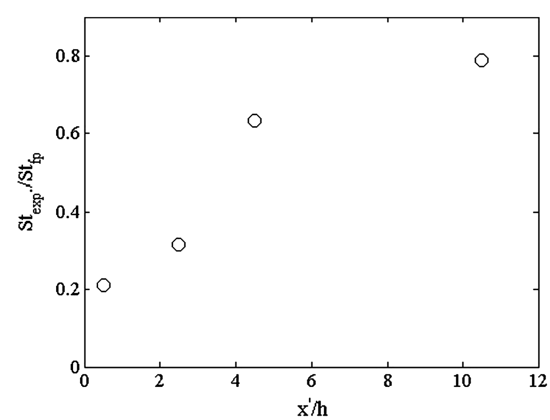

Fig. 8 Variation of nondimensional Stanton number in the downstream of the backward-facing step (2 mm step height) model.

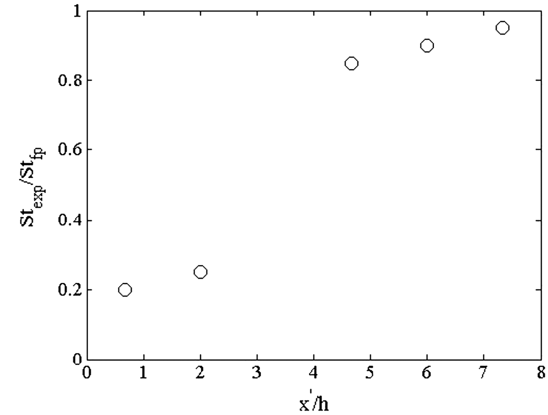

Fig. 9 Variation of nondimensional Stanton number in the downstream of the backward-facing step (3 mm step height) model.

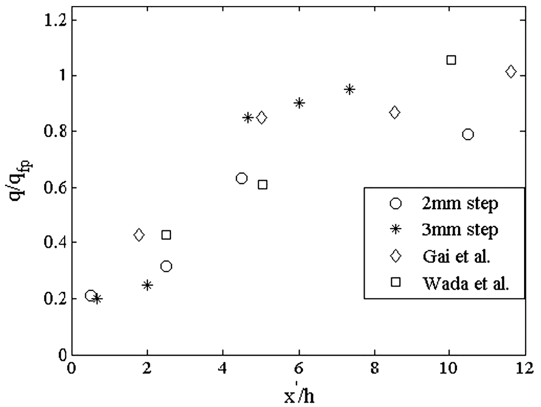

Fig. 10 Comparison of Gai et al. [9], Wada and Inoue [8], and present experiments (backward-facing step) for similar values of the parameters $M_\infty\tau$ and $V^*_{\infty,L}$ (present experiments: $M = 7.6$, hypersonic shock tunnel for 2 and 3 mm step height; Gai et al. [9] $M = 10$, expansion tube facility; Wada and Inoue [8]: $M = 10$, gun tunnel).

The nondimensional experimental Stanton number data is plotted along with important experimental results of Wada and Inoue [8] and Gai et al. [9] for backward-facing step models at hypersonic speeds as shown in Fig. 10. The similarity values of viscous interaction and hypersonic small disturbance parameters are calculated and compared with other facilities, which are tabulated in Table 2. All the data of measured heat transfer rates on the backward-facing step follows the same trend even though they are generated from different experimental facilities. It is quite clear that, at these moderate enthalpy levels, after separation the flow essentially goes back to flat plate regime in a linear fashion and there is no sudden nonlinear jump. It implies that (for the present experimental condition of Mach 7.6) whenever the flow encounters small changes in geometry it reattaches in a linear fashion (i.e., without any spikes) in the measured values of surface convective heating rates.

The results indicated that Gai's nondimensional parameter group (viscous interaction and hypersonic small disturbance) can be correlated to backward-facing step in the region of separated flows. From earlier experiments on backward-facing step models, Rom and Seginer [7] suggested a delineating value of 0.067 for the parameter $\frac{L}{h\sqrt{Re_L}}$, below which an overshoot in the heat flux was seen downstream of the step. Wada and Inoue [8] found the value of the delineating value to be 0.03. In the present heat transfer experiments no overshoot in heat flux is obtained, suggesting that other parameters in addition to $\frac{L}{h\sqrt{Re_L}}$ influence downstream of the step. The heat flux downstream of the step reaches a flat plate value observed by Gai et al. [3]. However, the increase in heat transfer rate is gradual for both the cases, namely 2 and 3 mm step heights. The reattachment process is shown to take place over a length of $\sim$6 step heights after the initial rise in heat flux. The start of initial rise in heat fluxes itself takes $\sim$4 step heights. For the current experiment (Mach 7.6 flow in a shock tunnel), the values of $\frac{h}{\sqrt{Re}}$ obtained are 1.036×10^{-5} (2 mm step) and 1.268×10^{-5} (3 mm step), respectively, at the moderate enthalpy condition.

VII. Measurement Uncertainties

The uncertainties in the freestream conditions and heating rate measurements have been estimated using sequential perturbation techniques [14,21]. The uncertainties associated with test flow conditions include contributions from uncertainties in shock-tube filling conditions (P_1 and P_4), shock speeds V_s, and measured outputs from the data acquisition system. Uncertainties in the flow conditions are shown in Table 1. Based on the uncertainties associated with the gauge characteristics, data acquisition system, data reduction techniques, and calibration, the measured values of heat transfer rates are believed to be accurate to $\pm 5\%$ with helium as driver gas. Various factors such as uncertainty in angle of attack, misalignment of Macor inserts, discontinuity in substrate and model properties, and departure from one-dimensional heat conduction during the run time contribute to the uncertainties in the measured Stanton number. Finally, the estimated uncertainties in the measured data are $\Delta q\infty = 0.064 q\infty$ and $\Delta St = 0.085 St$. All uncertainties are at 95% confidence interval levels.

Table 2 Viscous interaction parameter and small disturbance theory similarity parameters obtained by other researchers along with the values for the present shock-tunnel experiments for backward-facing step model

Test	$V^*_{\infty,L}$	$M_\infty\tau$	$V^*_{\infty,L}/M_\infty\tau$
Gai et al. [9]	0.019	0.918	0.02069
Wada and Inoue [8]	0.016	0.867	0.01854
Present experiments.	0.026 (3 mm step) 0.0318 (for 2 mm step)	0.316	0.0824

VIII. Conclusions

Based on the surface convective heat transfer measurements both the flow separation and reattachment points have been clearly identified in the hypersonic flowfield over backward-facing step models. The measured surface heat flux downstream of step (i.e., in the separated flow region) is compared with Gai et al.'s [9] nondimensional analysis. The variation of measured heat flux values indicate that after flow separation the heat flux values reach the flat plate value in a smooth fashion and this is consistent with their prediction. It is also shown for the first time from these experiments that Gai et al.'s [9] theoretical similarity analysis for backward-facing step geometry is also valid for moderate-to-low stagnation enthalpy flows. The flow takes nearly 10 and 8 step heights to reattach in case of 2 and 3 mm height backward-facing step models, respectively. The surface heat flux immediately downstream of the step is $\sim$0.4 W/cm^2. Experimental heat transfer data generated at lower enthalpy levels ($\sim$2.3 MJ/kg) on the backward-facing step will be useful for numerical code validations. Future studies will focus on directly measuring the skin friction variation in the separated flow regions. Also, the possibilities of using microelectromechanical system-based static pressure sensors to accurately map the static pressure distribution in the separated flow region are being explored.

Acknowledgments

The authors express their thanks to S. Rajagopal and P. Jeevan for technical assistance in running the tunnel and taking the measurements. The authors would also like to express their thanks to the Indian Space Research Organization-Space Technology Cell IISc for financially supporting this project.

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