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Heat Transfer Measurements using Infra-Red Thermography in Rarefied Flows

by

M. F. Westby

Farnborough, Hampshire

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HEAT TRANSFER MEASUREMENTS USING INFRA-RED THERMOGRAPHY IN RAREFIED FLOWS

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SUMMARY

Tests have been carried out in the Defence Research Agency Low Density Wind Tunnel to determine the heat transfer rate on a flat plate and a series of sharp slender cones. The tests were carried out in the transitional rarefied flow regime. An infra-red scanning camera system was used to determine surface temperatures and hence heat transfer rate. Data were compared with two analytical theories and one existing set of data. Results show that the IR system is at least as good at determining heat transfer rates as a thermocouple technique and has better spatial resolution. The technique is also sensitive enough to detect changes in the state of the flow over the surface of models.

Paper presented at the NATO Advanced Research Workshop "New trends in instrumentation for hypersonic research", ONERA Le Fauga-Mauzac, 27 April to 1 May 1992.

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1 INTRODUCTION

In continuum flow CFD can be used with some confidence for the prediction of heating rates on complex bodies. However, there are currently no theoretical or computational methods which can be used with total confidence for the prediction of aerodynamic heating in rarefied flows. This leaves experimental studies as the prime method for obtaining such data. It is important therefore, that an experimental technique is available which is able to measure heat transfer rates reliably and accurately in rarefied flows.

A measurement technique which appears to have the necessary attributes is infra-red thermography, using a scanning radiometer. IR systems are commercially available and have been used with considerable success in various types of hypersonic wind tunnel over a number of years. The main advantage of the system is that it is completely non-intrusive, consisting of a passive, remote detector. Also, data can be obtained at any point within the field of view of the scanner (depending on the spatial resolution of the scanner and the orientation of the surface being observed).

Two test programmes have been carried out in the Defence Research Agency Low Density Tunnel (LDT) related to aerodynamic heating. Both of these have involved the use of infra-red thermography to measure the rate of change of surface temperature on thin walled bodies. An initial test[1] established that IR thermography showed promise as a useful technique for determining heat transfer rates in the LDT. It was therefore decided, as a second stage, to test some very simple bodies for which analytical predictions of surface heat transfer rates existed.

2 EXPERIMENTAL DETAILS

2.1 Description of Test Facility

The DRA LDT[2] is a continuously operating facility which uses pure nitrogen as its test gas. It uses a graphite resistance heater to heat the test gas which is then expanded through the nozzle into an open-jet working section. The tunnel is connected to a set of mechanical vacuum pumps which have a sufficiently high pumping speed to sustain continuous running. The facility uses a contoured nozzle which generates a uniform flow with a Mach number of 9.84. The tests described in this paper were carried out at three calibrated test conditions. Reservoir pressure ranged from $1.791 \times 10^5 Nm^{-2}$ to $2.055 \times 10^5 Nm^{-2}$ and reservoir temperature was varied between 1170K and 1660K. The unit freestream Reynolds number range was $6.3 \times 10^4 m^{-1}$ to $1.24 \times 10^5 m^{-1}$.

2.2 Description of Models Used

Two types of model were constructed. The first type was a flat plate model 200mm long by 75mm wide. The surface upon which measurements were to be made was 0.5mm thick stainless steel with the leading edge ground sharp. The stainless steel plate was supported on an aluminium frame with the underside of the steel plate shielded from the free stream. At no point where measurements were made was the steel in contact with its supporting frame.

A series of slender sharp cones were also tested with half angles of 4°, 6°, 7°, 8° and 10°. These models were made of nickel using an electroforming technique, whereby a thin layer of nickel is deposited on a steel mandrel, which is removed at the end of the process. The cone models all had a nominal wall thickness of 0.4mm although, due to the manufacturing technique, there were slight differences between the five models. It should be also noted that the cone models were originally designed to be used as force testing models, where wall thickness is unimportant. Therefore, the wall thickness may not be constant along the length of the models.

All of the models were sprayed with a high temperature matt black paint. This gave the models an emissivity in excess of 0.9.

2.3 Tests Carried Out

The flat plate model was mounted so that tests could be carried out with the plate at angles of incidence between 0° and 30°. Measurements were made with the Infra-Red scanner over the length of the plate at three freestream test conditions and at angles of incidence of 0°, 5°, 10°, 15°, 20°, 25° and 30°. Oblique shock relationships were used to determine the flow conditions over the plate, downstream of the leading edge shock wave. As readings were only made along the centre-line of the model, it was assumed that data were obtained where the flow was two-dimensional.

All tests carried out using the cone models were at zero incidence where a sharp cone is the axisymmetric equivalent of a flat plate in truly two-dimensional flow. Again, three freestream test conditions were used and conical flow theory was used to calculate the flow conditions at the surface of the cone. Data were gathered along one meridian of each cone model at each test condition.

All of the tests carried out were repeated at least once to check the repeatability of the results. In some cases, especially where the flat plate was set at the larger angles of incidence, more repeat runs were needed with the scanner system set up differently to ensure that good readings had been made both near to the leading edge of the model and at the rear.

2.4 Heat Transfer Instrumentation

Surface heat transfer rates were measured during these tests by using an infra-red scanning camera system (an AGA 780), with its associated hardware and software. The system consisting of a camera, a main control unit (chassis) and a digital tape recorder (DTR). The scanner measures the intensity of electro-magnetic radiation in the 3 to 5μm waveband emitted by the body under test. This intensity is related to the surface temperature of the body by the Stefan-Boltzmann law. Thus, the temperature of a body can be determined, provided it is a black body emitter and that the system is calibrated accurately overall.

Calibration was carried out inside the working section of the tunnel to avoid the necessity of accurately determining the emissivity of the models and the transmissivity of the working section IR transparent window. A calibrated thermocouple was attached to the back of the surface of one of the models and the IR scanner was pointed at the front of the surface in the same position as the thermocouple. The entire model was then heated up using a diffuse hot-air blower until a stable temperature was reached. Measurements of surface temperature were then made using both the thermocouple and the IR scanner. This procedure was repeated at several different temperatures covering the whole range encountered during the tests. The IR system was then calibrated against the thermocouple output.

During runs, the output signal from the scanner was amplified and conditioned by signal conditioners contained in the main chassis. The DTR recorded images processed by the main chassis at a rate of one every second. After the completion of a run, the processed images were downloaded from the DTR into a microcomputer and further processed by a software package which produced a series of temperature maps of the model in the wind tunnel test section.

2.5 Experimental Procedure

The Low Density Tunnel uses a graphite resistance heater to produce the high stagnation temperature needed to avoid liquefaction of the working fluid (pure Nitrogen) in the test section. This results in a "warm-up" period of approximately 1 to 2 minutes (depending on freestream conditions) at the start of each run before the flow is correctly established with the reservoir conditions stabilised at the correct values.

It is important that the surface of the model under test is at a low and reasonably uniform temperature at the start of the measurement period. Therefore, the model to be tested was mounted on an injection rig mounted in the roof of the working section. This rig held the model outside the high-temperature free jet until stable flow conditions had been obtained and useful measurements could be made. The rig consists of a pivoted arm which can swing a model from outside the free jet to the centre of the core flow in under 0.1 second. This is fast enough for it to be assumed that heating of the model commences uniformly over the whole surface of the model when it is injected.

Once a stable flow had been established with the correct stagnation conditions, and just before the model was injected into the flow, the DTR was started. Up to 20 images were captured and recorded by the DTR at a rate of 1 per second. The scanner system was set up so as to record temperatures between approximately 20°C and 90°C. This allowed accurate derivation of heat transfer rates (see section 2.6) without excessive temperature gradients developing along the length of a model.

A run was terminated when a substantial part of the surface of the model under observation had exceeded the upper temperature limit of the scanner system (*ie* greater than 90°). At this point the tunnel was shut down, the DTR was stopped and the model was cooled down before the start of the next run.

2.6 Derivation of Heat Transfer Rates

To obtain surface heat flux data, a series of thermal images were obtained of the model under test during the course of a run. Data was acquired as soon as possible after the model had been injected into the flow at the start of the run. Spot temperature measurements were obtained at several points on the surface of the model after the data from each run had been downloaded into the microcomputer and processed by the software. Readings were taken from each image, providing a time-history of the surface temperature of the model these points. From this time-history, the rate of change of temperature, dT_w/dt, could be calculated.

A local value of heat transfer rate per unit area ($\dot{q}$) could then be deduced from the value of dT_w/dt and the thermal properties of the model wall material, using the relationship

$$\dot{q} = \rho_w c_w y \left(\frac{dT_w}{dt} \right) \quad (kWm^{-2}) \qquad (1)$$

where ρ_w is the density of the wall material, c_w is the specific heat capacity of the wall material and y is the thickness of the wall.

Two basic assumptions are implicit in this relationship. First, it has to be assumed that there is no temperature gradient across the thickness of the wall, *ie* that each element of the surface acts as a calorimeter. Secondly, the rate of heat conduction within the wall has to be small compared to the rate of convective heat transfer from the flow to the wall.

The stagnation temperature of the flow is an order of magnitude higher than the model wall temperature throughout the run. Thus, if the two previous assumptions are proved to be reasonable, the temperature rise throughout the course of the run should be linear with time at any point on the surface of the model.

The first assumption (zero temperature gradient through the thickness of the wall) was reasonable as the wall thickness was less than 0.5mm on each model and the gas pressure and density on the back face of the wall was very low in all cases. The initial heat pulse should have reached the inner surface of the wall material in less than 1 second. Thereafter, as there was no thermal path away from the back surface of the wall, there should have been no temperature gradient across its thickness.

The second assumption (neglecting internal heat conduction) is reasonable if temperature gradients along the surface of the models are small. This allows each element of the surface to be treated in isolation, with no reference being made to the surrounding elements of the surface. This was ensured by keeping the run time sufficiently short that the temperature of the wall was not raised to a point where internal heat conduction caused by temperature gradients became significant. To check that errors were not being caused by conduction, plots of temperature versus time were made. If heat conduction had been significant, dT_w/dt would have slowly increased as energy was transferred along the surface of the model by conduction. This was not detected in any of the plots of temperature versus time and so it could be assumed that the effect of internal heat conduction was negligible.

3 EXPERIMENTAL RESULTS

3.1 Presentation of results

Results are presented in Figs 1 to 9. Fig 1 shows the increase of temperature with time on the flat plate at an angle of incidence of 0°. It can be seen that temperature increases linearly with time, justifying the assumption that heat conduction within the wall of the model can be neglected. Fig 2 shows the surface heat transfer rate per unit area, $\dot{q}$, against distance from the leading edge of the plate. These results are derived from those given in Fig 1.

In order to plot the results meaningfully, the flow conditions behind the bow shock wave had to be calculated at each angle of incidence (or cone half angle) and at each of the freestream flow conditions.

To determine the flow over the plate, oblique shock relations were used to determine Mach number, static pressure, temperature and density behind the leading edge. Charts and tables[3] were used to calculate the flow conditions over the surfaces of the cones. The heat transfer rates per unit area were then non-dimensionalised into the form of Stanton number, where

$$St = \frac{\dot{q}}{\rho_2 U_2 C_p (T_o - T_w)} \qquad (2)$$

Stanton number data from the cone tests were divided by $4\sqrt{3}$ (see ref 4) in order that it could be compared with the flat plate data. Note that hereafter, all Stanton numbers quoted for the cone tests are those values which have been divided by $4\sqrt{3}$.

Unit Reynolds number downstream of the oblique shock wave was calculated using the Sutherland formula to evaluate the values of viscosity, where

$$\mu_2 = \frac{1.4296\times10^{-6}\, T_2^{3/2}}{T_2 + 117.0} \quad (kgms^{-1}) \qquad (3)$$

Data from one run (that illustrated in Figs 1 and 2) are also shown in Fig 3. Stanton number is plotted against Reynolds number, based on conditions downstream of the oblique shock wave and distance from the leading edge of the plate. Figs 4 and 5 plot Stanton number against Reynolds number for all of the data from the tests on the flat plates and cones respectively.

When plotting heat transfer data obtained in rarefied flow, it is conventional to plot $M_2^3 St$ against $\bar{\chi}$, where

$$\bar{\chi} = M_2^3 \sqrt{\frac{C^*}{Re_{2,x}}} \qquad (4)$$

$$C^* = \frac{\mu^* T_2}{\mu_2 T^*} \qquad (5)$$

and

$$T^* = T_o \left[\frac{1}{6} + \frac{\tfrac{1}{2} T_w}{T_o}\right] \qquad (6)$$

Data from all of the tests carried out on the flat plate model are plotted in Fig 6. Results for the sharp cones are plotted in Fig 7.

3.2 Comparison with Theory

Data were compared with two theories, viscous strong interaction theory[5], where

$$M_2^3 St = 0.0788 \left[1 + \frac{2.5 T_w}{T_o} \right]^{1/2} \bar{\chi}^{3/2} \qquad \textbf{(7)}$$

and a reference enthalpy method[4], where

$$M_2^3 St = \frac{0.332}{\sqrt{Re_{2,x}}} \left[\frac{T_2}{T^*} \frac{\mu^*}{\mu_2} \right] (Pr^*)^{-2/3} \qquad \textbf{(8)}$$

It can be seen from Fig 8 that the magnitude of all of the heating data from the flat plate tests is higher than the highest of the predictions by a factor of almost 2. However, the slope of the line of data is similar to that of the reference enthalpy method at values of $\bar{\chi}$ less than about 6. A point to note is that at a value of $\bar{\chi} \approx 6$, the slope of the flat plate data line increases to become close to that of the viscous strong interaction method. This shows that the IR system is sufficiently sensitive to detect differences in the state of the flow over the surface of the body in rarefied flow conditions (*ie* from merged to inviscid flow).

The data from the cone tests is in better agreement with the predictions but does not show the clear trends exhibited by the flat plate data. The reason for this is unclear but a possible explanation is that if the angle between the surface under investigation and the scanner is too acute, the temperature reading from the system is lower than the actual surface temperature. At the nose of the pointed cones it is difficult to be sure that the readings are being taken exactly along the meridian which is normal to the axis of the camera. Any small deviations from this line will result in readings which are erroneously low. This could well be the source of the deviation from the trend seen in the cone results at values of $\bar{\chi}$ greater than about 6. All of these data were acquired near to the noses of the cone models.

3.3 Comparison with Existing Data

Fig 9 compares the current data with that obtained by Hendry[6] using thermocouples attached to the back of a flat plate. It can be seen that over the range of $\bar{\chi}$ from around 2 to 30 the data coincide, within the bounds of experimental error. This shows that the IR thermographic technique can provide results at least as good as a more traditional method of measuring surface temperature. Also, the IR method has the advantage of resolution - it can produce temperature maps of whole surfaces. By comparison, a model instrumented with a relatively small number of thermocouples mounted in its surface can only produce discrete data points which may not adequately show important flow features.

4 CONCLUSIONS

Tests carried out in the DRA Low Density Tunnel have shown that a commercially available J fra Red scanner system is capable of measuring surface heat transfer rates accurately and repeatably in rarefied flows. It has advantages over other measurement techniques which use discrete transducers and sensors mounted on the surface of the model under test. Model manufacture is much less complex and the positions at which data can be obtained are not constrained by the position of fixed sensors.

List of Symbols

C^*	Chapman Rubesin constant
C_p	specific heat capacity of Nitrogen at constant pressure
c_w	specific heat capacity of model wall material ($Jkg^{-1}K^{-1}$)
M	Mach number
Pr	Prandtl number
$\dot{q}$	heat transfer rate per unit area (kWm^{-2})
Re	Reynolds number
St	Stanton number
T	temperature (K)
t	time (s)
U	flow velocity
x	distance from the leading edge (m)
y	thickness of model wall (m)
μ	viscosity ($kgms^{-1}$)
ρ	density (kgm^{-3})
$\bar{\chi}$	viscous rarefaction parameter

Subscripts and superscripts

o	reservoir conditions
w	conditions at the model wall
x	based on distance behind the leading edge
2	conditions behind the bow shock wave
*	evaluated at the intermediate temperature given using equation (6)

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2	M F Westby	The Royal Aerospace Establishment Low Density Wind Tunnel. Defence Research Agency (Aerospace Division) Technical Memorandum Aero 2277 (1991).
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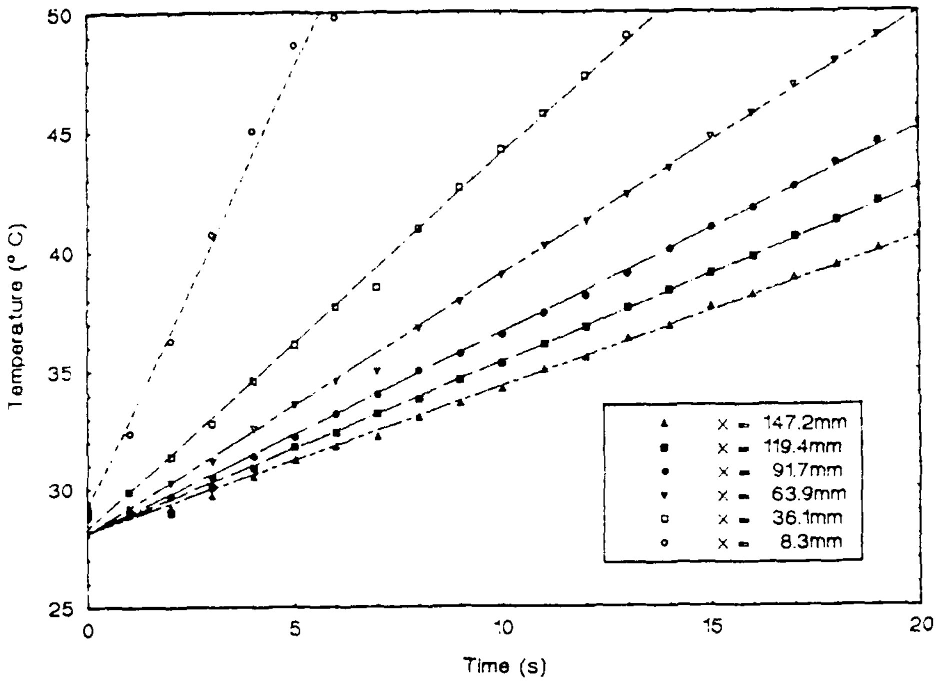

Figure 1. Variation of surface temperature with time at six locations on the surface of the flat plate. Plate at zero incidence. Data for $Re_{2,x} = 1.24 \times 10^5\ m^{-1}$.

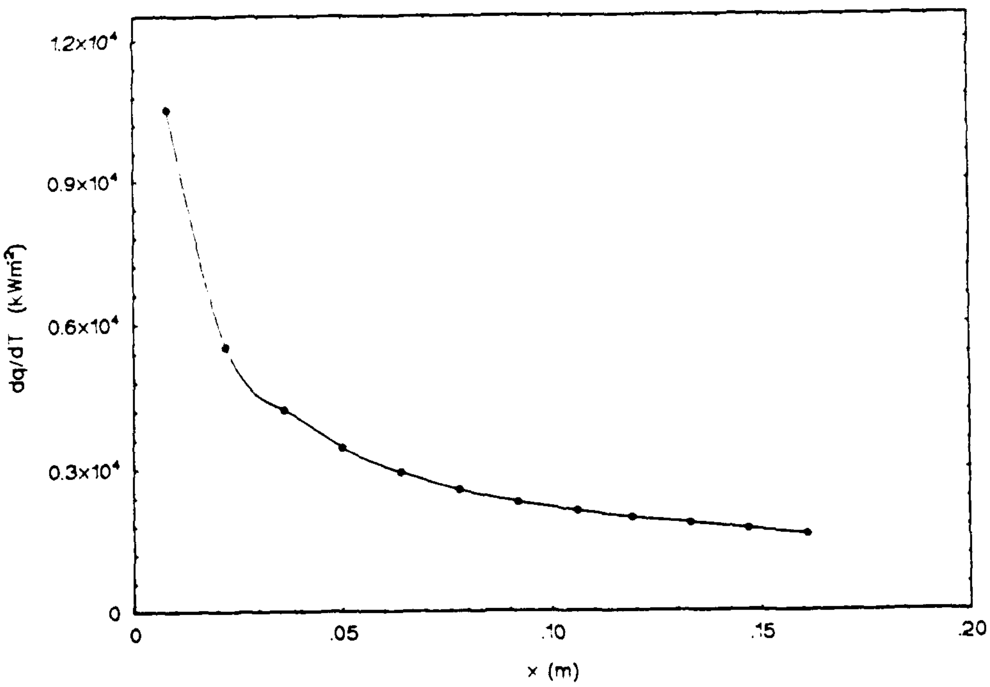

Figure 2. Variation of $\dot{q}$ with distance along plate. Data for $Re_{2,x} = 1.24 \times 10^5\ m^{-1}$.

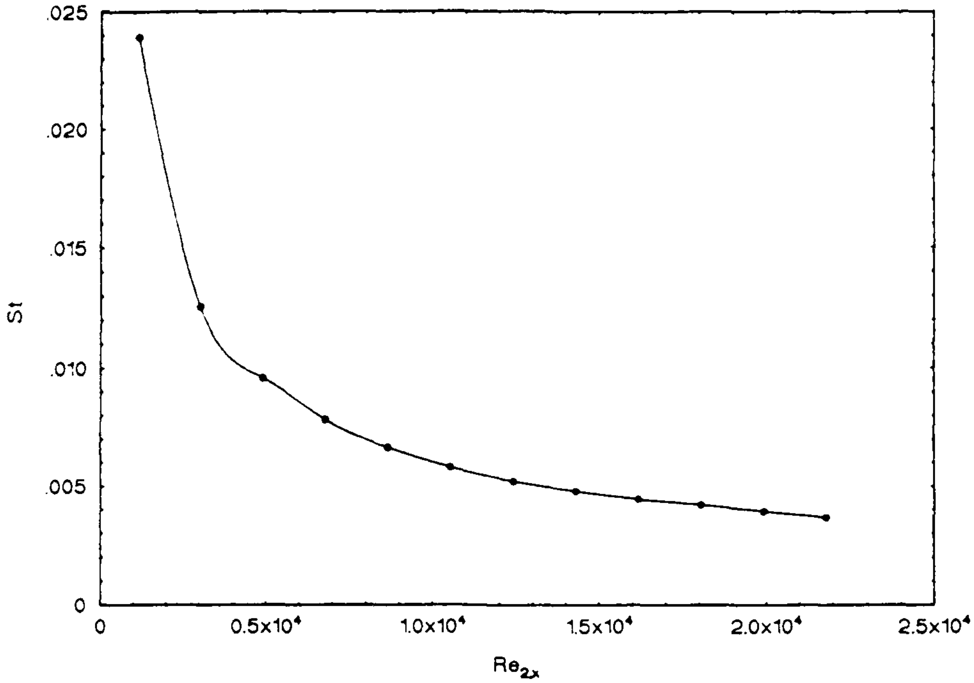

Figure 3. Variation of Stanton number with Reynolds number along plate. Data for $Re_{2,x} = 1.24 \times 10^5$ m^{-1}.

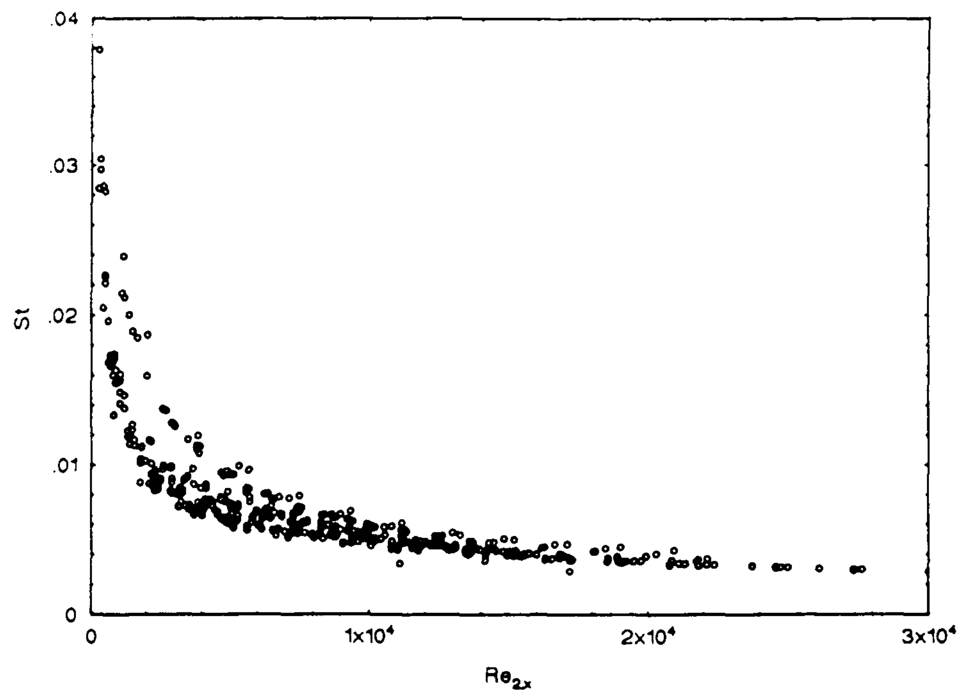

Figure 4. Variation of Stanton number with Reynolds number. Data for all plate tests.

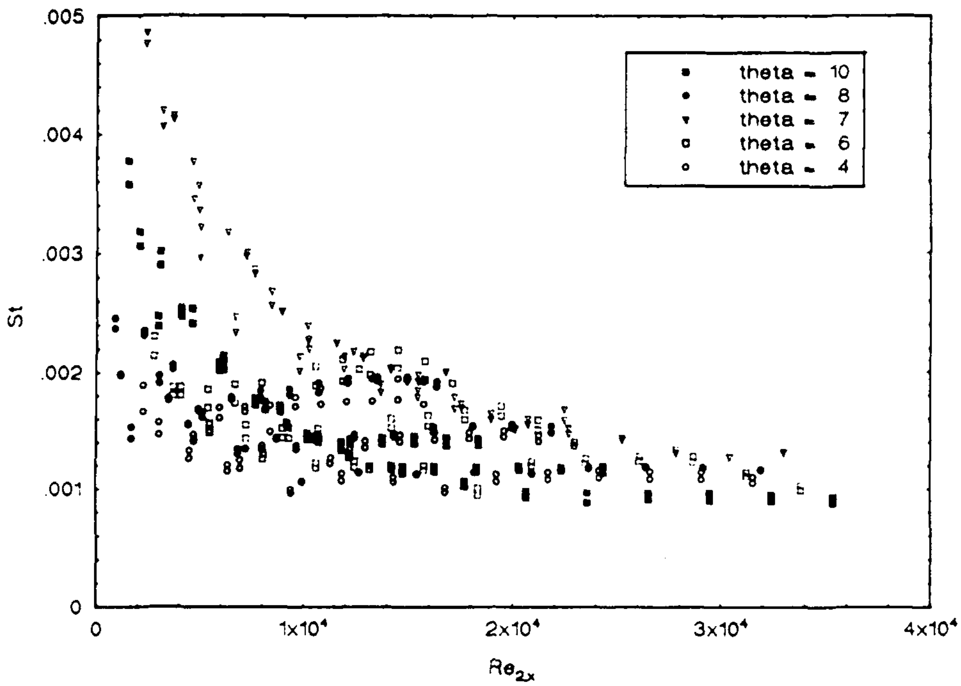

Figure 5. Variation of Stanton number with Reynolds number. Data for all cone tests.

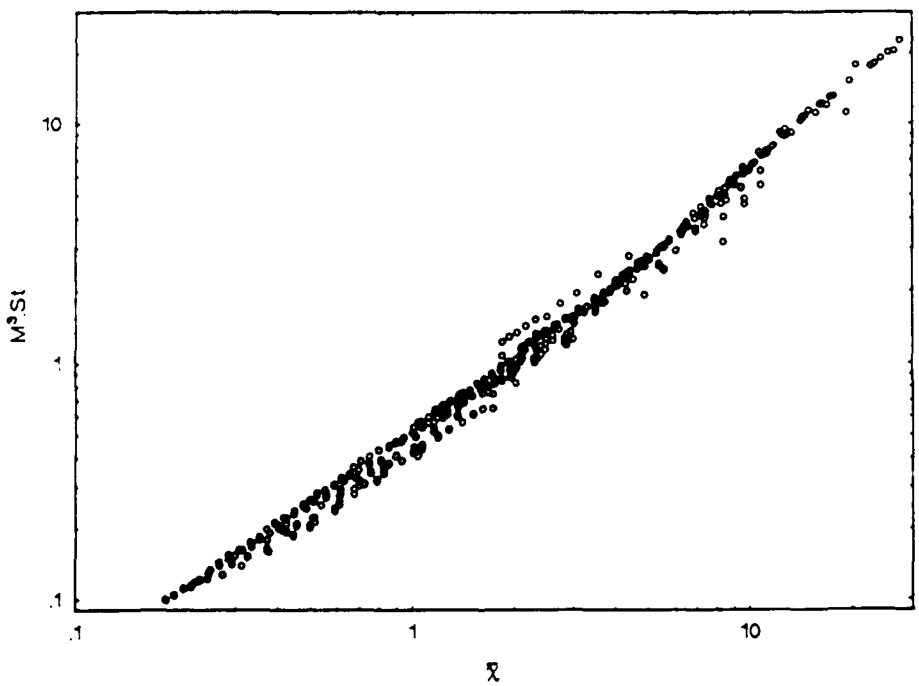

Figure 6. Variation of M^3St with $\overline{\chi}$. Data for all plate tests.

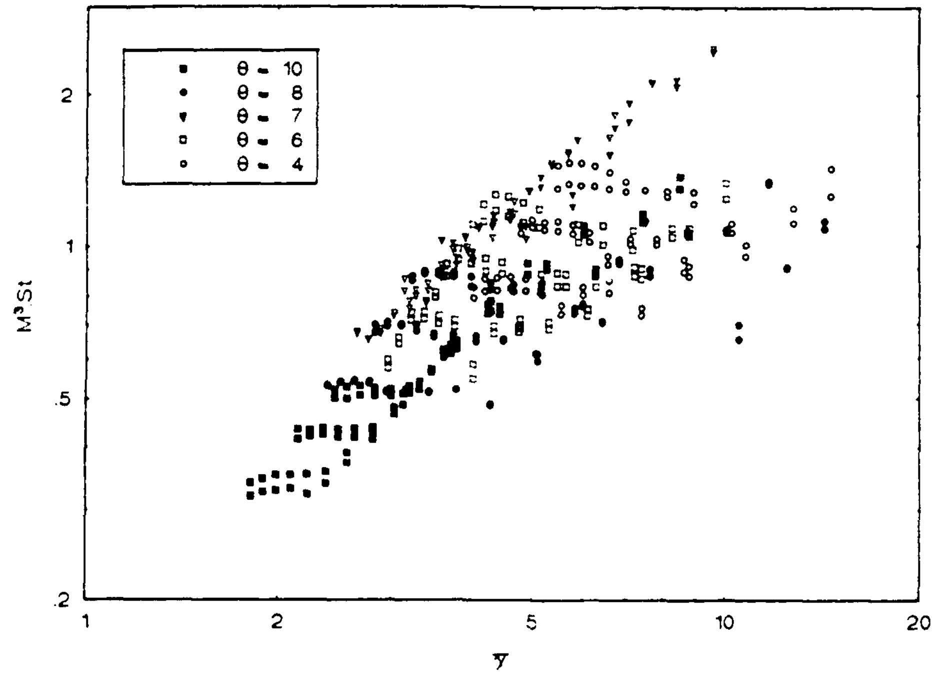

Figure 7. Variation of M^3St w: $\bar{\chi}$. Data for all cone tests.

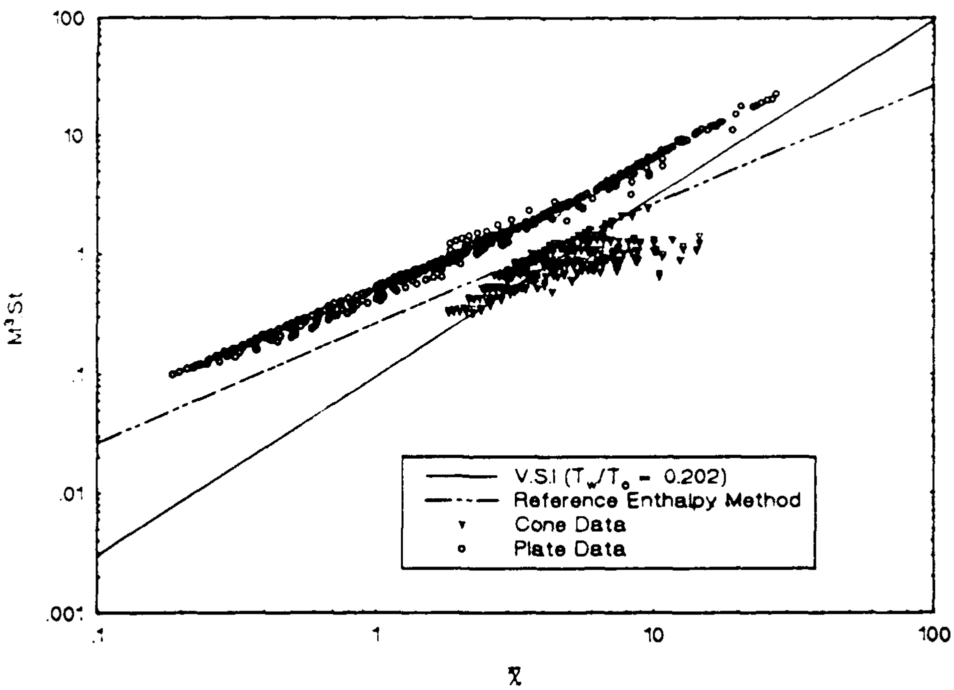

Figure 8. Comparison of all experimental data with Viscous Strong Interaction theory and a Reference Enthalpy method.

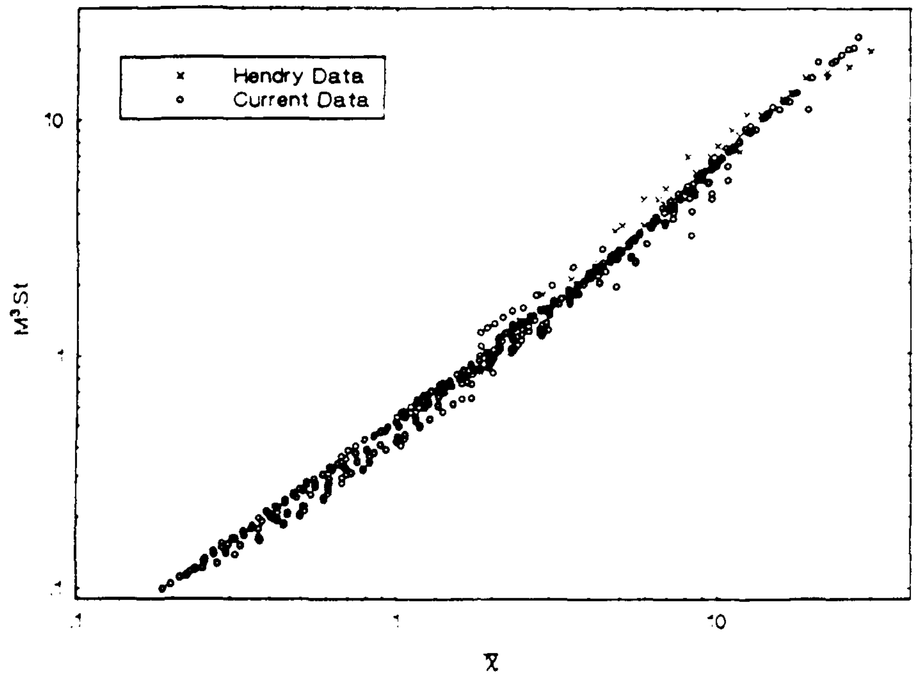

Figure 9. Comparison of data from plate tests with previous experimental data (Hendry[6]).

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16\. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

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17\. Abstract

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