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Direct Measurements of Skin Friction in Supersonic
Combustion Flow Fields

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Journal Article

The final report consists of an AIAA and an ASME paper. An experimental
investigation was conducted to measure skin friction along the chamber walls of
supersonic combustors. A direct force measurement device was used to
simultaneously measure an axial and transverse component of the small tangential
shear force passing over a non-intrusive floating element. Skin friction
coefficients between 0.001-0.005 were measured dependent on the facility and
measurement location. Analysis of the measurement uncertainties indicate an
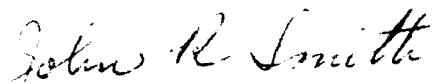accuracy to within $\pm$ 10-15% of the streamwise component.

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Scramjets, Hypersonics

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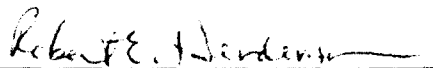
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Direct Measurements of Skin Friction in a Scramjet Combustor

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DIRECT MEASUREMENTS OF SKIN FRICTION IN A SCRAMJET COMBUSTOR

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Abstract

An experimental study was conducted to directly measure skin friction in the turbulent boundary layer of 3-D supersonic combustor flows. A floating element configuration was designed to detect two components of the small tangential shear forces due to the flow passing over a non-obtrusive instrument. The key feature of this arrangement is the use of a cantilevered sensing head extended from a very sensitive piezo-resistive displacement transducer. The strain sensor simultaneously measures displacement in the axial and transverse directions to the flow. The small overall deflection, on the order of 0.00254 mm (0.0001 in) of the stiff beam, means no self-nulling is required. Active cooling is employed to regulate the temperature of the sensor. A direct force calibration showed a highly linear output from the gauge. Testing was conducted in two separate supersonic combustion facilities. The test cell at NASA Langley Research Center consisted of a Mach 2 diverging duct combustor with H_2 fuel, a static temperature of 1222 °K and a static pressure of 0.60 atm at the measurement location. The second facility at United Technologies Research Center (UTRC) was a water cooled Mach 3 duct with hydrogen injected film cooling and combustion. There, nominal tunnel conditions of static temperature and pressure were 860 °K and 0.42 atm. Consistently repeatable output from the gauge during testing shows the skin friction with supersonic combustion is higher than for a corresponding non-combusting flow. Values of C_f of approximately 0.003-0.005 were found in supersonic combusting flows. An examination of potential uncertainties indicated that the results are probably accurate to within 10 percent for the main streamwise component.

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Nomenclature

C_f = skin friction coefficient

τ_w = wall shear force

q = dynamic pressure

S = area of sensing head

V = velocity

ρ = density

G = gap around floating element

D = diameter of sensing element

C = lip thickness of element

u^* = friction velocity

$U_e(x)$ = edge velocity

Subscripts:

x = streamwise component

z = transverse component

Introduction

Measurements of skin friction drag are important for both practical and scientific reasons. Information gathered for a specific device is important in performance assessment and correlations for a specific class of design dependent flows are useful in configuration development. Skin friction is also the key component in the so-called "friction velocity",

$$u^* = U_e\sqrt{C_f/2}$$

that is used as the scaling velocity in correlating turbulent boundary layer velocity profiles. These correlations and u^* are central to all turbulent transport model development. In addition, skin friction has a critical effect on the thrust available in a scramjet combustor. The presence of significant amounts of skin friction

in the combustion chamber in relation to the cross sectional area can drastically reduce the available thrust from the engine.

Experimental skin friction data can be obtained by using both direct and indirect measurement techniques. A direct measurement of shear force is preferrable to an indirect skin friction measurement which is inferred by the use of a Reynolds analogy or other assumed "laws". A thorough review of indirect methods may be found in Ref. (1). For the work here it was decided that direct measurements were essential, since the bases for the various indirect techniques are not well founded for 3-D, supersonic, combusting flow. Also, a simple, rugged design with good thermal protection was needed, because of the severe test environment of interest.

The configuration chosen is a floating wall element gauge that has been specifically developed for directly measuring skin friction in the boundary layer of supersonic combustion flows. The shear forces being measured over a small surface area require a very sensitive instrument in order to detect the slight frictional forces that are produced by the heated flow passing tangent to the combustion chamber walls at very high speeds. For example, in a $q = 0.47$ atm (1000 psf) flowfield, a typical C_f implies surface friction forces of only 96 N/m^2 (2 psf), but with a floating head surface area of approximately 0.323 cm^2 (0.05 in^2), the present design can accurately measure a force as small as 0.2 g and as large as 10.0 g. Historically, direct skin friction measurements have been scarce and difficult to obtain at the high temperatures and heat fluxes inherent in combustion flows. In a scramjet combustor, static temperatures are on the order of 1100-2200 °K at 0.5 to 1.0 atm static pressure.

A complete history of early direct measurement gauges is given by Winter[2]. This summary includes floating element gauges that are similar in concept to the type described here which were first introduced by Dhawan[3] in 1953. Since then, other skin friction balances have been developed for measurements in supersonic flow including work by Allen[4,5], Voisinet[6], Roensch and Cadwell[7], as well as Bruno and Risher[8]. Most of these were used only in moderate total temperature supersonic flows. Workers at the Applied Physics Laboratory have reported (Ref. (9)) limited measurements in a scramjet using a balance design from Ref. (8).

The particular deflection sensing device that

is the basis for the current design was first used in a cantilever arrangement by Schetz and Nerney[10]. Their key advancement was a non-nulling design made possible by the use of very sensitive crystal strain gauges. The non-nulling concept is less mechanically complex than a self-nulling device and consequently less susceptible to error. A nulling design also has a much slower time response. The concept of a non-nulling instrument using crystal strain gauges allows measurement of the small surface shear forces with very small deflections of the sensing head. For very small head displacements, the tilting of the head is small enough so that errors due to misalignment are minimal. Successful experiments were conducted using this sensor on gauges measuring skin friction in low temperature, low speed flows and in unheated supersonic flows. More recently, the addition of active cooling allowed an earlier version of the current gauge to operate in a high temperature environment. Some preliminary tests were made at the NASA Langley Research Center supersonic combustion facility in 1989. Those tests showed that the design was sound and that accurate measurements were possible. The next step was to design an advanced gauge that would have improved thermal protection and the ability to measure skin friction components in both axial and transverse directions.

Theoretical calculations of skin friction for supersonic combustion flow, reliable enough to be used in an actual vehicle design, are difficult to obtain. Methodology exists for calculating turbulent flows and estimating the effects of combustion for similar flow conditions, such as in Ref. (11) which predicts turbulent mixing and burning in the flowfield. Flowfield and boundary layer calculations were made for a specific scramjet configuration with a centerline hydrogen fuel jet. Overall, the magnitude of inferred skin friction values in supersonic combusting flow is consistently higher than for similar Reynolds number flow without combustion. These, and especially 3-D scramjet combustion flowfield predictions are subject to considerable uncertainty due to turbulence modelling issues. Thus, the successful outcome of these current experimental tests can provide accurate skin friction values that will permit calibration and refinement of available calculation methods and turbulence models.

Description of Gauge

General

The general configuration adopted is shown

2

in Fig. 1. The sensing head responds to tangential shear from the passing flow which is registered by the sensor. The head is mounted on a stainless steel rod which is connected to the tip of the sensing unit, a Kistler-Morse piezoresistive strain sensor. This Deflection Sensor Cartridge (DSC) is a complete multipurpose displacement transducer which has the capability of being very sensitive while still being stiff. The DSC-6 sensor being used, which is dual axis sensitive, precisely measures the minute deflections in two orthogonal directions simultaneously. The extended rod doubles the effective length of the moment arm of the sensor, thus increasing the resolution of the gauge. The outer housing is lined with a continuous channel for running cooling water around the assembiy. Also, the internal cantilever rod above the sensor is covered with fins and the entire internal assembly is immersed in a heat transfer fluid. This active cooling system is required for the safe, accurate operation of the sensor, since crystal strain gauges are quite temperature sensitive.

HOT GAS FLOW

FLOATING HEAD

TUNNEL WALL

HOUSING

CANTILEVER BEAM

DAMPING/HEAT TRANSFER FLUID

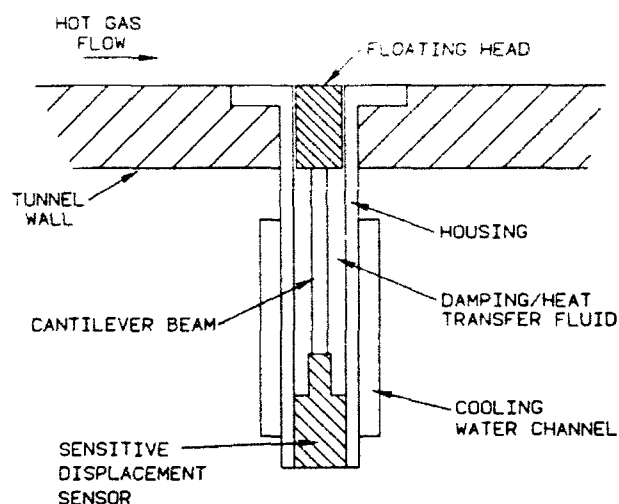COOLING WATER CHANNEL

SENSITIVE DISPLACEMENT SENSOR

Figure 1   Schematic of the Non-nulling Cantilever Beam Skin Friction Gauge Design

The fact that the gauge is small, having an overall length of 7.62 cm (3 in), allows it to be mounted in tight locations. The gauge can be mounted in any orientation; however, due to the presence of the internal fluid, the unit works best if the sensing head sits up or sideways with respect to the duct, rather than upside down from the duct top. Another important advantage of this arrangement and its small size is that the sensing head can be made to fit any contour for measurements needed on curved flow surfaces. This device, once assembled, is not delicate, since there is virtually no way to break the sensor by deflecting it past its operational limits. The

sensing head moves only the width of the gap between it and the surrounding gauge housing before stopping, which is well below the maximum deflection allowable for the sensor.

The specific geometry of the floating element is an important design consideration because it can introduce various potential error sources at the surface. As always, when using a floating element device to measure deflection, misalignment effects are a concern. These errors can be introduced due to misalignment with the surface, gap size, lip size and pressure gradients between the flow and the underside of the element. These concepts are discussed at length in the study by Allen[5] and were consulted extensively during the design of the sensing head. The sensing head shape used here was chosen to minimize errors introduced by the 0.01 cm (0.004 in) gap between the sensing head and the surrounding outer housing. The head has a thickness of 0.0254 cm (0.01 in) with a diameter of 0.615 cm (0.242 in) before tapering to a 0.462 cm (0.182 in) diameter leaving a thin lip at the flow surface. The head increases in diameter again at the bottom leaving a 0.0153 cm (0.006 in) gap between it and the outer housing.

For this particular design, the gap size is large in relation to the diameter of the sensing head (G/D), which makes the unit less sensitive to misalignment. In Ref. (5), Allen states that "the effect of gap size virtually disappears at zero misalignment." In Fig. 7 of Ref. 5, this is confirmed for a G/D ratio above 0.005. Our G/D of 0.0165 is far above this indicating no misalignment problems due to gap size can be expected. Similarly, in relation to gap size, effects due to lip size must be considered. The effects of misalignment and lip size given in Ref. (5) are in terms of the boundary layer thickness. These data are not available for the current test conditions of the gauge. However, Fig. 10 of Ref. (5) indicates that the sensitivity to misalignment decreases as gap to diameter ratio increases. For our case, the lip to diameter ratio (L/D=0.04) and the G/D ratio of 0.0165 together produce a floating element insensitive to these effects.

Usually a non-nulling design carries with it the spectre of misalignment effects due to the tilt of the floating element into the flow. Fortunately, this concern has been circumvented here simply because the deflections of the sensing head are so small that the intrusion of the head into the flow is virtually non-existent. The expected deflection of the sensor is 0.00013 cm (0.00005 in) which is approximately

0.000254 cm (0.0001 in) for the extended beam. The effective angle of deflection is 0.002 degrees which produces a protrusion of four micro inches into the flow (assuming the center of the sensing head is flush with the wall). This cannot contribute any distinguishable pressure gradients developing due to protrusion, expecially when accompanied by a large G/D ratio[5].

Yet another possible misalignment effect involves thermal expansion of the cantilever beam. There is a concern that although water cooled, the upper portion of the steel cantilever beam may expand vertically into the flow field, causing misalignment error. Ideally, the head is aligned approximately 0.005 cm (0.002 in) below the wall surface to counteract the effects of thermal expansion. This expansion is estimated to be on the order of 0.0127 cm (0.005 in) maximum for a 1.27 cm (0.5 in) length of carbon steel heating to 810 °K. The protrusion effects will be the same regardless if the element is sitting slightly below the test surface or above it, and for the relatively large G/D ratio being used here, all errors are less than 1 % of the total C_f at these protrusion magnitudes[4].
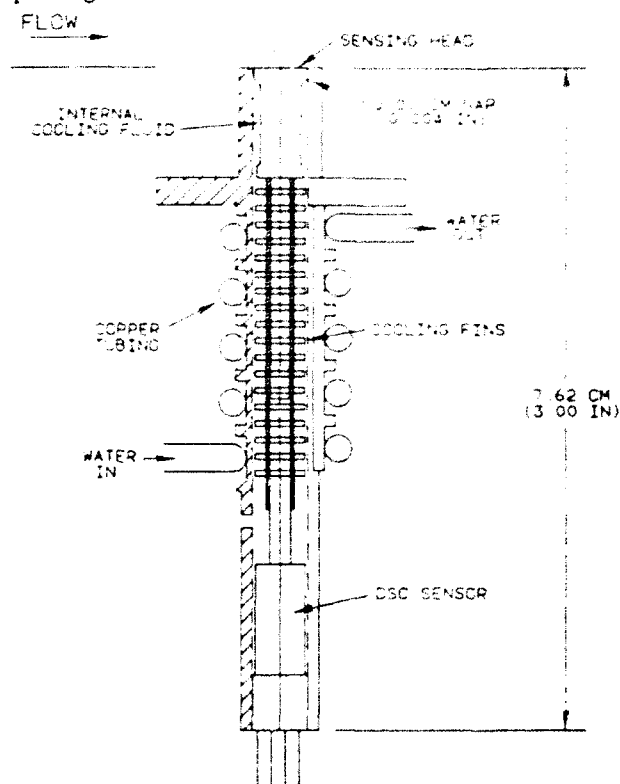
The heat transfer liquid surrounding the cantilever beam plays two other useful roles besides thermal protection for the sensor. First, the presence of a liquid in the cavity of the gauge minimizes pressure gradient effects by providing a more continuous surface and eliminating pockets of air underneath the sensing head[2]. Second, the liquid and the small gaps in the gauge combine to produce strong damping that limit the effects of facility vibrations that can be severe in scramjet tests.

Note that the sensing head must be made to the exact specifications of the duct wall of the facility in which it will be placed. Common material is essential for the head to simulate the surrounding tunnel wall conditions. Any significant change in temperature at the sensing head with respect to the rest of the wall alters the heat flux characteristics from the flow to the sensing head and ultimately the gauge will not measure the actual wall skin friction. Since the gauge was tested in two different facilities having distinct cooling requirements, the detailed designs are presented here separately.
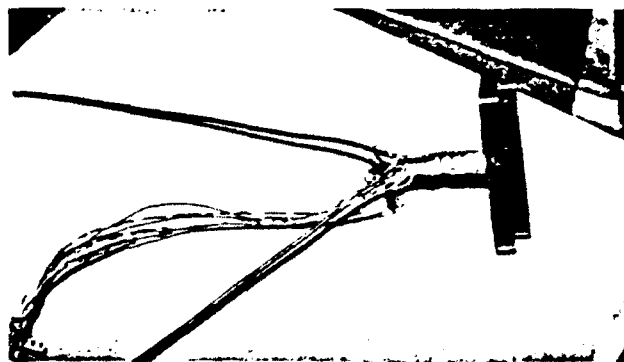
Design for NASA Langley Scramjet Combustor

The assembly drawing for the NASA Langley gauge is shown in Fig. 2a. The sensing head at

the flow surface has a diameter of 0.615 cm (0.242 in) and a 0.01 cm (0.004 in) gap between it and the surrounding gauge housing, both of which were made of carbon steel to match the uncooled duct wall. Set screw holes were placed at the base of the flange and at the bottom of the water channel for access to the internal housing. These openings were used for inserting heat transfer fluid as well as for inserting a thermocouple into the inner housing to monitor the temperature at the tip of the sensor. Figure 2b shows the gauge already placed into the oblong plug that goes into the tunnel wall opening.

a) Sectional Drawing

b) Photograph of Gauge Mounted in Duct Wall Plug

Figure 2   Skin Friction Gauge for NASA Scramjet Tests

4

Heat transfer and cooling were obtained by filling the internal housing with a combination of liquid metal and silicon oil. Originally, it was proposed that Gallium-Indium-Tin (GIT) be used for the entire length of the cantilever. This mixture is liquid at room temperature, although pure Gallium is not. The GIT has good heat conducting properties and a high surface tension. However, using GIT turned out to be impractical when it was found to oxidize readily, even in the presence of oil. Ultimately, liquid mercury was injected into the lower part of the housing (surrounding the sensor tip) up to the fifth cooling fin from the bottom. These lower fins were made out of stainless steel to prevent amalgamation. Dow silicon (1000 cs) oil filled the upper part of the channel and the gap around the sensing head. The upper fins were made of brass for good heat conduction. The high-viscosity oil was used to minimize the leakage of oil out of the 0.01 cm gap around the sensing head; a problem seen in previous tests when a lower viscosity oil was used. The gauge was mounted on the tunnel side wall for these tests. Therefore, in this case an additional precaution was taken to reduce the potential leaking. Before the actual tests were run, the gauge was placed in a vacuum chamber and the pressure brought down to 0.068 atm (1 psi) to force any trapped air bubbles inside the assembly to rise and be replaced with oil from a reservoir sitting on the sensing head. Removing air bubbles also prevented any problems with oil ejection during supersonic tunnel starting.

In addition, the oil played an important role in damping. It prevented excessive vibration of the gauge during testing. To thermally match the tunnel wall at the test facility, the gauge was designed with a 1.27 cm (0.5 in) thick head. The consequent large mass of the head resulted in a low natural frequency of the unit, which was brought down effectively to being overdamped by the heavy oil used in the internal assembly. This condition was characterized by an e-folding time of 0.075 sec. In comparison, the natural frequency of the unit without oil was measured at 150 Hz. During testing, tunnel vibrations were measured independently of the skin friction test using an interferometer. It was found that the tunnel vibrated at a frequencies of 15, 30, 600 and 4000 Hz, where the gauge was not sensitive. Vibration did not cause difficulty for this experiment because the gauge would respond to only extremely low frequencies, on the order of 1-3 Hz.
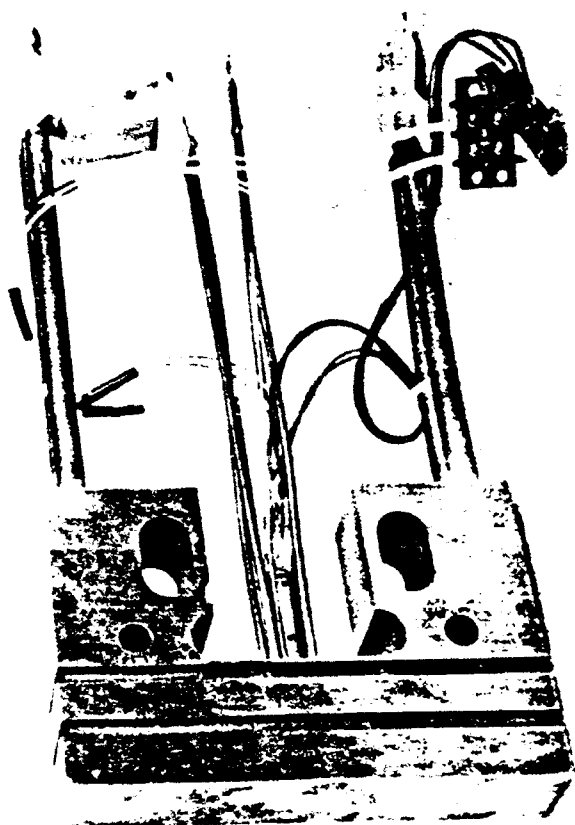
A brief theoretical study of this heat transfer problem was undertaken, since skin friction and convection heat transfer are closely related Reynolds analogy gives skin friction as proportional to the heat flux, although its application to this flow situation is limited. A transient heat transfer model of the sensing head and surrounding housing was developed for the purpose of studying the thermal characteristics of the basic design. The model simulated an adiabatic wall temperature rise from 1090 °K to 2920 °K in 5 sec which was held for 25 sec before the run was terminated. Radiation and water cooling considerations were included and various cases of cooling were analyzed. Results indicated that in a 30 sec run, the surface of the sensing head would exceed 650 °K even with heat transfer fluid filling the gap. It is likely that boiling of this fluid would occur around the sensing head. However, at the bottom of the cantilever, the temperature rises less than 0.5 °K above the initial value insuring that the sensor would not experience significant temperature changes. Also, the model indicated that thermal expansion at the end of the run would not be a concern if the surrounding test cell wall expands at the same rate.
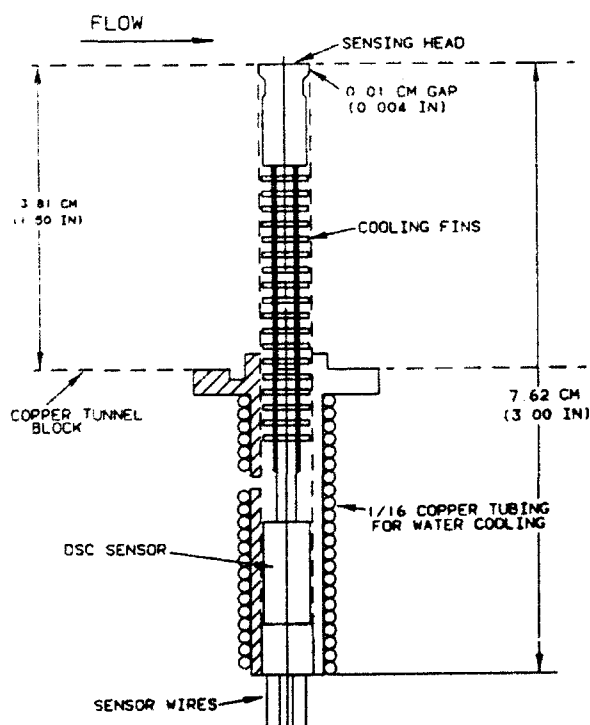
Design for UTRC Scramjet Combustor

In this case, the test cell was a water-cooled copper wall combustion facility, and the gauge had to be designed to fit into an existing solid copper block which slides in to become a section of the tunnel floor. A photo of the gauge in Fig. 3a shows how the gauge was inserted into the back of the block.

The sensing head was made of solid copper mounted on a stainless steel rod. The shape of the head was slightly different than that used for the test at NASA Langley, as shown in Fig. 3b, because lateral heat transfer out of the sensing head in this environment was more critical. In the UTRC facility, water cooling channels of 0.953 cm (0.375 in) diameter inside the copper block keep the tunnel wall surface temperature below 340 °K. Solid copper readily conducts heat, however, the heat transfer between the sensing head and the cooled copper wall is significantly altered by the 0.01 cm gap, even with a conducting fluid filling the gap around the sensing head. Estimates of this heat transfer problem using shape factors indicated that the temperature of the head could be 60 °K higher than the surrounding tunnel wall. Although due to the geometry of the overall water cooling channels, the temperature range across the tunnel wall with no skin friction gauge could be as much as 20 °K, there remained a concern of a

a) Photograph of Gauge Mounted in Copper Wall Block

FLOW

SENSING HEAD

0 01 CM GAP
(0 004 IN)

3 81 CM
(1 50 IN)

COOLING FINS

COPPER TUNNEL
BLOCK

7 62 CM
(3 00 IN)

1/16 COPPER TUBING
FOR WATER COOLING

DSC SENSOR

SENSOR WIRES

b) Sectional Drawing

Figure 3   Skin Friction Gauge for UTRC
Scramjet Tests

possible surface temperature gradient. Therefore, for compensation, two extra water channels were added to the block right next to the sensing head, as shown in Fig. 4. Through these, warm water was run in order to promote heat transfer from the sensing head across the gap to the copper block without further reducing the temperature of the block in the area near the gap which has already been cooled. The warm water temperature would ideally be slightly below that of the surrounding tunnel wall. These 0.318 cm (0.125 in) copper tubing channels were drilled 0.635 cm (0.25 in) down from the flow surface, 0.127 cm (0.05 in) from the sensing head and ran on each side of the head lengthwise to the duct.
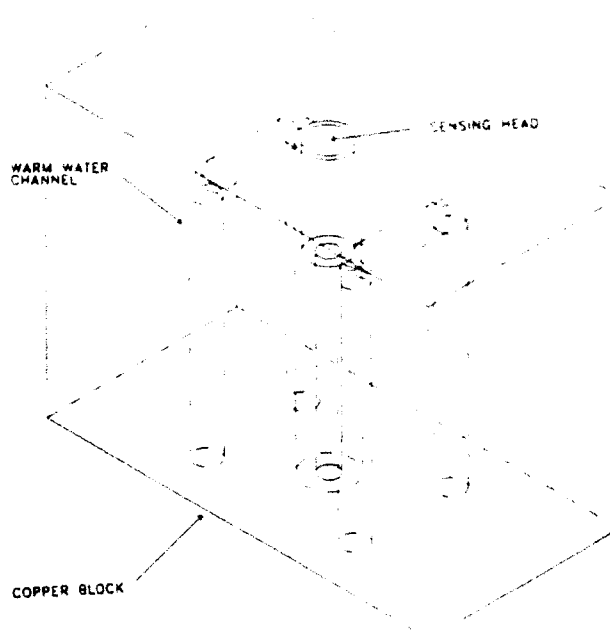

Figure 4   Extra Cooling Channels for Sensing Head in UTRC Copper Block

The block was 3.81 cm (1.5 in) thick, so a 0.635 cm (0.25 in) hole drilled through the block became the actual housing for the upper half of the cantilever (see Fig. 3b). The lower housing was then attached to the block by a brass flange. Copper tubing with a 0.159 cm (0.0625 in) diameter was wrapped tightly over the housing from the base of the block to the bottom of the sensor. This effectively maintained the sensor at a uniform temperature. Set screw holes were also drilled through the housing to allow injection of heat transfer fluid and to insert a thermocouple. As the duct wall is already water cooled, the unit would not be subjected to the severe conditions that would be found in an uncooled facility. Therefore, silicion oil alone was used to fill the internal housing to aid in the

6

transfer of heat outward to the outer housing and away from the sensor. Also, there was an obvious concern about using mercury in a copper block.

Experimental Procedures

The experimental set-up consisted of the gauge wired in both axes directly to a bridge completion box which converted the signal to an output voltage. The 1000 ohm resistors making up the strain gauges inside the DSC-6 sensor form two half bridges perpendicular to one another. The bridge completion box contains the two completing half bridges and a potentiometer for zeroing the signal from each axis. The gauge was powered by a +6 volt power supply, and the output was measured on a strip chart recorder. In the UTRC test, the output was also recorded on the test cell data acquisition system.

Calibration

In both tests, a direct force calibration was conducted using standard weights and a digital voltmeter. The gauge was clamped nearly vertical, so that by hanging the weights directly to the sensor head, the sensor is pulled in the streamwise direction. Outputs in millivolts were read in streamwise and cross-stream directions. The applied weights ranged from 10 ng to 10 grams. The curves remained linear and constant after repeated calibration as shown in Fig. 5 for the NASA Langley tests. The output of the cross-stream sensor axis was read as the weights were pulling the sensing head in the streamwise
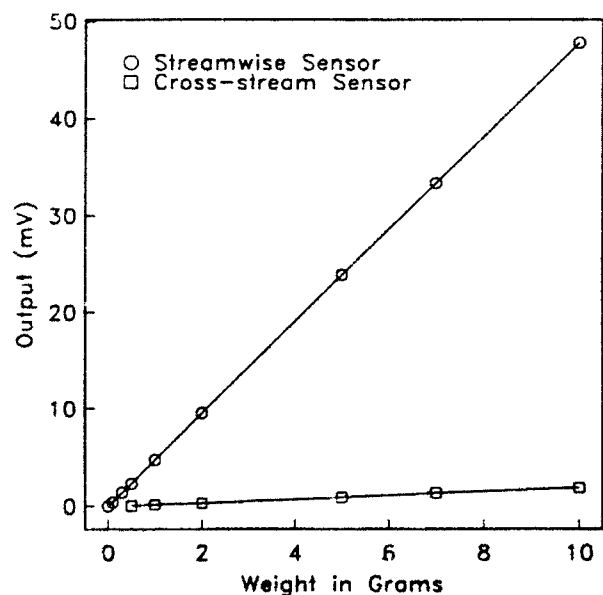

Figure 5   Skin Friction Gauge Calibration Curves

direction which had a magnitude of approximately four percent of the streamwise output. A reading was also taken with the weights hanging in the cross-stream vertical plane which gave the same reading as the streamwise value, indicating that the dual axis sensor does indeed have consistent strain gauges. The two gauges for the two tests used different DSC-6 sensors, so the calibration of each was slightly different. In either case, the presence of oil and/or mercury in the gauge did not affect the calibration.

NASA Langley Scramjet Test Facility and Procedures

The tests were run at the NASA Langley Research Center Vitiated Heater Facility. The test cell configuration, shown in Fig. 6, consisted of an air-oxygen mixer, a vitiated air heater connected to a Mach 2 nozzle, and a rearward-facing step injector block with a single, 0.61 cm (0.24 in) diameter, perpendicular fuel injection port located just before the divergent section. The 122 cm (48 in) long duct diverged at an angle of two degrees on the top side while remaining flat at the bottom. Three optical access stations are evenly spaced along the duct, of which the farthest was used for inserting the gauge into the duct. The gauge was mounted in an oblong plug that fit into the existing duct opening (see Fig. 2b).
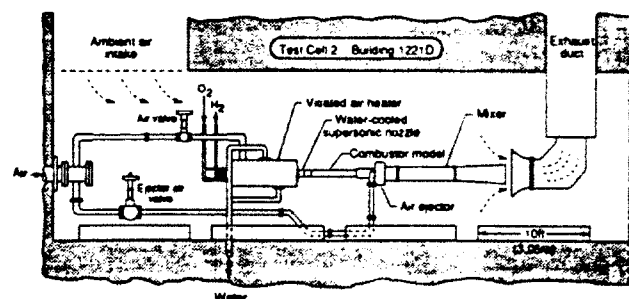

Figure 6   Schematic of NASA Langley Vitiated Heater Facility

Cooling water was run from a tap through 30.5 m (100 ft) of copper tubing immersed in a 55 gal drum before reaching the gauge to insure a constant water temperature of 289 °K. Nominal tunnel conditions for this test registered a static temperature of 1200 °K and static pressure of 0.60 atm at the measurement station. The computed 1-D local Mach number was 1.74, and the fuel equivalence ratio was 0.36. The normal run cycle for the test cell consists of several steps leading to the actual fuel burning phase. First, 3.4 atm air is pumped continually through the tunnel to purge any possible accumulation of hydrogen in the test

cell. The air ejector is turned on, and then the heater is started and allowed to stabilize before the full fuel flow is injected.

The recorder was initially set to a zero for each axis and run at a speed of 20 cm/min throughout each test. In order to explain the output strip-chart data, Fig. 7 is included to show how the dual-axis sensor is oriented with respect to the flow. Actual recorded outputs for three individual test runs with the same nominal tunnel conditions are shown in Fig. 8. These show the initial detection of output at the start of the low flow air, the vibration of the tunnel that was picked up when the ejector was turned on, the signal jump due to the igniter, and finally the peak when the fuel was added. Note that damping from the heat transfer fluid limited vibrations to a small percentage of the total signal.
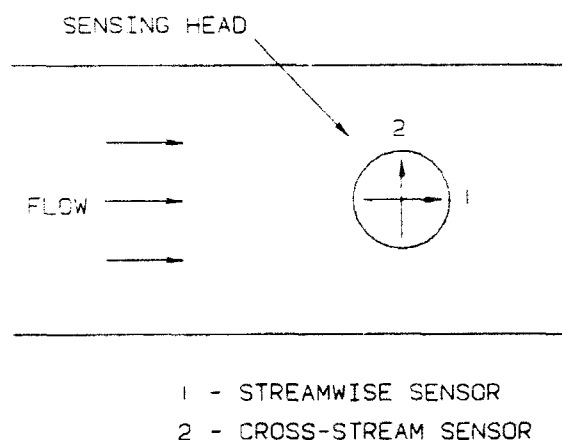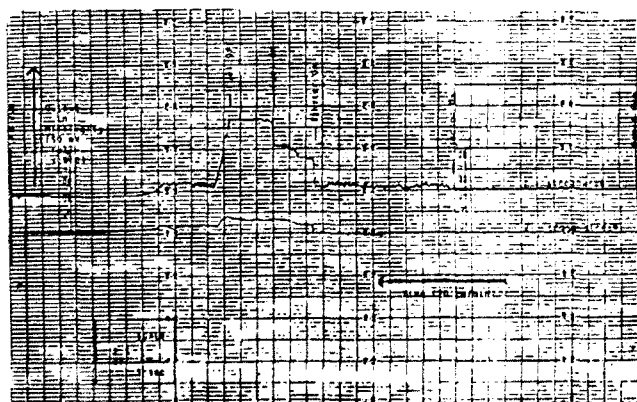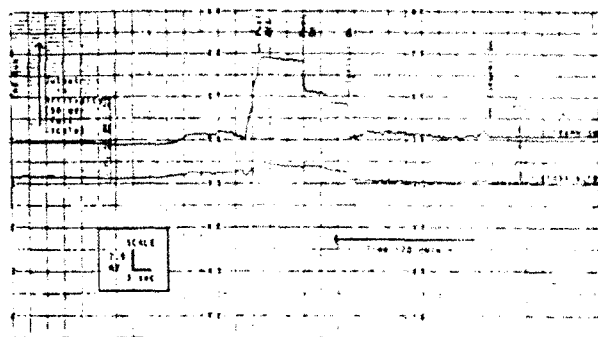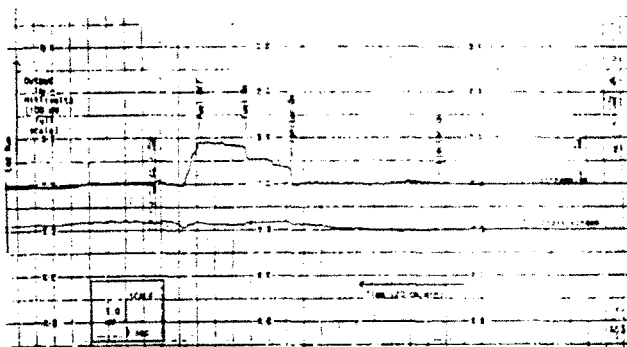

Figure 7   Orientation of Sensor Axes

1 - STREAMWISE SENSOR
2 - CROSS-STREAM SENSOR

b) Run 2

c) Run 3

a) Run 1

Figure 8   NASA Langley Test Skin Friction Gauge Output

UTRC Scramjet Test Facility and Procedures

The second tests were run at United Technologies Research Center Combustion Test Facility. The test cell configuration consisted of an air-oxygen mixer, a vitiated air heater connected to a Mach 3 nozzle, and a 0.19 cm (0.075 in) tangential hydrogen injection slot on the tunnel floor. A schematic of the geometry of this arrangement is included as Fig. 9. The duct diverged at an angle of two degrees on the top side while remaining flat at the bottom. The gauge was mounted 25.4 cm (10 in) downstream of the slot.

Cooling water was run through the 0.159 cm (0.0625 in) copper tubing from the same constant temperature water supply as the rest of the rig. Warm water for the extra copper block cooling channels was obtained from the output of the normal tunnel water supply which was nominally 10 °C warmer than the input cooling water. Water cooling for the test cell was turned on only several minutes before the test was run. This caused a concern that the output of the sensor may not have yet stabilized at the low cooling water temperature. Subsequent testing

8

on the sensor showed that the sensor output stabilized in 1.5 minutes for as much as a 20 °C change in sensor temperature, twice as much a temperature change as seen at UTRC. For this test, the nominal tunnel conditions registered a static temperature o: 860 °K anJ static pressure of 0.42 atm. Flow entered the duct at a Mach number of 3.0.
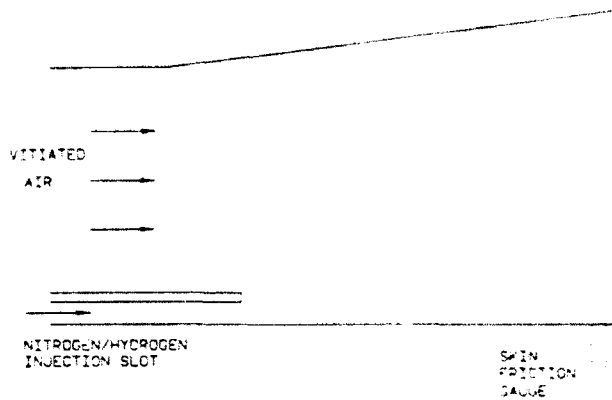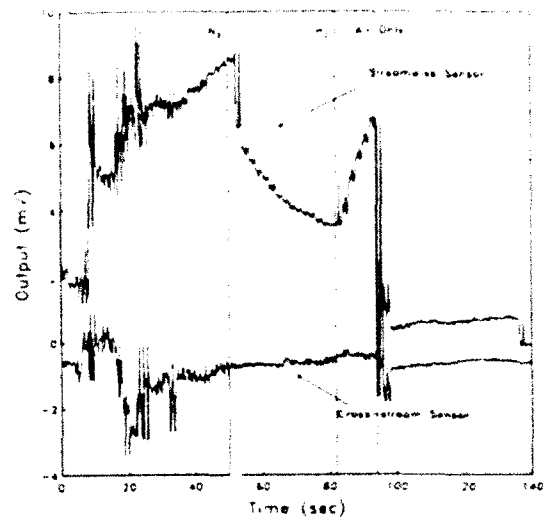
VITIATED
AIR

NITROGEN/HYDROGEN
INJECTION SLOT

SKIN
FRICTION
GAUGE
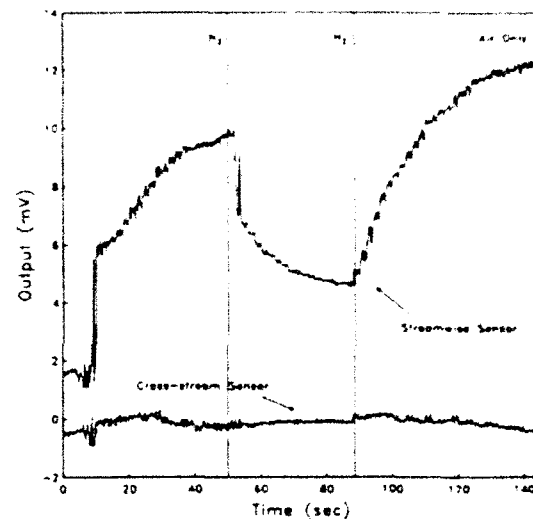
Figure 9   UTRC Duct Geometry anu Cuuge
Arrangement

The strip chart recorder was initially set to a zero for each axis and run at a speed of 914 cm/hr throughout each test. The data acquisition system ran for a total of 144 sec. In this case, the computer generated time history of the outputs for three individual test runs are shown in Fig. 10. These show the output changing during the test cycle. For the first two tests, vitiated air at a total temperature of 2200 °K entered the duct. The third test was run using air at 1390 °K. Nitrogen was initially injected into the flow from the slot on the lower wall of the tunnel. Then, the nitrogen was turned off and hydrogen was injected into the flow. In all cases, the gauge responded with a sharp decrease in output following the switch from nitrogen to hydrogen injection, even though combustion was occurring. The output signal increased steadily when the hydrogen was turned off. Note that the corresponding cross-stream signal changed only a small amount throughout the test cycle for these nominally 2-D flow cases.

Experimental Results
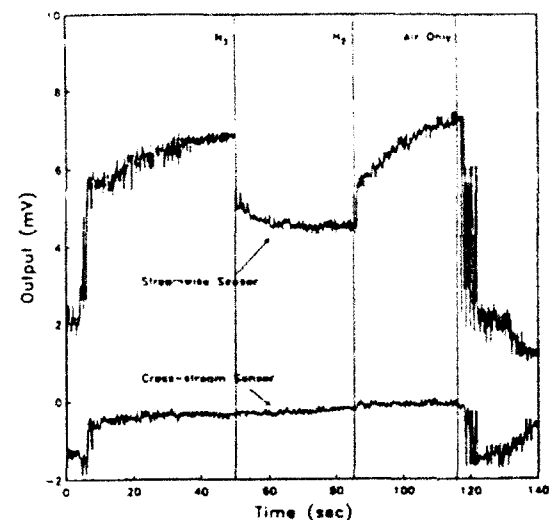
The gauge produceu repeatable results in both test environments and exhibited a reasonable response time by recording the distinct jumps between chan;ing tunnel conditions during the test cycle. Of great importance, though, is to note that the gauge reading went back to the same zero after each test.

a) Run 1

b) Run 2

c) Run 3

Figure 10 UTRC Test Skin Friction Gauge Output

9

For each test, average outputs for the gauge during the steady state portions of the run were compared with the pre-test calibration and were found to fall near the center of the calibration scale. These outputs were converted to shear forces and combined with calculated tunnel boundary layer edge conditions to produce a skin friction coefficient. The small cross-stream component throughout the UTRC test cycle indicates a nearly 2-D flow. The output of the cross-stream gauge being slightly positive or negative indicates only that the flow over the gauge tends to become slightly 3-D rather than remaining an exactly 2-D flow. However, in the NASA Langley case, the flow is expected to be strongly 3-D, since the fuel injection scheme for these tests was asymmetric due to the single fuel injection port in the top wall.

Calculations of skin friction were made using the flow conditions in the tunnel at the axial location of the gauge. First, skin friction is defined as

$$C_f = \frac{\tau_w}{qS}$$

where the area of the sensing head, $S = 0.02968$ cm^2 (0.0003194 ft^2), and

$$q = \frac{1}{2}\rho V^2$$

Table 1 lists the NASA Langley results at these measurement station conditions for three individual runs made with the same nominal tunnel conditions. These conditions represent time approximately six seconds through the eight second fuel burn cycle.

For the NASA Langley tests, the water cooling during the actual testing proved very effective. Thermocouples attached to the copper tubing at the water input and return points registered a constant temperature within 1 °K, the resolution of the thermocouple used. The thermocouple measuring the internal temperature of the gauge registered no change throughout the test cycle. The oil and mercury effectively dissipated the heat passing through the sensing head into the cantilever rod. Thermocouples attached to the outside of the 1.27 cm (0.5 in) duct wall at the same streamwise location as the gauge registered above 600 °K during the fuel burn. The sensing head of the gauge on the inside of the duct wall would have seen well above this temperature. It is reasonable to suggest that the cooling system as currently set up can handle significantly higher duct temperatures.

Table 1

NASA Langley Test Skin Friction Results

Measurement Station Condition	Run 1	Run 2	Run 3
Mach Number	1.74	1.74	1.74
Static Pressure (atm)	0.600	0.598	0.597
Static Temperature (°K)	1225	1223	1226
Velocity (m/sec)	1274	1275	1278
(ft/sec)	4182	4184	4192
Density (kg/m^3)	0.149	0.146	0.145
($\times 10^3$ slug/ft^3)	0.288	0.283	0.281
Shear Force (N)	0.0181	0.0199	0.0193
(lbs)	0.00407	0.00447	0.00433
C_{fx}	0.0051	0.0056	0.0055
C_{fz}	0.0009	0.0012	0.0005

Outputs for the UTRC tests shown in Fig. 10. were converted to coefficients at the end of each of the three flow conditions. The first location was just before the conversion from nitrogen injection to hydrogen injection which occurred in all cases 50 sec into the run cycle. The second readings were taken at the end of the hydrogen injection phase for each run. The third outputs were read at the end of the run cycle when the output from the gauge had stabilized. The test cell was shut down during Run 1 before the output had stabilized, so no reading was taken at the end of that run. The streamwise signal remained in a slight transient state because each injection phase was not long enough for the conditions in the tunnel to completely stabilize. Table 2 contains the results for the three runs.

The UTRC cross-stream data reveal a flow that is nearly two dimensional which allows the transverse component of the output to be used as a temperature compensation measurement. The C_f value at the end of the second run (after H_2 injection is shut off) looks quite high. For rough comparison, the well-know Van-Driest II skin friction formula for air flow over a flat plate at the nominal conditions approaching the injection station indicates $C_f \approx 0.003$. Of course, that does not include any influence of the vitiated air, the backward-facing step produced

10

Table 2

UTRC Test Skin Friction Calculations

Nominal Flow Conditions	Run 1	Run 2	Run 3
Mach Number	3.0	3.0	3.0
Static Temp (°K)	863	863	487
(°R)	1553	1553	877
Pressure (atm)	0.422	0.422	0.354
Velocity (m/sec)	1745	1745	1396
(ft/sec)	5725	5725	4580

	Nitrogen Injection	Hydrogen Injection	No Injection
Run 1			
Shear Force			
x (N)	0.0175	0.0073	-
(lbs)	0.00393	0.00164	-
z (N)	0.00102	0.00106	-
(lbs)	0.00023	0.00021	-
C_{fx}	0.0035	0.0015	-
C_{fz}	0.0002	0.0002	-
Run 2			
Shear Force			
x (N)	0.0200	0.0096	0.0252
(lbs)	0.00450	0.00215	0.00566
z (N)	0.00013	0.00005	0.00008
(lbs)	0.00003	0.00001	0.00002
C_{fx}	0.0040	0.0019	0.0050
C_{fz}	0.0000	0.0000	0.0000
Run 3			
Shear Force			
x (N)	0.0142	0.00909	0.0151
(lbs)	0.00319	0.00204	0.00339
z (N)	0.00022	0.00031	0.00013
(lbs)	0.00005	0.00007	0.00003
C_{fx}	0.0028	0.0018	0.0030
C_{fz}	0.0000	0.0000	0.0000

by the slot with no injection, or pressure gradients in the diverging duct. The steady, comparatively small output indicates that the sensor reading is not affected by any change of temperature during the test cycle.

Measurement Uncertainties

The largest contributors of uncertainty in both of these experiments concerned the method of calibration and calibration drift. Since calibration was done using a direct force measurement, it does not necessarily take into account the viscous effects that may be found in the actual flow. Even though the effect on calibration is minimal, this issue needs to be addressed further in the future.

Although the calibration curves were linear, the instrumentation noise contributed to drift which averaged two percent of the total output of the gauge during testing. This instrumentation includes the power supply, voltmeter, bridge completion circuit, strip chart recorder, and data acquisition system. In addition, the gauge only returned to its zero to within two percent of the original signal after deflecting.

*Manufacturing tolerances for the DSC-6 sensor specify only that the sensing axes are oriented at 90 degrees within 2 degrees. However, this possible error is corrected for by calibrating both axes. Any output from the gauge in the cross-stream direction during calibration is subtracted from the test cycle streamwise output readings and therefore does not contribute to uncertainty. The manufacturer's specifications on the gauge are 0.02 percent of full-scale per degree C. We have checked and found this to be accurate. In the present application, the gauge operates at about 2 percent of full-scale, so the temperature effect is magnified. All this results in a design requirement to maintain the temperature of the sensor to ± 2° C to keep the uncertainty introduced to less than ± 2 percent. This can be checked with a thermocouple near the sensor and/or the use of the inactive cross-stream component if the flow is 2-D.

The possibility of error due to asymmetric heating of the sensor also exists. Tests done on the sensor by itself showed that at constant temperature, the output is very consistent. A zero shift occurs when the temperature of the sensor changes and the greatest effect on sensor output occurs during the time of the actual

temperature change, especially if the heating/cooling is unsymmetric. The time rate of change of the gauge during testing was kept as small as possible for this reason.

The resultant moment caused by a pressure gradient along the sensing head may also be considered as a potential source of error. However, for these tests the measured axial pressure drop in the duct of 1.5 psia/ft (in the NASA Langley facility) turned out to be an insignificant percentage of the total moment registered by the gauge. Pressure gradients in the UTRC tests are also presumed small.

Since certain measurement error sources in this analysis turn out to be negligible, the final uncertainty is based on all relevant misalignment effects, calibration and zero shift considerations. These added together indicate an uncertainty level of 10 percent. The uncertainties mentioned here pertain to both the streamwise and transverse output values.

Conclusions

Results of this experiment show that the basic cantilever beam floating element design for measuring skin friction in a high temperature environment is sound and that it has the potential for accurate measurements when designed to fit a specific test facility. The experiments are important because theoretical models are not available to accurately predict skin friction in this complicated flowfield.

The extended cantilever arrangement increased the output to an accurately detectable level. As expected, the shear forces measured were higher than the levels expected for a similar flow without combustion. The gauge successfully measured the shear force in two orthogonal directions and indicated that the transverse shear totaled approximately 20 percent of the streamwise force with a strongly 3-D fuel injector arrangement.

It was found from the results of the UTRC test that slot injection significantly reduced skin friction and that H_2 was more effective than N_2. Nitrogen injection reduced C_f by 20 percent from the vitiated air flow with no cooling. Hydrogen injection with combustion reduced C_f to less than 0.002, for a total reduction of over 60 percent.

These particular test results indicate that no serious moment due to a pressure gradient normal to the sensing head existed, however, this may still become a significant factor in another test environment. Fortunately, this moment can be accounted for in the existing design without attempting to quantify the effect and calibrate it out of the output. The gauge can be fitted with another identical set of four strain gauges halfway up the cantilever beam. These would be connected as overlapping bridges which when added together leave only the force effect on the sensing head in the output signal.

With a viscous calibration method incorporated into the experiment, the gauge is ready to be tested in a wider variety of flow situations. Higher temperatures and Mach numbers will exercise more fully the potential for the gauge. It would also be very useful to now combine a heat flux gauge with the skin friction gauge in order to increase the available information with which to interpret the data.

Acknowledgements

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