N93-13670

SKIN FRICTION MEASUREMENTS IN HIGH TEMPERATURE HIGH SPEED FLOWS

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SUMMARY

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. The floating head is mounted to a stiff cantilever beam arrangement with deflection due to the flow on the order of 0.00254 mm (0.0001 in.). This allowed the instrument to be a non-nulling type. A second gauge was designed with active cooling of the floating sensor head to eliminate non-uniform temperature effects between the sensor head and the surrounding wall. Samples of measurements made in combustor test facilities at NASA Langley Research Center and at the General Applied Science Laboratory (GASL) are presented. 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 ±10-15% of the streamwise component.

NOMENCLATURE

C_f	=	skin friction coefficient
D	=	diameter of floating head
G	=	gap around floating head
L	=	lip thickness of head
P_t	=	total pressure
q	=	dynamic pressure
T_t	=	total temperature

C-3

τ_w = wall shear force
ρ = density
V = velocity

Subscripts:

x = streamwise component
z = transverse component

INTRODUCTION

Knowledge of drag resulting from skin friction is important for numerous engineering applications. Before a complete understanding of many flow fields both internal and external can be obtained, an accurate calculation or measurement of skin friction is required. In many combustor testing programs, accurate measurement of skin friction is necessary to correctly determine combustion efficiency. In addition, relatively small amounts of skin friction can seriously limit the available thrust from a scramjet combustor.

The current techniques employed in the measurement of skin friction fit into two general categories, those being either an indirect or direct method. Indirect methods involve measurement of the velocity gradient or heat transfer at the combustor wall. Reference [1] contains a review of many of the strategies adopted in these methods. Uncertainties with these methods can be quite large, especially in a compressible 3-D turbulent boundary layer, because a mathematical model or Reynolds analogy type relation is required to deduce the skin friction. For these reasons and considering that the flow types of interest in these studies are high heat flux and combusting, a direct shear force measurement technique was adopted. Reference [2] presents some limited measurements in a scramjet at the Applied Physics Laboratory. DeTurris, Schetz, and Hellbaum [3] present skin friction measurements in scramjet combustors from several test programs.

A direct force measurement device is a relatively straight forward concept, but when applied to the severe testing environment of a supersonic combustor boundary layer, it can quickly become a difficult and complex engineering problem. A gauge design has been developed for, but not limited to, measurement of skin friction in supersonic combustion boundary layers. This design is comparable, although somewhat improved, to the design of Ref. [3]. Also, in an attempt to further optimize these gauge designs, a technique was developed to thermally match the gauge sensor head to the surrounding combustor wall by internal cooling. These gauges are capable of measuring shear stress in both axial and transverse directions to the flow path, and have been tested in both heated and unheated supersonic flows.

The basic configuration of the skin friction gauges consists of a cantilevered floating element. A history of early direct measurement designs which includes floating element designs is presented by Winter [4]. Skin friction balances that have been developed for supersonic flows include the efforts of Roensch and Cadwell [5], Allen [6,7], and Voisinet [8]. The balances of these studies were primarily subject to supersonic flows with only moderate total temperatures.

The frictional forces that are a result of the supersonic combusting flow passing tangent to the combustion chamber walls are small in magnitude. However, since the shearing force is being measured over only a small area, it is necessary for the skin friction gauge to be very sensitive. The present designs have the ability to measure forces from a fraction of a gram to over ten grams accurately. The first of the two designs uses a deflection sensing device that was first used by Schetz and Nerney [2] and recently by DeTurris et al. [3]. This device employs piezoresistive crystal strain gages. This type of strain gage is exceedingly sensitive with gage factors in the area of 150, which is comparative to a gage factor of near 2 for common foil strain gages. This kind of sensitivity enabled the adoption of a non-nulling type design. Several benefits are obtained with a non-nulling design over a self-nulling design. First, the non-nulling design is less complex in that it does not require a series of mechanical linkages which can introduce substantial error in the measurement. Second, the time response of the non-nulling device is superior to that of the nulling device. Since the piezoresistive strain gages have a high gage factor, the cantilevered floating element of the current designs undergo extremely small deflections during a measurement. This renders insignificant any misalignment effects that could cause an errant measurement. One difficulty that is introduced by these crystal strain gages is that they are sensitive to temperature. An active cooling system near the gages was developed to minimize any error introduced by temperature gradients in the strain sensing elements.

Matching the sensing element thermally to the facility is critical to making an accurate skin friction measurement. The gauges have been designed to exactly match the tunnel wall thickness, materials and cooling pattern. This minimizes interference of the gauge with the rest of the wall so that the shear measurement represents the general wall conditions as opposed to only the local conditions proximate to the sensing head. It was determined that a temperature mismatch between the actual floating head of the skin friction gauge and the surrounding wall of the combustion chamber can introduce significant error in the shearing force measurement. An optimized design has been developed that actively cools the floating head of the instrument and retains the benefits of the uncooled head design. This design is needed specifically for high heat flux cases. Because of the importance of the wall heat flux and temperature conditions for proper skin friction measurements, the possibility of making simultaneous measurements of all three quantities has been investigated. This is also useful for considering the application of a Reynolds analogy to these severe flow conditions. A discussion of a thin film heat flux gage is reported in an accompanying paper [9]. This is also a direct reading gage capable of operating at comparable conditions. Future work could incorporate these two sensors into a single gauge.

DESCRIPTION OF GAUGES

A schematic of the skin friction gauge design which employs the displacement sensitive transducer is shown in Fig. 1. The floating head of this instrument is mounted on a cantilevered tube which is fit onto the sensing arm of the displacement sensor. The displacement sensor is a commercially available Deflection Sensor Cartridge (DSC) capable of sensing deflection in two orthogonal axes simultaneously. Encapsulated into the DSC are piezoresistive strain gages making it sensitive to very small deflections. Output from the sensor is enhanced by arranging the strain gages into a half Wheatstone bridge. One gage is in tension and one in compression for each axis. Output resolution is also increased by the extension of the effective moment arm on the DSC by the cantilevered tube. Heat transfer through the instrument is a primary concern since the strain gages are temperature sensitive. The outer housing is cooled by a continuous water cooling channel and, in addition, the cantilevered beam surface area is increased with fins. Also, the entire DSC-beam-floating head assembly is immersed in a silicon based heat transfer fluid.

The facilities that these instruments are designed to operate in are inherently crowded on the exterior. This necessitates three basic configuration requirements. First, the gauge must be small. The current gauges in use are all about three inches in length and a half an inch in diameter. Second, the instrument may be required to be mounted in any orientation dependent on the desired measurement location. Due to the presence of the internal heat transfer fluid these gauges operate best when the floating head is oriented either up or on its side with respect to the duct, although inverted operation is possible. Third, these instruments must be rugged. The delicate components of these sensors are enclosed in a metal housing which protects them from ordinary activity around the testing facilities. The strain gages are protected from thermal damage by the cooling system and the DSC cannot be over stressed since the maximum amount the floating head can move is the width of the gap between it and the housing which is far below the maximum allowable deflection for the sensor.

It is possible to introduce misalignment effects due to the tilting of the floating head in a non-nulling type gauge. This effect has become insignificant because of the sensitivity of the piezoresistive strain gages. The gauge is designed with a very stiff beam that will result in only small deflections of the sensing head, but the sensitivity of the DSC is more than adequate to accurately detect the small deflection. The expected maximum deflection of the sensing head is 0.00025 cm (0.0001 in.) which translates into a protrusion of four micro inches into the flow. By itself, this small protrusion should be insignificant, but the floating head geometry is designed to eliminate this type of misalignment effect as well.

Floating head misalignment effects are always a concern with these types of instruments. Allen [6] did a systematic study to identify and minimize these effects by considering specific geometric attributes of the floating head. Those studied were the effects of gap size, lip size, misalignment with the surface by either protrusion or recession, and pressure gradient effects between the top and underside of the floating element. The results of this study were referred to extensively in the design of the current sensor heads. The head for these gauges has 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. These dimensions were chosen to minimize the effects of the 0.01 cm (0.004 in.) gap between the head and the surrounding housing. The head also has a small lip at the lower end leaving a 0.0153 cm (0.006 in.) gap between it and the housing.

Allen [6] found that there was no advantage to having as small a gap size as possible. In fact, a skin friction balance is less sensitive to protrusion error with a large gap size. For the DSC gauge design, the gap to diameter ratio (G/D) is 0.0165 which is considerably larger than the lower limit suggested by Allen of 0.005. Effects due to the size of the floating head lip must also be considered. Again, Ref. [6] was consulted to choose a lip to diameter ratio (L/D) of 0.04. The gap to diameter ratio taken with this lip to diameter ratio combine to produce a design unaffected by gap size and lip protrusion effects.

The heat transfer fluid contained in the cavity serves several purposes. It not only provides thermal protection for the piezoresistive strain elements, but also aids in eliminating the effects due to a possible pressure gradient acting on the top surface of the floating head [3]. Moreover, the fluid produces strong damping to limit errors introduced by facility vibrations and cantilever beam oscillations.

Design for NASA Langley Vitiated Air Tunnel

An assembly drawing for the NASA Langley gauge is shown in Fig. 2. This gauge is similar to that for the same facility in the study of Ref. [3], except that a cooling channel has been added to the top of the outer housing in the area that fits inside of the chamber wall. The outer housing and floating head are constructed of carbon steel to match the tunnel chamber walls. Temperature of the DSC is monitored by a type K thermocouple mounted adjacent to the DSC in the heat transfer fluid. The heat transfer fluid consists of a silicon based oil (1000 centistoke viscosity) which is filled through a small access hole on the side of the outer housing.

Design for the GASL Test Series

An assembly drawing for the DSC based gauge for the first tests conducted at the General Applied Science Laboratory is depicted in Fig. 3. This gauge is constructed of copper to match the chamber walls of the GASL facility. The tunnel walls for this test are 4.76 cm (1.875 in.) thick, therefore the sensor head of the balance was lengthened to 2.54 cm (1.0 in.) to aid in transferring heat from the gauge. The temperature of the DSC was monitored by a thermocouple inserted through an access hole in the housing near the unit. A dummy balance was constructed for these tests which contained a copper/constantan thermocouple on the surface of the sensor head. This dummy balance and the skin friction balance were mounted in an oblong plug which bolted into the tunnel wall. Also, the plug in which both gauges were mounted was fitted with another copper/constantan thermocouple on its surface to measure chamber wall temperature. This complete package enabled the measurement of two skin friction components, sensor head temperature, and combustion chamber wall temperature.

The balance used for the second series of tests at GASL is essentially the equivalent of the one for the first test series with a few exceptions. For this second test series, a balance similar to that of Fig. 3 was inserted into a housing consisting of a circular 1.27 cm (0.5 in.) diameter, 4.76 cm (1.875 in.) long plug with a flange for a bolt circle to secure the unit into the chamber wall. Also, the DSC cooling system pressure was increased to approximately 350 psi (1035 kPa).

Cooled Sensor Head Design

The basic gauge configuration is shown in Fig 4. The gauge is a non-nulling type similar to the previously discussed designs. The shear sensing head is supported by a quartz cantilevered tube with an outside diameter of 0.062 cm (0.238 in.) and an inside diameter of 0.40 cm (0.157 in.). However, instead of using the Displacement Sensitive Cartridge to measure the sensor head deflection, piezoresistive semiconductor strain gages are mounted directly to the cantilevered quartz tube. At the location of the strain gages, the tube is machined square with an abrasive diamond wheel cutter to provide a secure smooth base to mount the strain gages and insure orthogonality of the measurement axes. This geometry was found effective in providing enough mass flow of cooling fluid to the sensor head and adequate resolution from the strain sensing elements. The sensor head is mounted to the tube which is then mounted into the base with a ceramic-like high temperature cement. This cement has the ability to withstand temperatures up to 2500°F (1650 K) and has a tensile strength of 425 psi (2929 kPa).

The strain gages are piezoresistive semiconductor type gages. These gages provide several advantages over conventional foil gages including higher sensitivity, resistance, and fatigue life, as well as small size. Kulite 750 ohm semiconductor strain gages are used in this instrument. These are ruggedized gages encapsulated into an epoxy/glass matrix with large solder tab terminals. Overall dimensions of each gage are 0.11 cm (0.28 in.) by 0.06 cm (0.14 in.). Four gages are mounted to the quartz cantilevered beam with a thin layer of a high temperature strain gage cement and coated with several layers of both polyurethane and an acrylic for protection from the environment. The gages are arranged in a half Wheatstone bridge, one gage in tension and one in compression for each axis of measurement while the sensor head is displaced. This provides compensation for any axially imposed strain which may arise from an axial force on the sensor head. Bridge completion is accomplished externally with precision resistors and a potentiometer for pretest output balance. The strain gages are powered by a +5 volt regulated DC power supply.

A flow pattern for sensor head cooling is developed through a co-axial tube arrangement. A stainless steel 0.160 cm (0.063 in.) tube is mounted along the centerline of the instrument to provide an inflow passage for the cooling fluid to the back side of the sensor head. Heat transfer calculations were made with a finite element code to determine the optimum thickness of the sensor head. In this calculation the sensor head thickness was varied to determine the thickness that would closely match the sensor head temperature with the surrounding combustion chamber wall. A heat flux that is expected from a scramjet combustor and a convection coefficient which is obtainable with water as the cooling fluid were prescribed as boundary conditions. A sensor head thickness of 0.083 cm (0.0325 in.) was found to be effective (see Fig. 5). The cooling fluid is exhausted from the instrument by flowing back along the outside of the stainless steel tube and inside of the quartz tube. At the base of the quartz beam the exiting liquid passes through a manifold and out through a 0.317 cm (0.125 in.) copper line. A variable convection coefficient at the sensor head is obtainable by regulating the pressure of the incoming cooling liquid. Tests were conducted, and it was determined that the sensor head cooling system is able to withstand pressures up to 500 psi (3450 kPa). Bench tests showed that the flowing water did not influence the tangential force measurement.

The gage is enclosed by an outer housing constructed of copper as is the floating element sensor head and the cantilever beam base. The gauge is mounted into the test facility with screws through a flange on the outer housing. As with all of the previously discussed designs, the cavity between the beam and the housing is filled with a silicon based heat transfer fluid, primarily in this case for vibration damping and pressure gradient effect minimization. A calculation was performed to estimate the natural frequency of the instrument and was found to be 1.5 kHz. Overall length of the gauge is 8.89 cm (3.5 in.). The sensor head was designed in a similar manner as the previous designs with a slightly larger diameter 0.812 cm (.320 in.) and a 0.013 cm (0.005 in.) gap. Lip size was set at 0.051 cm (0.020 in.).

EXPERIMENTAL PROCEDURES

Each measurement axis of the DSC forms half of a Wheatstone bridge; the crystal strain gages have a nominal resistance of 1000 ohms. Bridge completion is external to the instrument with 1000 ohm precision resistors and a 500 ohm potentiometer for pre-test output balancing. The DSC is powered by a +6 volt DC power supply. For the most part, data is recorded with a two channel strip chart recorder. At the NASA Langley and GASL tests data were also recorded with a PC-AT based 12 bit, 16 channel A/D card with one multiplexed channel equipped with an electronic ice point to record up to 16 thermocouple inputs. During the second set of tests at GASL, data were also recorded on GASL hardware at a 4 Hz acquisition rate.

Calibration

The DSC gauge and the cooled-head gauge are calibrated by applying a force in the axis of measurement and recording the output voltage from the wheatstone bridge. A digital voltmeter was used to record a series of data points, and a least squares linear regression was performed on the data yielding a linear calibration curve. In order to apply the force directly to the measurement axis, the gauge is clamped vertical and weight standards are hung by a thin line from the sensor head. This enables the application of the force to be "on-axis," although a slight amount of output is registered by the transverse axis. This transverse output is due to a small tolerance on the orthogonality of the transducer axes. The magnitude of this transverse sensitivity output is less than

5% of the axial output and is accounted for in the data reduction. Figure 6 contains a sample calibration for this type of instrument.

NASA Langley Scramjet Test Facility

Tests were conducted at the NASA Langley Vitiated Air Test Facility. Vitiated air was expanded to Mach 3.0, and fuel was injected through a perpendicular scheme. Skin friction measurements were recorded near the rear and on the centerline of a 2 degree, 122 cm (48 in.) long diverging duct located just downstream of the fuel injector. Cooling water was supplied at 500 psi (3450 kPa) with nominal tunnel test conditions of T = 3000 R (1667 K) and P_t = 500 psia (3450 kPa).

GASL Facility and Test Procedures

Tests were conducted at the General Applied Science Laboratory in two separate test series. DSC based gauges were used to measure skin friction in both test series. Some results were obtained with the cooled head skin friction gauge during the last test series. Measurements were acquired in a scramjet combustor model in both the constant area and diverging sections. Nominal combustor entrance conditions include M = 3.3, T_t = 4000 R (2222 K), and P_t = 800 psia (5510 kPa). The heat flux in the combustor was estimated at 400 BTU/ft^2/sec.

EXPERIMENTAL RESULTS

A small sample of results are presented here, although many test runs were conducted with the DSC based gauge in all of the test facilities. The gauges proved to be reliable over extended periods of operation. Frequency response of these gauges is more than adequate to capture the frequently changing conditions exhibited by the combustors including start and finish of a fuel cycle.

A skin friction coefficient was calculated for all of the tests presented here. The skin friction gauge measures the tangential force due to the flow over the sensor head, which is related to the wall shear, τ_w, by the flow wetted area of the sensor head. A skin friction coefficient can be readily calculated by

$$C_f = \frac{\tau_w}{q} \qquad (1)$$

where q is the dynamic head of the flow given as

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

Table 1 summarizes the results obtained with the DSC based gauge from some of the tests. The values of q used to calculate the skin friction coefficients for the GASL tests are based on flow conditions at the combustor entrance.

A sample result of the output from the NASA Langley tests is depicted in Fig. 7. A streamwise skin friction coefficient ($C_f = 0.0042$) was calculated from an average of the gauge output between 12 and 15 seconds. The transverse or cross-stream measurement is shown to be small compared to that of the streamwise component suggesting a near 2-D flow field at the measurement position.

Figure 8 illustrates both the streamwise and cross-stream wall shear measured for GASL Test Run 112. The friction gauge was located in the side wall of the constant area section of the combustion chamber downstream of a rearward-facing step. An average value of the wall shear at a point with steady fuel conditions was used to calculate a skin friction coefficient. The interval over which the average was taken is indicated on the plot between the vertical dashed lines. For Test 112, τ_w = .11 lb_f/in^2 (760 N/m^2) in the streamwise direction and τ_w = 0.043 lbf/in^2 (295 N/m^2) for the cross stream component. The streamwise and cross-stream skin friction are listed in Table 1. Shear and friction coefficient values are listed in Table 1, as well. During Test 112, the temperature of the sensor head was recorded as well as the temperature of the combustion chamber wall adjacent to the sensor head (Fig. 9). A temperature difference of up to 400 R (222 K) was obtained during these and other test runs. Considering this temperature discrepancy and its possible effects on the accuracy of the skin friction measurements was a leading factor for designing the cooled head skin friction gauge.

Figure 10 presents data measured for different fuel conditions where the fuel equivalence ratio was ramped from 0.5 to 0.8. These skin friction measurements are based on a combustor inlet reference dynamic pressure. The test runs are representative of data recorded in the constant area section of the combustor. Relatively high values of skin friction are reported for these test cases in the streamwise direction (see Table 1). Cross-stream components for this location can be as much as 35% of the streamwise values.

Cooled Head Skin Friction Gauge Results

A first test for this type of skin friction gauge was conducted in a cold Mach 3.0 supersonic flow. Output from this test is shown in Fig. 11. This result indicates that the gauge has an excellent time response, apparent by its following of the start of the supersonic tunnel on the left of the figure and unstart of the tunnel on the right of the figure. Output reached a steady constant value which translates into a skin friction of $C_f = 0.0015$. A calculation of the skin friction coefficient based on the boundary layer height measured from a nanoshadowgraph of the measurement position indicates a skin friction coefficient of $C_f = 0.0014$.

The gauge was installed into the constant area section of the combustion chamber of the last GASL test series to make a skin friction measurement. Some limited success was achieved. Figure 12 illustrates the output for the streamwise direction of Test 602. An average was taken over the range during which fuel was being injected and a skin friction coefficient was calculated to be $C_f = 0.0023$. Table 2 contains the results from this test run as well as Test 601.

MEASUREMENT UNCERTAINTIES

The largest source of error is due to heating of the DSC or in the case of the cooled head gauge of the strain gages themselves. The manufacturer of the DSC specifies the temperature sensitivity to be 0.02 percent of full scale. Presently the gauge operates at about 2 to 3 percent of full scale, which would magnify this temperature error potential. This results in a requirement of keeping the DSC temperature to ± 2°C. The cooling system integrated into the DSC design has been able to keep the DSC to ± 1°C, which results in an uncertainty less than ± 2%.

Further uncertainties can be due to asymmetric heating of the crystal strain gauges. A zero shift is the result of a temperature change of these elements. If the temperature change is symmetric then the output can be corrected with the known temperature sensitivity. If heating is asymmetric correction is not possible. For the DSC based gauge this error is virtually eliminated by the active cooling system around the housing. In the case of the cooled head gauge this type of system is not as effective. In the future, tests are planned with spray cooling on the outer housing that should reduce these errors.

Pressure gradients in the combustion chamber can result in a moment on the sensing head. Pressure drop in the duct at NASA Langley is approximately 1.5 psi/ft (34 kPa/m). This results in a negligible moment on the balance. Pressure gradients in all tests are assumed small.

Many of the measurement uncertainties with these instruments result in negligible effects. Overall uncertainty is based on the effects of the misalignment, possible zero shift, and calibration concerns. This results in an overall uncertainty of 10-15%.

CONCLUSIONS

Results of these experiments confirm the validity of a floating element, non-nulling, cantilever skin friction balance design. Accurate measurements were obtained in very high heat flux supersonic environments. Measurements were improved over those previously reported by active cooling of the DSC with continuous high pressure water channels surrounding the balance.

Dual axes measurements indicate nearly 2-D flows in the NASA Langley facility and in the constant area section of the combustor during the early test series at GASL. Results from the later test series at GASL show transverse shear to be up to 90% of the streamwise value in the diverging section of the combustion chamber indicating a highly 3-D turbulent flow.

The design of an active cooling system for the floating element proved to be a feasible design option to further improve the accuracy of these types of non-nulling balances. Encouraging preliminary results from both a cold and high heat flux supersonic flow were obtained. Accuracy will be improved with better control over heating of the piezoresistive strain gages. Ultimately a heat flux sensor could be added for measurement control to precisely match thermal conditions.

ACKNOWLEDGEMENTS

The invaluable assistance provided by all the involved employees of NASA Langley Research Center and the General Applied Science Laboratory is greatly appreciated. Also acknowledged are the efforts of D. J. DeTurris and K. M. Chadwick (graduate research assistants at Virginia Tech) in obtaining much of the data presented.

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Test Facility	NASA Langley Batch 5 Run 28	GASL Test 112	GASL Test 564
Mach no.	3.0	3.3	3.3
P_t (psia)	500	800	800
T_t (R)	3000	4000	4000
V (ft/sec)	5000	6300	6300
q (psf)	4100	10700	7800
τ_{wx} (psi)	0.122	0.11	0.125
τ_{wz} (psi)	0.032	0.043	0.0535
C_{fx}	0.0042	0.0014	0.0023
C_{fz}	0.0005	0.0006	0.0010

Table 1 - Summary of the DSC based skin friction gauge results

Test Facility	GASL Test 601	GASL Test 602
Mach no.	3.3	3.3
P_t (psia)	800	800
T_t (R)	4000	4000
V (ft/sec)	6300	6300
q (psf)	7800	7800
τ_{wx} (psi)	0.160	0.181
C_f	0.0029	0.0033

Table 2 - Cooled Head Friction Gauge Results

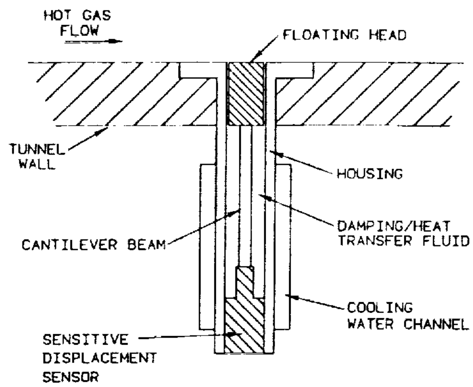

Fig. 1 Schematic of a Skin Friction Balance

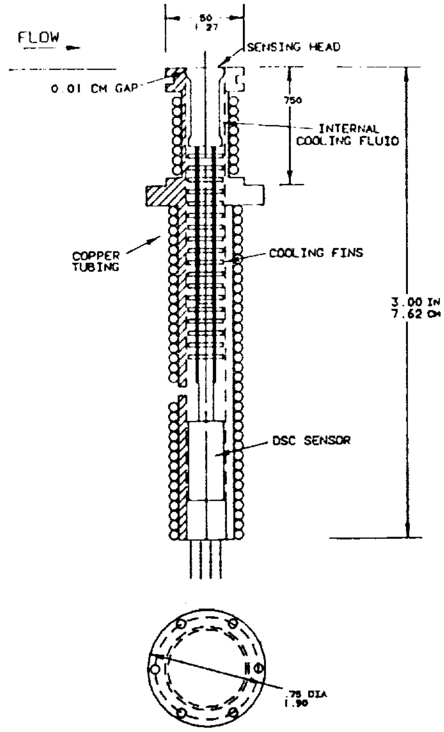

Fig. 2 Schematic of NASA Langley Skin Friction Balance

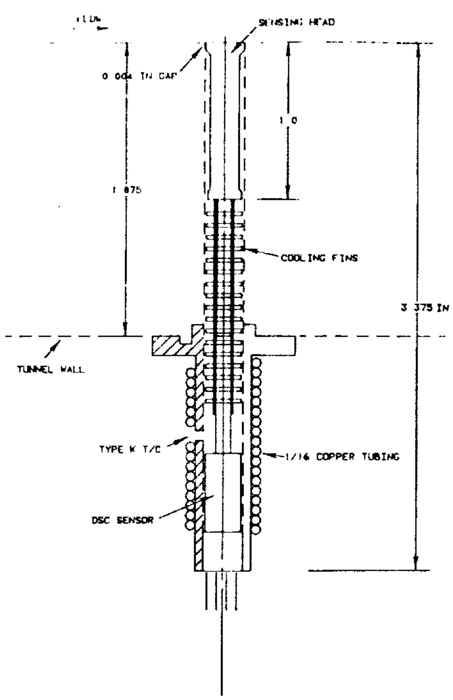

Fig. 3 Schematic of GASL Skin Friction Balance

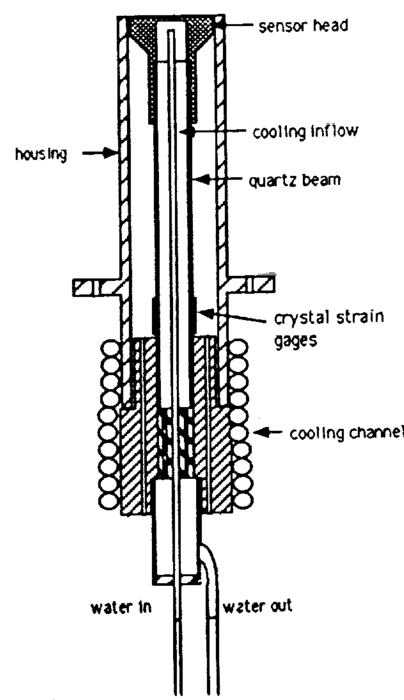

Fig. 4 Cooled Head Skin Friction Balance

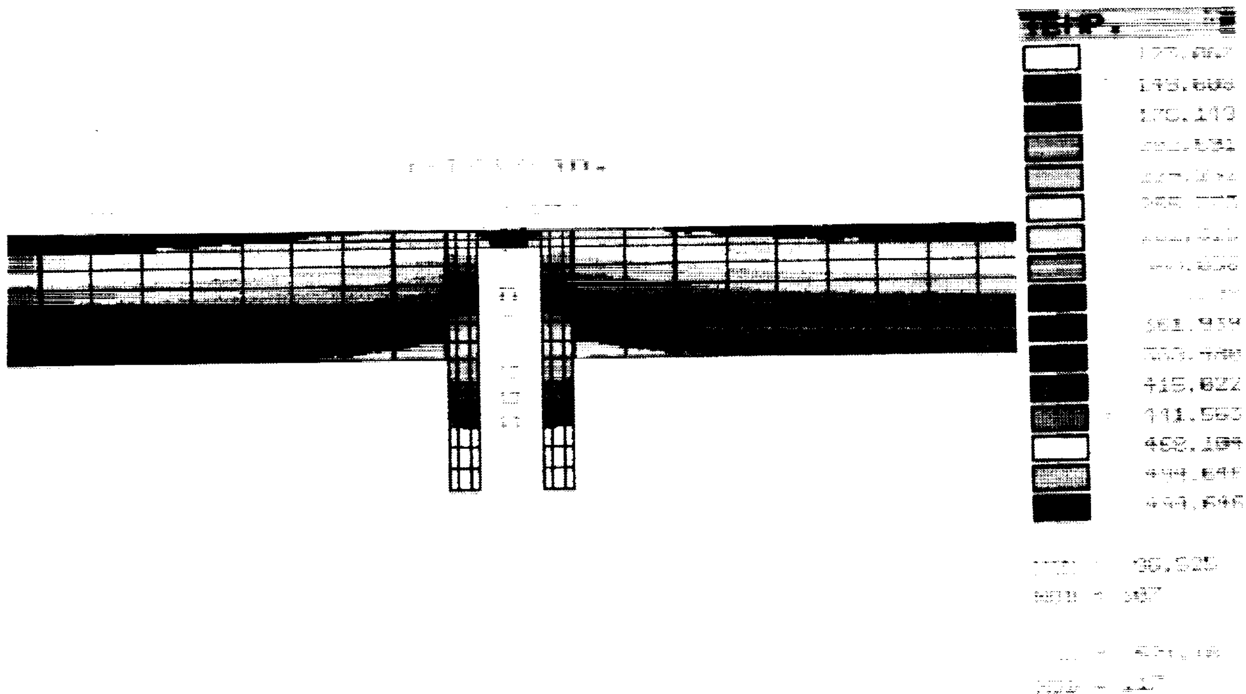

Fig. 5 Cooled Head Heat Transfer Contour

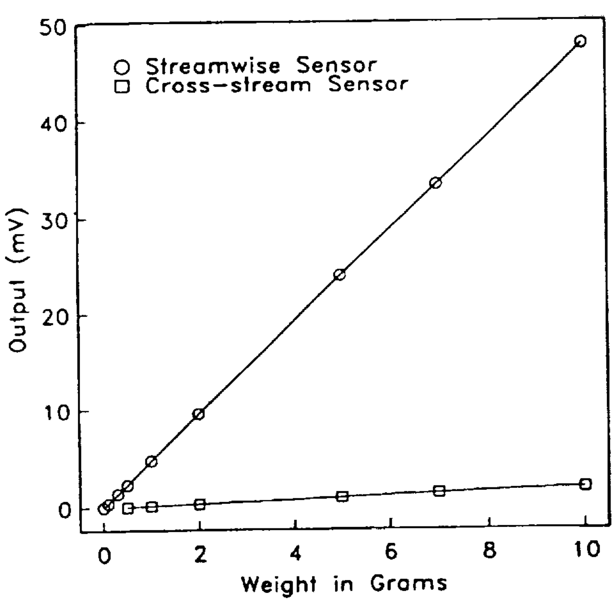

Fig. 6 DSC Balance Calibration

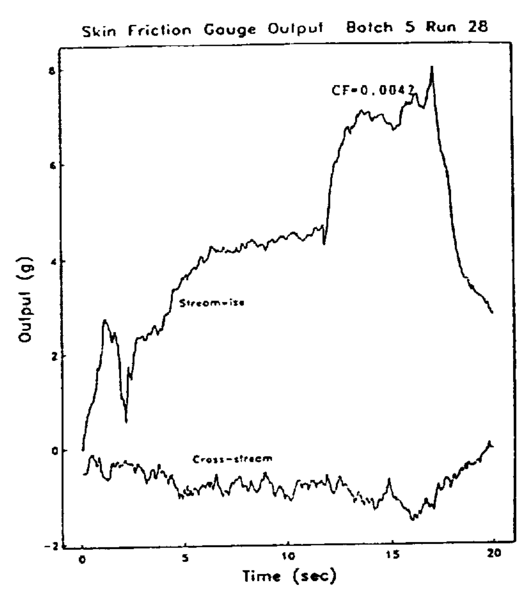

Fig. 7 NASA Langley Test Run 5 Results

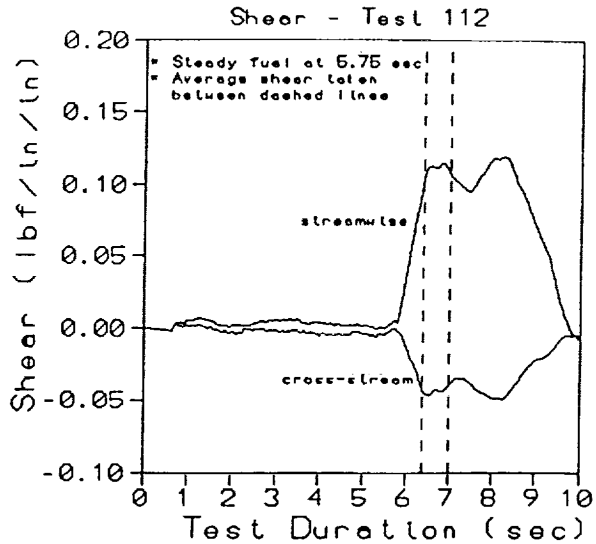

Fig. 8 GASL Test 112 Results

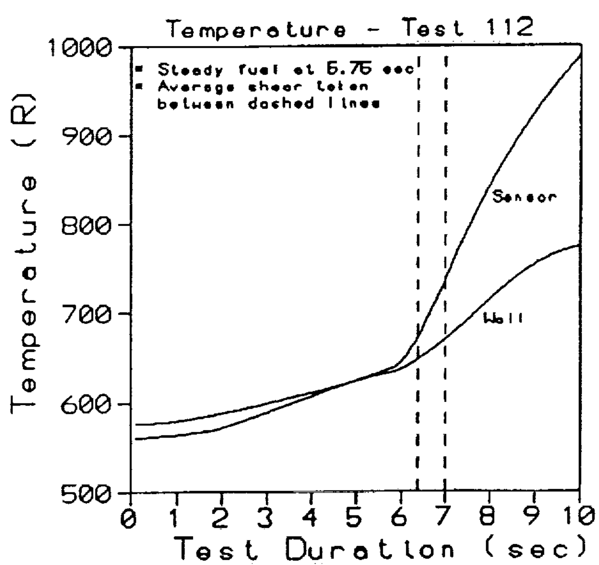

Fig. 9 GASL Test 112 Temperature Mismatch

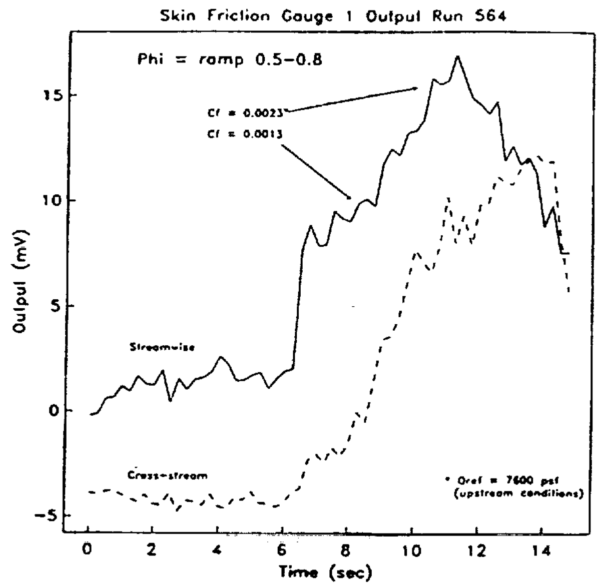

Fig. 10 GASL Test 564 Results

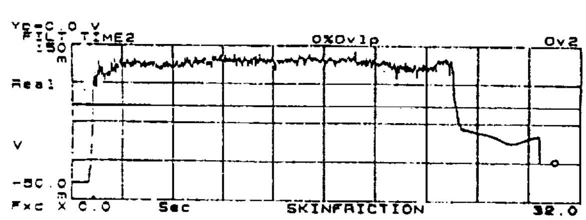

Fig. 11 Cooled Head Balance Cold Supersonic Flow Results

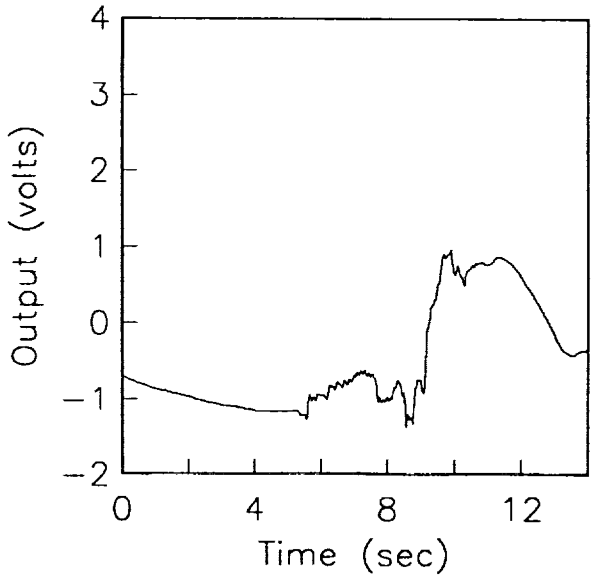

Fig. 12 GASL Test 602 Cooled Head Balance Results