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FACILITY FOR CALIBRATING HEAT FLUX SENSORS IN A CONVECTIVE ENVIRONMENT

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ABSTRACT

The National Institute of Standards and Technology (NIST) presently conducts heat flux sensor calibrations using standard radiation methods. In practice, however, many heat flux sensors are used in test environments where convective heat transfer dominates. Equivalent fluxes in radiation or convection can produce different sensor responses due to sensor surface properties (e.g., emissivity, roughness) and near-surface structure (e.g., transmissivity, temperature distribution). These issues are being addressed at NIST by the development of a convective heat flux facility. By extending calibration capabilities to include a primarily convective environment, direct comparisons of sensors in controlled convective and radiative environments will be possible.

This report describes the progress of the convective heat flux calibration facility under development at NIST. A low-speed wind tunnel has been built to produce a boundary layer shear flow above a constant temperature copper plate. Independently controlled heaters and temperature monitoring systems have been designed and installed to provide an isothermal surface with a known reference heat flux. Wind tunnel configuration and test section instrumentation details, as well as characterization of the flow and the temperature distribution in the plate, are described. Initial heat transfer measurements and results from numerical modeling efforts and hot-wire anemometry are reported.

INTRODUCTION

Development of the convective heat flux calibration facility at NIST was begun in response to the needs of the heat transfer community [1]. No standard facility has existed for calibrating heat flux sensors in a primarily convective environment. Presently most sensors used to measure heat flux in convective flow situations are calibrated in a known radiation field. At the same time, the heat transfer community has recognized that total heat flux uncertainties for measurements in any given application are presently no better than ± 10% [2].

Heat flux is by definition a quantity in motion, thermal energy moving through a surface, having the SI units of watts/m^2. It is fundamentally difficult to measure this flow without at the same time disturbing it. Each sensor has structure that can disturb the flow of energy, and therefore disturbs the quantity it seeks to measure. Accurate measurement of heat flux consequently requires understanding the errors produced by any given sensor which can also vary depending on the nature of the incident energy.

Heat flux is composed of radiation, convection, and conduction. Each of these forms of energy transfer affect a sensor differently. Radiation is defined in terms of wavelength spectrum, intensity, and angular distribution. Any given sensor absorbs, reflects, and transmits according to its own surface properties which may not match those of the surrounding surface. In addition, radiation is not actually absorbed at the surface, but within the first micrometer of the surface [3], which is on the order of the thickness of thin-film gages. This could significantly affect measurements of radiative heat flux for these sensors.

Convection, heat transfer via fluid motion, is purely a surface phenomena. Heat flux will be disrupted if there is any discontinuity at the sensor edge or if the sensor surface roughness differs from the surrounding surface. Conduction of energy through the sensor can be affected by sensor structure. If the sensor structure includes lower thermal conductivity elements (such as adhesive or resistance layers) these will alter the surface temperature profile relative to the surrounding surface and thus change the heat flux. Heat flux calibration and measurement are not simple because the output from the sensor depends not only on the heat load, but on the thermal boundary conditions by which it is applied.

The difficulties of measurement and calibration, presented briefly here, are discussed in detail in reference [1]. A collective realization of the absence of standards for calibration and lack of understanding of the issues involved in heat transfer measurement led to the formation in 1994 of an American Society of Mechanical Engineers (ASME) Heat Transfer Division committee, which lead to a workshop in

January, 1995 of the heat transfer community at NIST. The purpose of this workshop was to discuss the issues involved in calibration and measurement and to delineate the scope of a project begun at NIST in 1995. A full report of this workshop is given in reference [1], while a good summary is presented in [2].

The goal of the NIST project is to develop three heat flux calibration facilities as standards for calibration to a desired uncertainty of ± 2%, and to better understand the difficulties of measuring heat flux in different environments. These facilities apply to three different regimes: a low-speed convection flow to allow calibration in a well documented laminar shear flow, a higher flux conduction facility, and a radiation facility. These facilities will allow, for the first time, a sensor to be placed in different environments with calibrations traceable to NIST standards. This report documents the progress of the convection facility.

FACILITY DESIGN

The convection facility was designed to produce a repeatable laminar flow across a heat flux sensor embedded in a heated isothermal plate. The maximum heat flux with the present design and hardware is 5 kW/m^2. Measurements from the sensor are calibrated against the power required to heat a guarded reference section located alongside the sensor in the plate. Flow velocity measurements and the two-dimensional geometry of the test section allow numerical predictions as a secondary estimate of the heat flux (Figure 1). Following are details of the wind tunnel construction, test section components, and instrumentation.

Flow Conditioning

The convection facility is depicted in Figure 2. Elements upstream of the test section constitute the flow generation and conditioning portion of the facility. Flow is generated by a 94.4 L/s blower, driven by a 0.746 kW AC motor equipped with a variable-frequency drive which permits speeds to be set in 0.1 Hz increments with 60 Hz full scale. The flow is then passed through the following conditioning elements which, unless described otherwise, are made of 12.7 mm-thick high-pressure phenolic laminate:

muffler – a 1.2 m x 1 m x 0.5 m (inside dimensions) box of 19 mm plywood, lined with open-cell "egg crate" foam. Inlet and outlet connections are through nominal 102 mm ID rigid plastic pipe fitted with rubber vibration isolators.

Round-to-square transition – a sheet metal duct with a 102 mm round inlet and a 102 mm square outlet covered with a course mesh screen.

First diffuser – an 899 mm long unit which expands flow cross section to 275 mm x 254 mm. An aluminum splitter plate on the vertical centerline and another on the horizontal centerline divide the diffuser into four equal channels.

Heat exchanger – three Al liquid-to-air, tube-fin heat exchangers.

Second diffuser – a 216 mm-long unit which expands the flow cross section to 300 mm x 300 mm, with the same splitter-plate arrangement as in the first diffuser.

Honeycomb – a 207 mm section of aluminum honeycomb, with 6 mm hexagonal cells.

Screen section – a combination of three stainless steel square mesh screen assemblies, with screens of progressively smaller mesh: 0.85 mm, 0.65 mm, and 0.51 mm wire spacing respectively.

Settling section – a 338 mm-long duct.

Contracting nozzle

The contraction is a 164 mm-long, aluminum, two-dimensional nozzle. It reduces the flow cross section from 300 mm x 300 mm to 10 mm x 300 mm. The curved boundary was prescribed based on the approach of reference [5] and is defined by the equations

$$y[\mathrm{mm}] = \pm \begin{cases} 5. + 0.9667\left(150.-.00005487\,x^3\right); & 0 \le x \le 135\,\mathrm{mm} \\ 5. + 0.004296\left(150. - x\right)^3; & 135\,\mathrm{mm} \le x \le 150\,\mathrm{mm} \end{cases}$$

where x is in the streamwise direction (Figure 2). The 30:1 contraction ratio was chosen to minimize inlet turbulence intensity and provide a "top-hat" velocity profile. The nozzle geometry was analyzed using a finite-element code that predicted exit velocity profiles for given inlet velocity profiles. Results showed that there was no significant difference in the effect of a uniform inlet velocity profile vs. a parabolic profile on the outlet velocity profile indicating that the outlet profile is independent of the inlet profile. In addition, the outlet profile was shown to be nearly uniform with a very thin boundary layer entering the test section [6].

Heated plate

The present design of the test section includes a heated, isothermal, pure copper plate beneath a laminar shear flow of lower temperature air. A drawing of the bottom side of the plate is shown in Figure 3. The grooves divide the plate into thermally semi- isolated regions, for a total of 6 regions (labeled A-F) heated independently by six DC power supplies. Regions A, B, and C are divided based on symmetry, but each is heated by one power supply with the semi-regions joined in series. By independently heating the six regions, the variation in heat flux along the plate can be matched, and conductive perimeter losses can be compensated. A thermocouple array (described below) is embedded at the same depth as the grooves to monitor the surface temperature condition. Presently the top and side walls of the test section are made of clear plastic in order to allow visual access and simplicity of the initial design. With this present design, including the plate without a highly polished surface, radiation losses are estimated to be 3 %.

Heaters

Immediately beneath the copper plate are polyimide/metal foil resistance heaters (0.1 mm thick). A cut-away of the test section looking upstream is shown in Figure 4. Below the heaters is a 1.9 cm layer of foamed styrene insulation and beneath this another foil resistance guard heater mounted to a thin aluminum plate to null bottom conductive losses. This heater is independently controlled with a seventh DC power supply. Below this is a 3.8 cm layer of insulating foam and then a supporting aluminum plate. The lower support plate and heated copper plate are both supported by two phenolic side pieces that bolt to the upstream nozzle and also serve to reference the plate position relative to the nozzle exit slot.

Sensor

The present design places the heat flux sensor in a copper cylinder that seats against the lip seen in the center hole of the plate in Fig. 3. This allows the sensor surface to be set flush with the upper surface of the plate at a known distance from the inlet of the test section. The cylinder that holds the sensor extends down through the layers of insulation and mounts to the lower support plate such that no threads are required in the heated plate, Fig. 4. A second cylinder, which has a flat face with no opening for a sensor, serves as a reference for looking at thermal disturbances in the plate without a sensor present.

Reference region

The reference value for the desired true (i.e. undisturbed) heat flux at the sensor location is determined from the power input to the region of the plate labeled REF in Fig. 3, where the REF region and sensor location are equidistant from the leading edge. The average flux level at REF is taken as the power input to the region divided by the REF area including half the groove width. Power is found by independently measuring voltage across the REF region heater along with the voltage drop across a precision resistor to measure heater current. The temperature gradients across the groove surrounding the REF region and in the insulation below are controlled to minimize conduction losses. The heaters in the surrounding regions and on the lower guard plate serve to drive the temperature gradients towards zero at which point all power input to the REF region would exit by convection from the upper surface. Deeper grooves surrounding the REF region are used to gain better control of lateral conduction.

Thermocouple array and data acquisition

The plate surface temperatures are monitored with 32 fine gage type T (Cu-Constantan) thermocouples. Careful ice-point calibration of these thermocouples has allowed uncertainties of ±0.05°C for absolute temperature measurements. Two differential thermocouple pairs will monitor the temperature difference across the deep groove on each side of the REF region. Power input to the surrounding regions allows the temperature difference across the gap to be nulled. Uncertainty in the conductive losses out the side and bottom of the REF region is the largest uncertainty, on the order of ± 5 % in this initial system. The thermocouple, heat flux sensor, and power signals are collected with a unified PC based data acquisition system.

RESULTS

Direct Numerical Simulation

An in-house direct numerical simulation (DNS) computer model of the flow and plate is under continued development [7]. This code is a two-dimensional (fully three-dimensional available) solution of the full thermally-compressible Navier-Stokes equations including buoyancy and transient effects. The code models thermal conduction within the plate/ sensor housing/ insulation, and convection and diffusion in the laminar flow above the plate. This model of the test section serves as an additional measure of the heat flux at the sensor location. With the present plate design, knowledge of the horizontal heat flux distribution along the plate is required to relate the REF region power to the sensor heat flux due to the larger area covered by the REF region in the flow direction. The DNS code provides the heat flux as a function of distance across the reference region. This profile is used to find the ratio of the average heat flux across the REF region to the average across the sensor region, where the two regions are centered at the same distance from the leading edge, Fig. 1.

The DNS code in its present form has predicted heat flux based on the present plate and insulation design, and using the measured nozzle exit velocity profile (discussed below) as input. The predicted heat flux along the plate is shown in Fig. 5. The flux is seen to drop rapidly, coming to a more uniform value across the region of the sensor at 40 mm downstream. The peak in the flux occurs at the leading edge of the plate after a rise across a 3.2 mm layer of balsa wood insulation separating the aluminum contraction nozzle from the heated plate.

The model also gives temperature within the plate and inside the boundary layer along the test section centerline. Temperature variations within the plate were shown to be very small with the maximum variation seen near the leading edge where the temperature drop was less than 0.1 K.

Nozzle exit flow

Hot-wire anemometry measurements have been used to provide accurate inlet conditions for the simulation of the test section. The hot-wire measurements have shown reasonably good agreement with the nozzle exit velocity profile as predicted by the finite-element code (discussed earlier in the facility design section) in terms of boundary layer thickness and approximate profile. However, whereas numerical results predicted a flat top to the profile, the anemometer measurements show a 3% overshoot at the edge of the boundary layer ($U_{max}/U_{center} = 1.03$). In addition, spanwise measurements have shown uniform flow across the central 95 % of the test section width at the nozzle exit (one traverse: velocity across this region was limited to the range of $U_{center} \pm 0.2$ %).

The profile as measured at the exit of the nozzle with the test section removed is given in Fig. 6 for the highest Reynolds number attainable (Re_h = 20,000, height h = 10 mm). As can be seen, the entire boundary layer is only 0.5 mm thick. Corrections for near wall effects were done according to the method given by Wills [8], with corrections of less than 1% outside the boundary layer, 2% at 0.4 mm, 6% at 0.25 mm, and 30% at 0.1 mm (a 30% decrease from the measured velocity). Absolute accuracy in placing the hot-wire was accomplished by traversing the wire to the wall until it touched. Calibration was performed in a laminar jet calibrator apparatus. Multiple probes, calibrations, and traverses have demonstrated uncertainties in the measured Ucenter velocity of ± 1% (primarily due to probe differences, with individual probes giving repeatability of ± 0.2 % estimated standard deviation), and ± 0.03 mm in spatial location relative to the wall.

The turbulence intensity (defined here as the rms fluctuating component of velocity divided by the mean center velocity) leaving the nozzle is approximately 0.2 % outside of the boundary layer and less than 1% everywhere, with the measured increase in the boundary layer perhaps due to probe interference effects.

Preliminary temperature measurements

The thermocouple matrix in the plate has shown a total variation across the plate of 0.5 °C when ΔT ($T_{plate} - T_{air}$) is 40°C. Much of this variation is spanwise and may be due to uneven conduction losses at the wall. Total variation in the temperatures around the reference region was less than 0.1°C when measurements were taken.

Preliminary heat flux sensor measurements

Presently two sensors have been tested in the facility. One sensor is a sputtered thin-film thermopile design while the second is a Schmidt-Boelter design [9]. Initial measurements show agreement between the two sensors (using the manufacturer supplied calibration), the numerical model, and the reference region. The reference region flux is 10 % above the numerical prediction with the two sensor measurements falling in between. This variation is within the uncertainties of the facility in its initial configuration where the expanded (two times the estimated standard deviation) is approximately ± 10% for each of these measures.

SUMMARY

Details of the construction of the convection heat flux calibration facility at NIST have been presented along with a discussion of the methodology and instrumentation used to find the undisturbed value of the heat flux for calibrating heat flux sensors. Results from numerical modeling, and hot-wire measurements of the flow exiting the contraction, have been presented along with initial heat flux measurements.

These results are very encouraging and work is progressing toward understanding facility capabilities and improving measurement precision while running at a single velocity and T_{plate}/T_{air} condition. Future work includes installing differential thermocouples around the reference region along with a larger array of thermocouples in the insulation below. The facility will be configured to run at several velocities and temperature differentials, with computer control of individual heaters. Design changes necessary for improved facility precision are being considered. Comparative calibrations in the radiation facility should be completed soon.

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REFERENCES

[1] Moffat R.J., Danek C., "Final Report: The NIST/NSF Workshop on Heat Flux Transducer Calibration", at NIST in Gaithersburg, MD, January 23 and 24, 1995.

[2] Diller, T.E., "Heat Flux Calibration -- Progress Toward National Standards," Proceedings of the 41st International Instrumentation Symposium, Denver, CO, May 7-11, 1995.

[3] Incropera, F.P., and DeWitt, D.P., Fundamentals of Heat Transfer, 2nd Ed., John Wiley and Sons, New York, 1985.

[4] Kays, W.M., and Crawford, M.E., Convective Heat and Mass Transfer, 2nd Ed., McGraw-Hill, New York, 1980.

[5] Morel, T., "Design of Two-Dimensional Wind Tunnel Contractions," J. Fluids Engineering, pp.371-377, June, 1977.

[6] Personal communication with A. Johnson of The Pennsylvania State University.

[7] Personal communication with R. Davis and E. Moore of NIST Chemical Science and Technology Laboratory division.

[8] Wills, J.A.B., "The correction of hot-wire readings for proximity to a solid boundary," J. Fluid Mechanics, v.12, p.388-396, 1962.

[9] Diller, T.E., "Advances in Heat Flux Measurements," Advances in Heat Transfer, v.23, Academic Press, Boston, 1993.

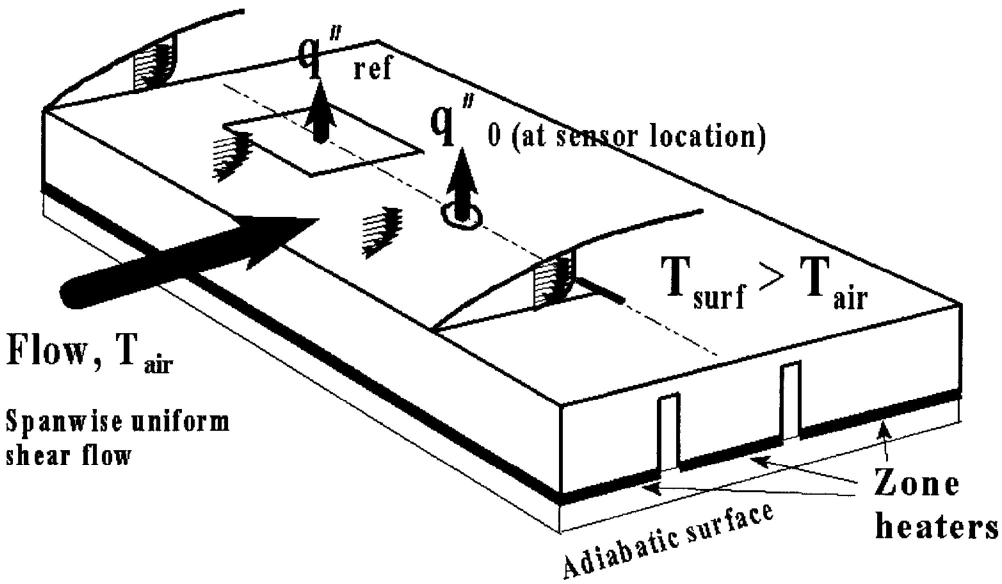

Figure 1 Heated plate below laminar boundary layer with reference region to give measure of undisturbed heat flux at sensor location.

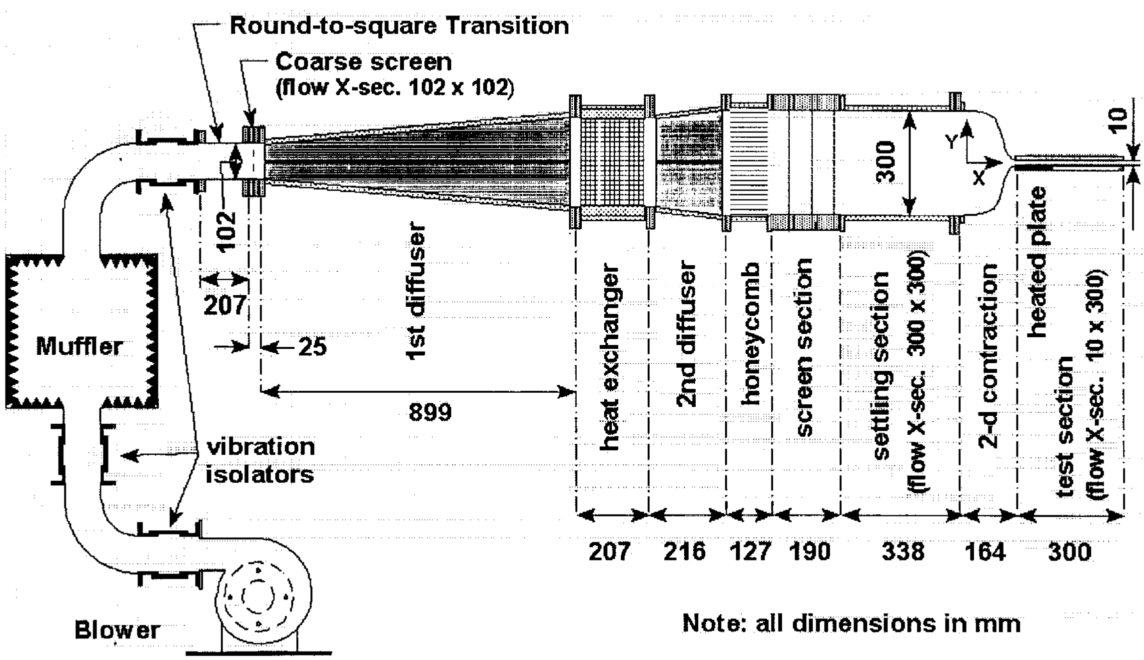

Figure 2 Schematic of flow conditioning in wind tunnel.

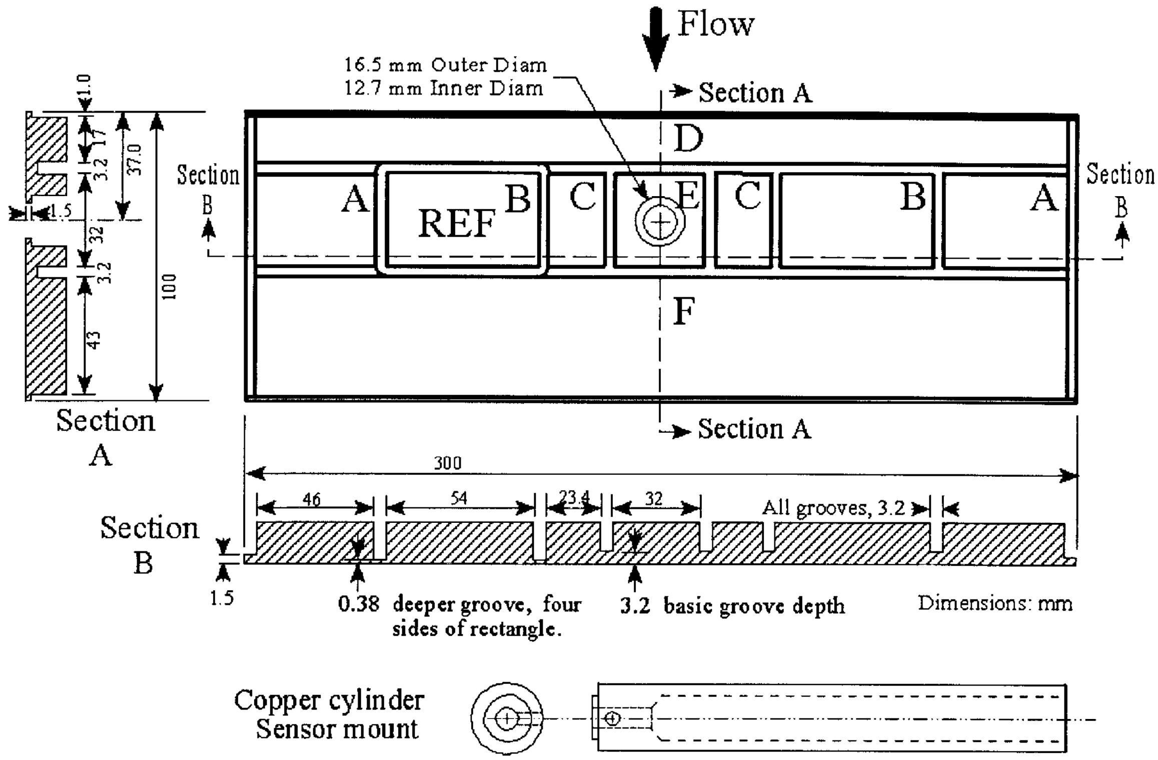

Figure 3 Bottom view of heated plate showing location of sensor, separate regions of plate, and sensor housing.

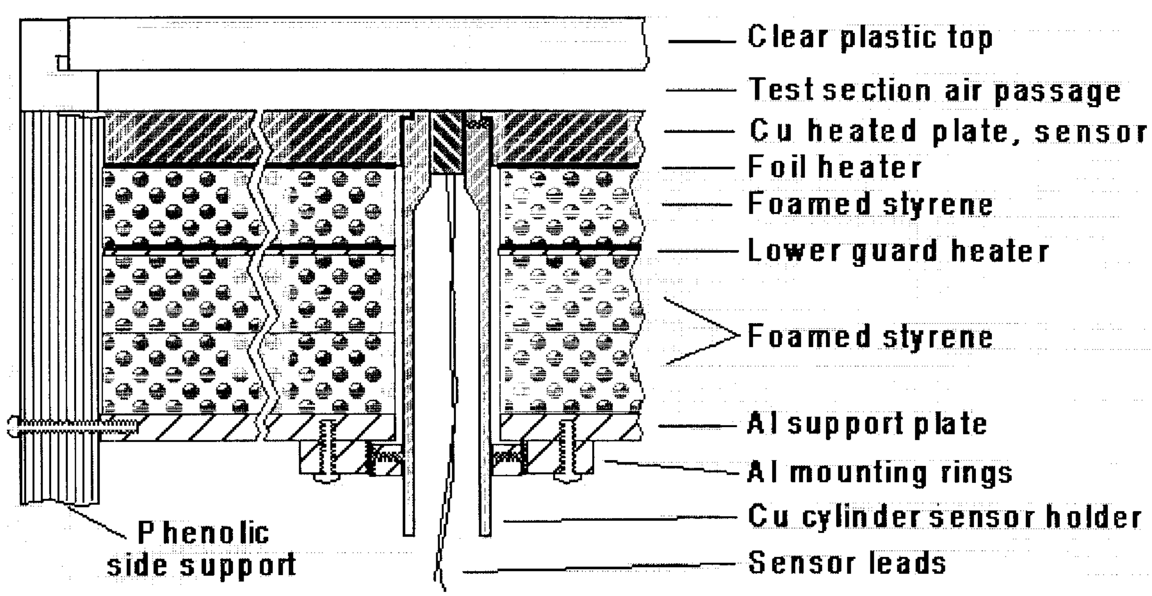

Figure 4 Cut-away of test section looking upstream into the nozzle exit, showing layering beneath the heated plate and mounting of the heat flux sensor.

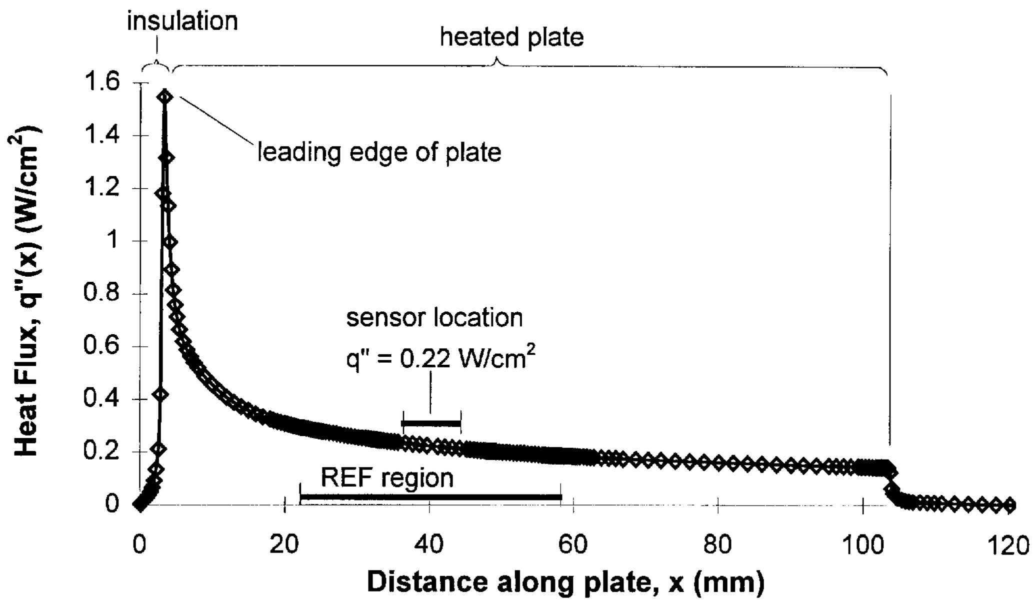

Figure 5 Heat flux along plate starting from nozzle exit as predicted by DNS model of plate and flow.

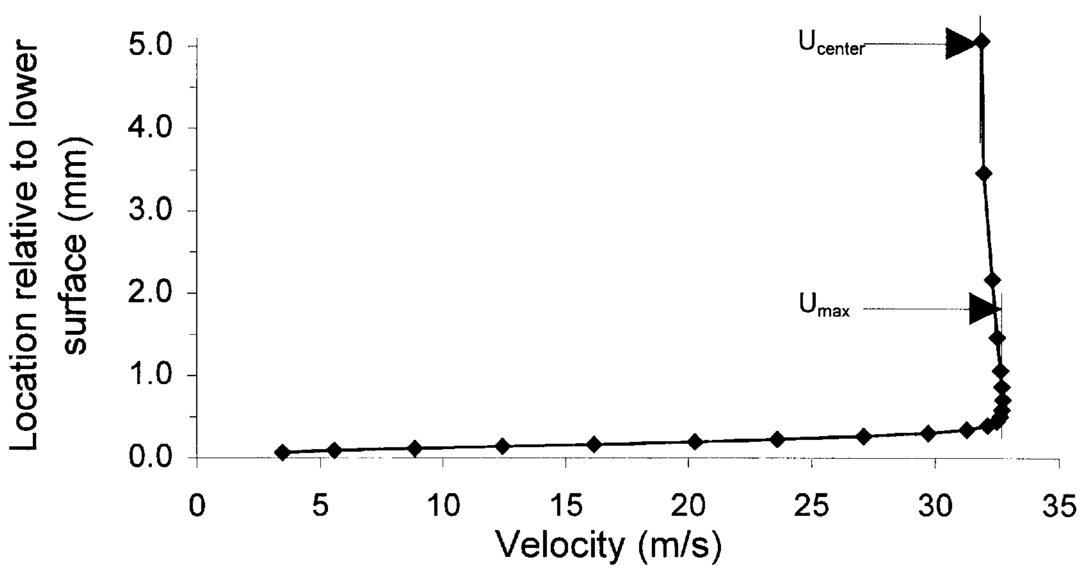

Figure 6 Measured velocity profile of flow exiting lower half of contracting nozzle. Hot-wire data corrected for near-wall effects. The standard uncertainty (estimated standard deviation) is 0.3 m/s except near wall (lower half of boundary layer) where uncertainty rises due to probe/ surface interaction and uncertainty in applied correction.