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Department of Mechanical Engineering
Penn State University, University Park, PA 16802

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SWEPT SHOCK/BOUNDARY LAYER INTERACTION EXPERIMENTS IN SUPPORT OF CFD CODE VALIDATION

by G.S. Settles and Y. Lee

INTERIM TECHNICAL REPORT FOR
THE PERIOD JANUARY 15, 1989 - JANUARY 14, 1990

Funds for the support of this study have been allocated
by the NASA-Ames Research Center, Moffett Field, CA
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Dr. C.C. Horstman, Technical Officer
NASA-Ames Research Center
Experimental Fluid Dynamics Branch, MS 229-1
Moffett Field, CA 94035

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SUMMARY

Research on the topic of shock wave/turbulent boundary-layer interaction has been carried out under the subject Grant during the past one-year period at the Penn State Gas Dynamics Laboratory. Skin friction and surface pressure measurements in fin-induced, swept interactions have been conducted, and heat transfer measurement in the same flows are planned. The skin friction data for a strong interaction case (Mach 4, fin angles = 16 and 20 deg.) were obtained, and their comparison with computational results was published (Ref. 1). Surface pressure data for weak-to-strong fin interactions were also obtained and remain unpublished. The heat transfer measurements for the same interactions are planned for early 1990.

INTRODUCTION

The study of shock wave/turbulent boundary-layer interaction is very important for the solution of internal and external aerodynamic problems in the design of high-speed vehicles and associated numerical simulations. However, only a little knowledge in this field has been available in the past, and more extensive experimental work is still needed for a sufficient understanding of the fluid dynamics of such flows. When an oblique shock wave impinges on a solid surface, a large separation bubble of reverse flow can form, generating a complicated 3-dimensional flow structure. It was found that the peak pressure, peak skin friction and peak heat transfer occur near the region of reattachment of this separated flow. These peak ratios are of great practical importance in predicting high aerodynamic and aerothermal loading due to interacting flows on high-speed flight vehicles.

Therefore, the present experimental program is being conducted to provide "benchmark" data that can be used both to obtain a clear understanding of the physical behavior of swept shock wave/turbulent boundary-layer interactions, and as a fundamental database for CFD code validation.

Since our results of skin friction measurements have already been reported in the literature, only a brief description of the surface pressure measurements and the design of the heat transfer experiments is given in this report. A copy of the most recent published paper on the skin friction measurements is attached as an Appendix.

SURFACE PRESSURE MEASUREMENT

As in our previous experiments, a flat plate was used to produce a supersonic equilibrium turbulent boundary layer. This boundary layer interacts with the planar oblique shock generated by a sharp, unswept-leading-edge fin.

Surface pressures were measured at 96 pressure taps which were radially distributed on the flat plate with respect to fin leading edge. This was found to produce sufficiently-detailed data in the interaction region. This radial pressure-tap distribution was based on the theory of quasiconical symmetry of the interaction flowfield, which has been supported by many previous investigators.

A two-channel Scanivalve system was used for scanning the 96 pressure taps during the tunnel running time. The signal from the Scanivalve pressure transducer passed through a low-pass filter, the cutoff frequency of which was 30 Hz, and thence was routed to the data acquisition system (Metrabyte Dash-16 analog-to-digital converter board). The A/D conversion rate of the pressure was 2 kHz, and 15 data points were averaged for each surface pressure. Besides the surface pressure, stagnation pressure, reference static pressure, and stagnation temperature were also measured for the calculation of Reynolds number and Mach number.

The total data-acquisition time for the whole process required about 22.4 seconds. During each scanivalve "step," a dwell-time of about 0.3 seconds was allowed to elapse before data were taken. This dwell-time was checked and proved to be sufficiently long to allow the pressure in the pressure tubes to equilibrate.

Weak-to-strong swept interaction cases were tested over a broad range (from Mach 2.5, fin angle = 6 deg. to Mach 4, fin angle = 22 deg.).

Since the wind tunnel stagnation pressure is slightly decreasing during the data acquisition process, each measured surface pressure was normalized by the stagnation pressure measured at the same instant. A weak streamwise pressure gradient which existed on the flat plate with no fin in place (presumed due to weak reflecting waves in test section) has been removed from the data, and the final surface pressure distributions for four cases tested are tabulated in Table 1.

The validity of the current pressure measurement was roughly checked by comparing the local peak pressure ratio calculated from the four measurements with the correlation equation suggested by J. R. Hayes AFFDL TR 77-10). It was found that a good agreement occurred between our measured peak pressures and the Hayes correlation. Also an extensive error estimate was carried out, taking into account electric noise, repeatability, and calibration uncertainty. The detailed analysis of these surface pressure data is under way and will be available soon.

HEAT TRANSFER MEASUREMENT

Basis for the Measurements

The thermal investigation of complicated shock wave/turbulent boundary-layer interactions involves many difficult problems. One of these is the fact that many conventional heat transfer measurement techniques cannot be directly applied to tests in near-adiabatic wind tunnel facilities. Also, to measure high spatial resolution steady-state heat transfer coefficient distributions and high-frequency fluctuating temperature variations in fin interactions (which is current purpose of this study), the development of a new measurement technique was needed.

Recent heat transfer measurement using advanced multi-layered thin-film gauges were carried out at MIT and in Japan. However, these multi-layered heat transfer gauges were found to be very difficult and time-consuming to fabricate, and needed to be handled with extreme care.

An entirely new type of technique which can provide qualitative local heat transfer coefficient distributions has been developed and reported in the literature (Refs. 2-5). This method uses a thin foil heater to generate a uniform heat flux over the surface of interest and a liquid-crystal-coated sheet to sense the local surface temperatures. The heat convection equation is then used to calculate the local heat transfer coefficient from the measured surface temperatures and the known heat flux from the heater. However, this method has been used only for relatively low-speed flow cases, and cannot produce quantitative heat transfer data.

Here we combine these new heat transfer measurement technologies to obtain a high-resolution, high-frequency techniques which works even though the flow is naturally in a near-adiabatic condition. The heated-film concept is used in conjunction with an array of thin-film plated gauges which are fabricated by way of microlithography.

The initial step of this study is to check the validity of the heat transfer technique by comparing the experimental results for the case of the flat plate with no fin in place with the computational calculations. After this, the interaction itself will be primarily studied.

The Design of System Components

The current heat transfer measurement system consists of four parts: the surface temperature sensors, heater element, insulation board, and additional temperature sensors to measure the temperature gradient across the insulation board (see Fig. 1). The heat transfer coefficient can be calculated by dividing the difference between the surface temperature and the adiabatic wall temperature by the heat dissipated through the sensor from the thin foil heater. The exact heat flux through the sensor is obtained by considering both the total heat generation from the heater and the heat loss through the insulation board. The basic equations of the system are also illustrated in Figure 1.

1) Surface Temperature Sensors

A radial distribution of 38 temperature sensors (radius = 3.50 inches from the fin leading edge) on the flat plate was chosen from the symmetry of the fin interaction to maximize the data resolution. Commercially-available temperature sensors cannot be used because they do not have a suitable size and the high frequency response we need, and further have difficulties being installed on our heater without disruption of the flowfield.

Therefore, in this study, thin film resistance-temperature-detector (RTD) sensors deposited on a plastic substrate by vacuum-deposition are being used. Such thin-film temperature sensors, which are being currently manufactured by the NASA-Langley Research Center, have sufficiently-high frequency response and are easy to install on our flat plate.

2) Heater Element

The heat flux from a foil heater can be calculated from the relationship between the electrical resistance of the heater and the current supplied to it. To calculate accurate heat transfer coefficient distributions, it is very important that the heat flux generated by the heating element over the surface is uniform. Several types of heating elements have been checked, and it is believed that the thin foil resistor-type heater is suitable for our purpose. Commercially-manufactured Inconel unetched-foil heater material has been chosen, because the uniformity of heat flux from the heater surface can be quantitatively checked. This calibration method was described by Simomich and Moffat (Ref. 3), where the voltage-drop distribution was measured at specific intervals across the heater surface for a set voltage applied across the two copper bus bars and a given current.

3) Insulation

We need as much heat flux from the heater as possible for a good signal-to-noise ratio. But, since the heat flux from the thin foil heater is limited because of the small resistance of the heating element (Inconel), and since most of the heat flux is dissipated by convection to the high-speed flow in the test section, low-conductivity insulation is important. This insulation should also be rugged against the temperature variation and high shear stress on the surface during the test. "Rexolite" polymer plastic (thickness = 3/16 inches) has been chosen for this purpose.

4) Measurement of dT/dy Across Insulation Board

Fast-response thermocouples are installed on both sides of the insulation board to measure the temperature gradient across the board. The response of these thermocouples is much slower than that of the surface temperature sensors, however. Therefore, the heat loss through insulation board cannot be calculated at the same rate as the surface temperature variation, and the heat convection equation, which is used for the calculation

of heat transfer coefficient, cannot be applied at the same high-frequency rate. For this reason, the possibility of high-frequency-fluctuating heat transfer measurements using this technique remains undecided. But the steady-state heat transfer measurement, which is one key purpose of this study, is possible. The surface temperature variation at high frequency is also measurable.

5) Data Acquisition

For high-speed data acquisition, a LeCroy system is used having an 8-channel, 12-bit waveform recorder with a digitizing and sampling rate of up to 5 Megasamples/sec. Further consideration of signal conditioning (filtering and amplification) is under way.

Plans and Schedule

All components of the heat transfer plate have been fabricated or obtained save the sensors themselves. A first try at fabricating these by NASA-Langley personnel had some minor problems which are now being corrected. It is expected that fabrication will be complete by the end of April, 1990. Calibrations and initial testing will then take place. Initial data from this set of experiments is expected during the Summer of 1990.

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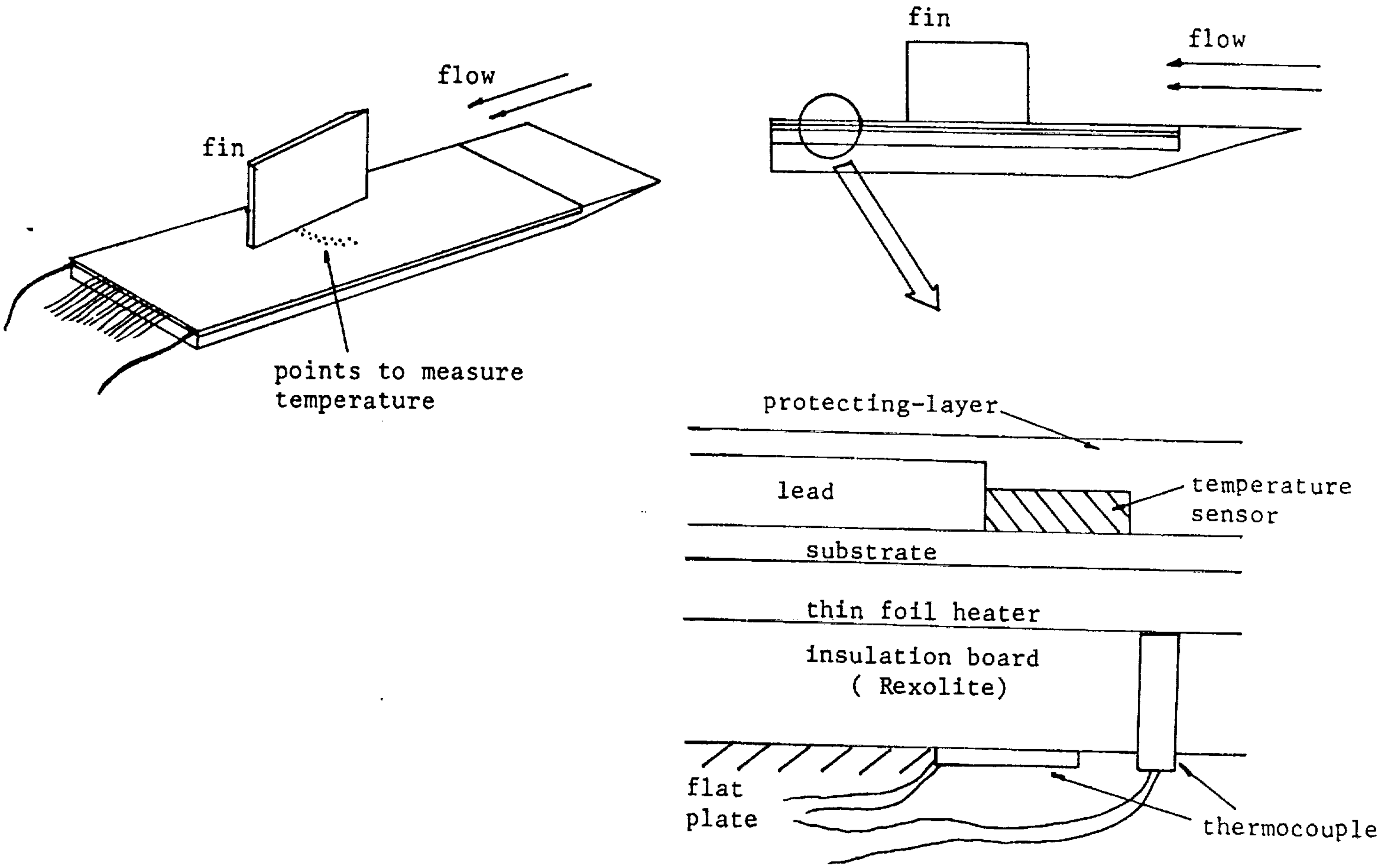
Table 1. Static Pressure (P/Pinf) Data along the Arc, R= 4.0 in.

beta	M = 3.0 alpha=10	M = 3.0 alpha=16	M = 4.0 alpha=16	M = 4.0 alpha=20
14	1.931			
16	1.905			
18	1.844	2.991	4.058	
20	1.708	2.932	4.165	
22	1.608	3.057	3.324	5.050
24	1.517	2.933	2.177	5.534
26	1.476	2.382	1.568	4.804
28	1.456	1.830	1.493	2.520
30	1.463	1.630	1.631	1.579
32	1.405	1.580	1.820	1.508
34	1.310	1.658	1.835	1.742
36	1.190	1.763	1.773	1.862
40	1.006	1.707	1.584	2.005
44	1.005	1.577	1.022	1.878
47.5	0.999	1.183	0.996	1.701
50	1.005	1.009	1.000	1.376
52.5	0.996	1.002	1.000	1.005
56	1.000	1.001	1.000	1.004
58	1.000	0.999	1.000	0.999

Figure 1. The Structure of Heat Transfer Mesurement System and Heat Convection Equation



$$h = \frac{q''_{conv}}{(T_{wall} - T_{adiabatic})}$$

where

$$q''_{conv} = q''_{heater} - q''_{conduction-loss} - q''_{radiation-loss}$$

and

$$q''_{heater} = V \times i = i \times R^2$$

$$q''_{conduction-loss} \sim 0.05 \times q''_{heater}$$

$$q''_{radiation-loss} \sim 0.001 \times q''_{heater}$$