NASA-CR-199368

IN-34-CR
10 CIT
65722
p 7

FINAL GRANT REPORT

NASA LANGLEY GRANT NAG–1–1400

(including Supplements NAG–1–1400–1 & NAG–1–1400–2)

Covering the Period January 1, 1992 to December 31, 1994

TURBULENCE MEASUREMENTS IN HYPERSONIC BOUNDARY LAYERS USING CONSTANT-TEMPERATURE ANEMOMETRY

and

REYNOLDS STRESS MEASUREMENTS IN HYPERSONIC BOUNDARY LAYERS

Prof. Eric F. Spina

DEPARTMENT OF MECHANICAL, AEROSPACE, & MANUFACTURING ENGINEERING
SYRACUSE UNIVERSITY
SYRACUSE, NY 13244

April 1995

(NASA-CR-199368) TURBULENCE MEASUREMENTS IN HYPERSONIC BOUNDARY LAYERS USING CONSTANT-TEMPERATURE ANEMOMETRY AND REYNOLDS STRESS MEASUREMENTS IN HYPERSONIC BOUNDARY LAYERS Final Report, 1 Jan. 1992 - 31 Dec. 1994 (Syracuse Univ.) 7 p

N96-12970

Unclas

G3/34 0065722

The research performed under the subject NASA Langley Grants (NAG-1-1400 & NAG-1-1400-2) began during Summer 1991 when the principal investigator (PI) served as a NASA/ASEE Summer Faculty Fellow in the Experimental Flow Physics Branch. At this time a strong collaborative research relationship was developed between Catherine B. McGinley (a NASA research engineer) and the PI. Quite simply, any progress that has been made on this research grant would not have been possible without Ms. McGinley's technical excellence, dedication, hard work, and co-mentorship of my graduate students. While the grants have been completed, the research has continued and several more papers are expected to be submitted to conferences and journals.

I. SCOPE OF THE PROJECT

The primary objective in the two research investigations performed under NASA Langley sponsorship (*Turbulence measurements in hypersonic boundary layers using constant-temperature anemometry* and *Reynolds stress measurements in hypersonic boundary layers*) has been to increase the understanding of the physics of hypersonic turbulent boundary layers. The study began with an extension of constant-temperature thermal anemometry techniques to a Mach 11 helium flow, including careful examinations of hot-wire construction techniques, system response, and system calibration. This was followed by the application of these techniques to the exploration of a Mach 11 helium turbulent boundary layer ($T_0 \sim 290\ K$). The data that was acquired over the course of more than two years consists of instantaneous streamwise mass flux measurements at a frequency response of about 500 kHz. The data are of exceptional quality in both the time and frequency domain and possess a high degree of repeatability. The data analysis that has been performed to date has added significantly to the body of knowledge on hypersonic turbulence, and the data reduction is continuing. An attempt was then made to extend these thermal anemometry techniques to higher enthalpy flows, starting with a Mach 6 air flow with a stagnation temperature just above that needed to prevent liquefaction ($T_0 \sim 475\ F$). Conventional hot-*wire* anemometry proved to be inadequate for the selected high-temperature, high dynamic pressure flow, with frequent wire breakage and poor system frequency response. The use of hot-*film* anemometry has since been investigated for these higher-enthalpy, severe environment flows. The difficulty with using hot-film probes for dynamic (turbulence) measurements is associated with construction limitations and conduction of heat into the film substrate. Work continues under a NASA GSRP grant on the development of a hot-film probe that overcomes these shortcomings for hypersonic flows. Each of the research tasks performed during the NASA Langley research grants is discussed separately below.

1. Testing of Constant-Temperature Anemometry in Hypersonic Flow

The application of constant-temperature thermal anemometry to hypersonic boundary layers was reviewed and extended in this research task[1]. The use of *constant-temperature* anemometry runs contrary to the traditional use of constant-current anemometry (CCA) in hypersonic flows. The pioneering research on supersonic turbulence in the 1950's was performed exclusively with constant-current anemometers because of the simplicity of the electronic circuit. In particular, the frequency response of the CCA system is maintained with an R–C compensation unit, as compared to the feedback control system needed for constant-temperature operation. The high-bandwidth, high-gain, low-noise amplifiers needed to produce stable constant-temperature circuits have been available only for the past fifteen years. Automatic compensation for the thermal inertia of the wire is the main advantage of the CTA system over constant-current operation, where the compensation must be set manually.

There are applications where constant-current operation is still preferred over the constant-temperature mode, however. The anemometer output in high-speed flows is sensitive both to stagnation-temperature fluctuations and to mass-flux fluctuations. At low overheat ratio (wire temperatures scarcely above T_0), a hot-wire anemometer is primarily sensitive to T_0', while it is primarily sensitive to $(\rho u)'$ at higher overheat ratio. Anemometer response to T_0' is highly non-linear at low overheat, and the very large gain needed in the CTA feedback loop can create stability problems. The constant-temperature system is thus a poor choice to make T_0' measurements, and CCA systems are preferred in such applications. On the other hand, when an anemometer is operated at high overheat ratio ($\tau \approx 1$), the contribution of T_0' to the anemometer output can be neglected (Smits *et al.*, *Experiments in Fluids* 1983). If the measurement of mass-flux fluctuations is the primary goal of the experiment, constant-temperature operation is preferred because of the automatic compensation of the hot wire. Furthermore, operation at high overheat avoids the need to make measurements at numerous overheat ratios, and instantaneous mass-flux can be measured. High-overheat operation has been utilized exclusively in this investigation, and instantaneous mass flux has been the measurement objective.

A review of heat-transfer issues in supersonic anemometry indicated that most relevant problems have been resolved, even in the slip-flow regime encountered in most hypersonic flows. The Mach-number independence of the flowfield around the blunt wire simplifies the heat-transfer relation significantly. For example, both the recovery factor and the *Nu–Re* slope are exclusive functions of the Knudsen number when the Mach number is greater than about 2. As a result, excellent empirical correlations exist for both of these important parameters, with well-defined asymptotes in the limits of continuum and free-molecular flow. While there was some confusion in the 1960's as to which temperature

---

[1] For a summary of this research task, see Spina, E.F. and McGinley, C.B., "Constant-temperature anemometry in hypersonic flow — critical issues and recent results," *Experiments in Fluids*, **17**, pp. 365-374, 1994.

properly characterizes the heat transfer in the supersonic flow–field, the stagnation value is clearly preferred as the temperature at which to evaluate fluid properties. One issue that would benefit from further analysis is the effect of overheat ratio on the heat–transfer relation. Three researchers have now examined this effect, and no clear Mach–number, Knudsen–number, or Reynolds–number trend exists. Furthermore, there does not even appear to be a satisfactory flow model to explain the variation of the Nu–Re correlation with temperature loading of the wire. The understanding of this issue and the entire heat–transfer problem would be enhanced by a CFD solution of the flowfield around a heated cylinder placed in a supersonic stream.

Measurements in the freestream of a Mach 11 helium flow have shown that constant-temperature anemometry can successfully be applied to hypersonic flows. Modern electronics have greatly improved the CTA frequency response, and the hot–wire response at Mach 11 reached as high as 600 kHz (which was somewhat greater than the spectra roll–off frequencies). The calibration of the hot wires for mass–flux sensitivity produced heat–transfer correlations in terms of the Nusselt and Reynolds number that agreed with previous results from constant–current anemometers. Recovery factor, Reynolds-number exponent, and the non-linear dependence of the Nu–Re relation on stagnation temperature were all quantified for the Mach 11 helium flow.

2. Hypersonic Boundary Layer Flow Physics Measurements

The objective in this research task was to apply CTA hot wires to a relatively benign hypersonic boundary layer flow to obtain information on turbulence characteristics at high Mach number[2]. Hot-wire measurements were taken in a Mach 11 helium boundary at two Reynolds numbers and a stagnation temperature of about 290 K. The majority of these measurements were acquired and reduced by Catherine McGinley, with collaborative analysis and interpretation.

Continuous turbulence measurements were made in a hypersonic helium boundary layer. The turbulence measurements were made using constant–temperature anemometry, and the frequency response was maintained at a value greater than $10U_e/\delta$. The resulting wide–band power spectral density distributions are smooth and highly repeatable. The rms of the mass–flux fluctuations reached as high as 60% of the local mean in the center of the boundary layer. The instantaneous mass–flux signals illustrate that the intermittency extends very deep into the boundary layer. Data taken at two different Reynolds numbers indicate the possible presence of a Reynolds–number effect in the lower half of the boundary

---

[2] For a summary of this research task, see McGinley, C.B., Spina, E.F., and Sheplak, M., "Turbulence measurements in a Mach 11 helium boundary layer," AIAA Paper 94-2364, presented at the 25th AIAA Fluid Dynamics Conference, Colorado Springs, CO, June 1994.

layer in all of the turbulence statistics examined. Furthermore, the higher–order moments of the fluctuations exhibited clear differences when compared to subsonic and supersonic data.

3. Extension to Mach 6 Air Measurements

An attempt was made to extend the constant-temperature hot-wire anemometry techniques to a higher temperature flow, namely a Mach 6 air flow with $T_0 \sim 475\ F$. The combination of high-overheat operation and the relatively low oxidation temperature of tungsten necessitated the use of a platinum alloy, platinum–rhodium, which has a considerably lower tensile strength. As a result, wire breakage was frequent, and it was not possible to obtain a full boundary-layer profile.

Survivability of the 5 μm platinum–rhodium wire in the freestream was demonstrated at a stagnation pressure of $69 \times 10^5\ N/m^2$, although the wires had to be mounted with considerable slack to prevent breakage. The hot wires were calibrated in the freestream and then lowered into the boundary layer, where their rate of survival greatly decreased. Of equal concern was a frequency response lower than that observed at Mach 11, and the severe (electro-mechanical) strain gauging of the system.

4. Development of a Microsensor Hot-Film Probe

Upon the failure to extend hot-wire anemometry to moderate-enthalpy Mach 6 air flows, development of a hot-film probe began as a robust technique for making turbulence measurements in severe flows. This study began as part of NAG–1–1400–2, but has been funded separately by a NASA-Langley GSRP grant for the past two years[3].

The hot-film probe that has been developed represents an advancement of an existing concept. Optimization for hypersonic flow is achieved through sensor placement, the use of high-temperature materials, and state-of-the-art microphotolithographic fabrication techniques. The constant-temperature micro-sensor hot-film anemometer is a promising new instrument for making effectively continuous *qualitative* turbulence or transition measurements in moderate enthalpy hypersonic flows. The probe has displayed excellent durability in flow environments (Mach 6 air, $p_0 = 68\ atm$) in which hot wires did not survive. Furthermore, the maximum frequency response of the probe represents a significant improvement over previous designs, reaching as high as 800 kHz. This is essential since a Mach 6 air boundary layer with $Re_\theta \approx 6000$ has significant energy content above 100 kHz. The obstacle preventing *quantitative* measurements is the characterization of the effect of

---

[3] For the current state of this research task, see Sheplak, M., Spina, E.F., and McGinley, C.B., "Dynamic characterization of a hot-film probe for hypersonic flow," AIAA Paper 95–6110, presented at the AIAA 6th International Aerospace Plane and Hypersonic Technologies Conference, Chattanooga, TN, April 1995.

the substrate on the static and dynamic sensitivity of the system. Current plans include testing of hot-film substrate materials with lower values of thermal conductivity. In addition, several dynamic calibration techniques are currently being pursued in an attempt to estimate the transfer function of the probe in various flow environments.

II. GRADUATE STUDENT SUPPORT

One graduate student, Mr. Mark Sheplak, was appointed as a research assistant on the NASA Langley grants. Most recently, Mr. Sheplak has been a NASA GSRP Fellow (since July 1993), and he has been in-residence at NASA Langley for 2.5 years beginning in June 1992. Mr. Sheplak is in the process of writing his dissertation on the development and testing of a hot-film probe for hypersonic turbulence measurements. The NASA grants and the GSRP fellowship have allowed him to utilize unique national hypersonic facilities and micro-electronic fabrication capabilities.

III. RESULTING PUBLICATIONS

The citations of the published abstracts, conference papers, and journal papers that have benefited from NASA support during the period of these two grants follow:

1.) Sheplak, M., Spina, E.F., and McGinley, C.B., "Progress in hot-film anemometry for hypersonic flow," under review by *Experiments in Thermal and Fluid Science*, 1995.

2.) Spina, E.F. and McGinley, C.B., "Constant-temperature anemometry in hypersonic flow — critical issues and recent results," *Experiments in Fluids*, **17**, pp. 365-374, 1994.

3.) Spina, E.F., Smits, A.J., and Robinson, S.K., "The physics of supersonic turbulent boundary layers," *Annual Review of Fluid Mechanics*, **26**, pp. 287-319, 1994.

4.) Sheplak, M., Spina, E.F., and McGinley, C.B., "Dynamic characterization of a hot-film probe for hypersonic flow," AIAA Paper 95–6110, presented at the AIAA 6th International Aerospace Plane and Hypersonic Technologies Conference, Chattanooga, TN, April 1995.

5.) Sheplak, M., Spina, E.F., and McGinley, C.B., "Hot-film anemometry in hypersonic flow," AIAA Paper 94-2232, presented at the 25th AIAA Fluid Dynamics Conference, Colorado Springs, CO, June 1994.

6.) McGinley, C.B., Spina, E.F., and Sheplak, M., "Turbulence measurements in a Mach 11 helium boundary layer," AIAA Paper 94-2364, presented at the 25th AIAA Fluid Dynamics Conference, Colorado Springs, CO, June 1994.

7.) Spina, E.F. and McGinley, C.B., "Constant-temperature anemometry in hypersonic flow — critical issues and sample results," invited paper presented at the *Third International Symposium on Thermal Anemometry*, held at the ASME Fluids Engineering Division Meeting, Washington, D.C., June 1993.

8.) Sheplak, M., Spina, E.F., McGinley, C.B., and Kegerise, M.A., "Dynamic characterization of a hot-film probe for hypersonic turbulence measurements," Forty-Seventh Annual Meeting of APS Division of Fluid Dynamics, Atlanta, GA, November 1994.

9.) Sheplak, M., McGinley, C.B., and Spina, E.F., "A microsensor hot-film probe for hypersonic flow," Forty-Sixth Annual Meeting of APS Division of Fluid Dynamics, Albuquerque, NM, November 1993.

10.) McGinley, C.B. and Spina, E.F., "Hypersonic constant-temperature anemometry," Forty-Fourth Annual Meeting of APS Division of Fluid Dynamics, Tempe, AZ, November 1991.

In addition, at least two additional journal papers and one conference paper are in preparation.