Cryogenic Tunnel Measurement of Total Temperature and Pressure

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A newly developed, 3-mm-diam. dual hot-wire aspirating probe was used to measure the time-resolved stagnation temperature and pressure in a transonic cryogenic wind tunnel. Measurements were taken in the freestream of the settling chamber and test section. Data were also obtained in the unsteady wake shed from an airfoil oscillating at 5 Hz. The investigation revealed the presence of large fluctuations in the settling chamber occurring at the blade passing frequency of the driving fan of the tunnel. These fluctuations decrease at the test section. The rms value of the fluctuating stagnation pressure decreased from 17.5% in the settling chamber to 3.7% in the test section. Fluctuating stagnation temperature decreased from 12.3% to 8.4%. Measurements in the wake of the oscillating airfoil showed a fluctuating stagnation temperature of as much as 42K in rms value.

Nomenclature

A = area
A_c = channel area at hot-wire plane
a = hot-wire calibration constant
C_p = specific heat at constant pressure
d = hot-wire diameter
k = fluid thermal conductivity
k_w = thermal conductivity of wire
ℓ = wire length
m = hot-wire calibration constant
Nu = Nusselt number
P = pressure
Q_c = conductive heat loss at hot-wire ends
R = gas constant, resistance
R_a = hot-wire resistance at room temperature
R_s = bridge resistance in series with hot wire
r = recovery factor
t = time
T = temperature
V = voltage
v = specific volume
Z = compressibility factor
γ = ratio of specific heats
μ = fluid viscosity
ρ = density

Subscripts

T = stagnation condition
w = hot wire
∞ = freestream condition

Superscripts

$( )^*$ = choked condition

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Introduction

THE present worldwide economic situation has placed on the aircraft industry a severe problem that requires the development of more fuel-efficient aircraft. Wind tunnel testing is necessary to investigate methods for improving aircraft efficiency. Although good progress has been made recently in computational fluid dynamics, many complex three-dimensional flows cannot yet be adequately dealt with analytically. For the near future, it appears that theoretical solutions obtained with the powerful new computers must have experimental measurements to support and guide their calculations.

The requirements to simulate full-scale flight Reynolds numbers in wind tunnels have prompted an effort to develop transonic wind tunnels with very high unit Reynolds numbers. The recent development and application of cryogenic wind tunnels represent a major advance in aerodynamic testing technology. The principal advantage of cryogenic tunnels is the ability to achieve full-scale values of Reynolds numbers in tunnels of moderate size at reasonable values of operating pressure. A very important secondary advantage to the aerodynamicist is the ability to vary temperature, pressure, and speed independently, enabling separation of the effects of Reynolds number, aeroelasticity, and Mach number in a cryogenic tunnel capable of operating over a range of pressures.[1]

Transonic cryogenic wind tunnels are by their very nature complex and sophisticated experimental tools. An assumption basic to wind tunnel testing is that a moving medium approaching a stationary aircraft (the wind tunnel case) is equivalent to the aircraft traveling through stationary medium (the free-flight case). Thus, the accuracy of free-flight simulation depends on the quality of the flow in the test section.[2]

Recently, much emphasis has been placed on turbulence and noise in transonic facilities. Experiments have shown that these tunnel disturbances may significantly influence boundary-layer transition and the character of buffet onset.[3] It is necessary to be able to measure the conditions in a given test section to ensure that consistent, smooth, uniform flow can be achieved. Of particular interest are the detailed time-resolved measurements of stagnation temperature and pressure as a function of location.

Time-resolved measurement of gas total (stagnation) temperature has always been a difficult task. Conventional thermocouples lose frequency response above 1 kHz while compensated thermocouples have yet to be successfully demonstrated. More complex schemes using multiple constant temperature hot wires have been demonstrated in low-speed, incompressible flowfields.[4] These techniques are not easily extendable to high-dynamic-pressure, high-speed compressible flows such as those found in transonic cryogenic wind tunnel testing. There are several reasons for this. First, for a given probe, the heat transfer from a heated wire orientated normal to the flow is a function of three fluid variables: velocity, density, and total temperature. This makes the calibration of the hot-wire probe very time-consuming. Also, since the heat transfer from the hot wire is a function of the combined effect of three fluid variables, it is difficult to separate the individual effects of these variables. Finally, the dynamic pressure is high and wire breakage can be excessive due to aerodynamic loads on the wire.[5]

The purpose of this paper is to describe the time-resolved measurements of stagnation temperature and pressure in a transonic cryogenic wind tunnel using a newly developed aspirating probe. The probe was originally developed to make time-resolved measurements in a transonic compressor stage[6] and is now being adapted to a high-dynamic-pressure, transonic cryogenic wind tunnel. The experiment was performed in the NASA Langley Research Center 0.3-m transonic cryogenic tunnel. Measurements of time-resolved stagnation temperature and pressure were taken in the unsteady wake shed from an oscillating airfoil. Turbulence intensity in the freestream of the settling chamber and the test section was also measured. Data acquired from the experiment will be presented and discussed in the following sections.

Experimental Background

The 0.3-m transonic cryogenic tunnel at NASA-Langley Research Center is a fan-driven, closed-circuit wind tunnel using nitrogen as the working fluid.[1] The injection of liquid nitrogen into the tunnel circuit, just downstream of the test section, allows cryogenic total temperatures to be obtained. For steady operating conditions the heat of compression of the fan is removed by the injection of liquid nitrogen. Under equilibrium conditions the excess mass is removed from the circuit through an exhaust system located just upstream of the settling chamber. The test section is 0.203 m (8 in.) wide and 0.610 m (24 in.) high with slots in the floor and ceiling.

A new instrument was developed to make direct, quantitative, time-resolved measurements of the fluid temperature and pressure in the tunnel. This is the dual-wire aspirating probe shown in Fig. 1. It consists of two coplanar constant temperature hot wires at different overheat ratios operated in a 1.5-mm-diam channel with a choked exit so that the flow past the wires is at constant Mach number (0.2). Thus, the mass flux by the wires is a function only of freestream total temperature and pressure and is not otherwise affected by changes in freestream velocity or density. The hot wires are operated in two separate constant temperature anemometer circuits yielding two independent measurements from which the two unknowns, freestream stagnation temperature and pressure, can be uniquely determined. No electronic compensation or foreknowledge of the mean flow characteristics is required. Also, the diffusion of the flow in the channel reduces the dynamic structural load on the wires. At typical operating conditions for transonic cryogenic tunnels, such as the National Transonic Facility, the dynamic drag can be reduced by a factor of 13. For the unsteady wake experiment (to be described later in this section) in the 0.3-m transonic cryogenic tunnel (TCT), the hot wires lasted for more than 10 h at a freestream Mach number of 0.7, stagnation pressure of 5 atm, and stagnation temperature of 98 K, thus proving the ruggedness of the aspirating probe. The probe's angular response is ±20 deg for a 1% change while its frequency response extends past 20 kHz. Further details of the dual-wire aspirating probe's construction and calibration can be found in Ref. 7.

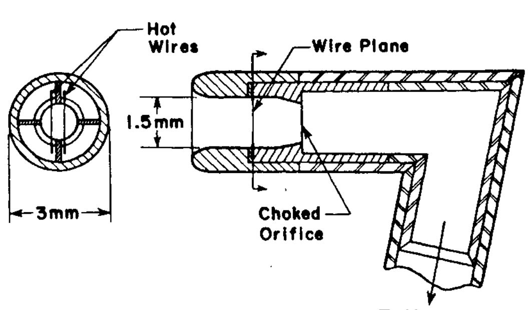


Fig. 1 Dual-wire aspirating probe geometry.

The dual-wire aspirating probe was first calibrated in the settling chamber of the tunnel. The probe was mounted to the inside of the settling chamber using a plug contoured into the inside surface of the 1.219-m (4-ft) diam settling chamber. The probe was located downstream of the three damping screens and was calibrated for stagnation pressure from 1.2-4.9 atm and stagnation temperature from 98-250 K. A functional relationship of the form[7]

$$V^2 = \frac{(R_s + R_w)^2}{R_w} \times \pi \ell k \left\{ a \left[\frac{d}{\mu} \frac{P_T}{\sqrt{T_T}} \frac{A^*}{A_c} \frac{\sqrt{\gamma}}{R} \left(\frac{2}{\gamma+1} \right)^{(\gamma+1)/2(\gamma-1)} \right]^m \right\} \times (T_w - rT_T) + Q_c \tag{1}$$

can be fit to the measured voltage vs pressure at different freestream temperatures, and the empirical constants a and m can be derived. The procedure uses all available data points and minimizes the error between the correlation using Eq. (1) and the calibration. A typical wire calibration is shown in Fig. 2. Because the range of temperature in the tunnel is large (288-98 K), the lead resistance change due to temperature cannot be neglected. This is incorporated in the determination of the calibration constants a and m by accounting for the lead wire resistance change in Eq. (1). The ratio of the conductive heat loss (Q_c) to the convective heat transfer to fluid can be estimated using[8]

$$\frac{d}{\ell} \cdot \frac{1}{\sqrt{Nu}} \left(\frac{R_a}{R_w} \cdot \frac{k_w}{k} \right)^{1/2} \tag{2}$$

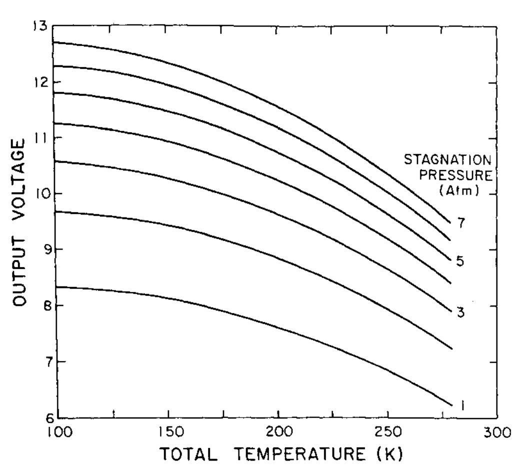


Fig. 2 Typical aspirating probe wire calibration in nitrogen gas.

Conductive heat loss from the wire to the probe support is typically 12% of the total energy input to maintain the wire at constant temperature. It is found from Eq. (2) that the heat loss by conduction at the wire ends remains relatively constant over the entire operating range of the tunnel. Typically, the wire operating resistance R_w is 5 Ω and the series resistance R_s is 50 Ω. The calibrations for the two wires can be combined to yield the overall probe response as a function of the anemometer bridge voltage for the two wires (Fig. 3).

The correlation using Eq. (1) is used to interpolate between the calibration points obtained in the experiment. This procedure should be more accurate than linear interpolation or any kind of curve-fitting technique. Calibration for each individual wire is still necessary to get accurate measurements.

After the steady-state calibration, the probe was mounted on a traversing rake to survey the unsteady wake from an oscillating airfoil in the test section of the 0.3-m transonic cryogenic tunnel (Fig. 4). The objective of the test was to determine the extent of Reynolds number effects on the oscillating pressure distribution of a supercritical airfoil. The 14%-thick SC(2)0714 airfoil was chosen because of the interior volume available for instrumentation and the quality of the documented data. Measurements were made at each Mach number and Reynolds number in the test section over a range of angles of attack. The airfoil was oscillated over a range of frequencies and amplitudes around a mean angle of attack. For the data to be presented later, the test condition was at a stagnation pressure of 160 kPa, stagnation temperature of 130 K, and freestream Mach number of 0.72.

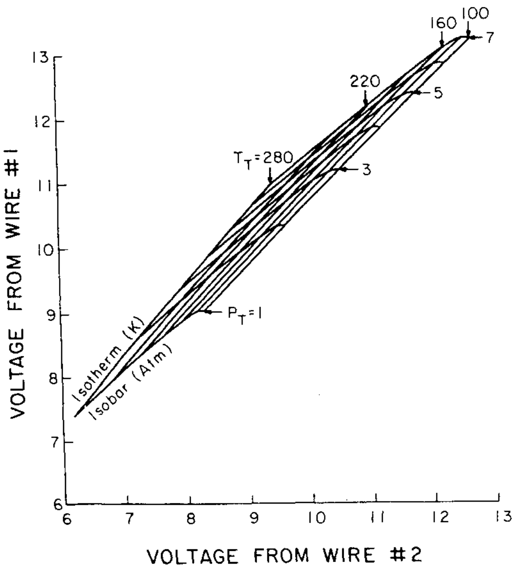


Fig. 3 Dual hot-wire aspirating probe calibration in nitrogen gas.

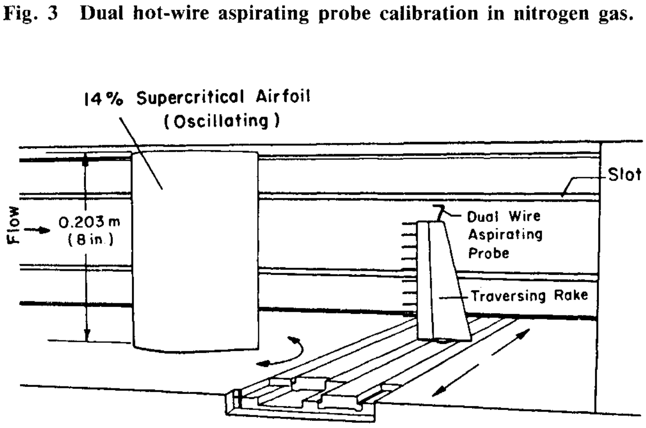


Fig. 4 Mounting arrangement of the aspirating probe in the test section of the tunnel.

The corresponding Reynolds number based on chord length is is 10×10^6.

The temperature and pressure sensitivities of the aspirating probe are set by the difference in temperature between the two wires, but the resolution is limited by the system noise. The anemometer noise level is 2-mV peak-to-peak when the probe is operated in a quiescent atmosphere. When the vacuum pump is turned on and the orifice becomes choked, the anemometer noise level is 20-mV peak-to-peak. This increase in noise level is probably due to flow past the sensor in the channel and is consistent with the tape recorder resolution (20 mV peak-to-peak). An error analysis of Eq. (1) showed that an uncorrelated 20-mV peak-to-peak voltage uncertainty on each wire yields 5.0% and 1.8% uncertainty in stagnation temperature and stagnation pressure, respectively.

The system noise level can be reduced by improving the recording/data-acquisition system and by having a smooth inside wall on the probe inlet. This can reduce the system noise to that of the 2-mV anemometer noise, which corresponds to 0.3% and 0.5% uncertainty in temperature and pressure, respectively.

Data from the probe were recorded on a seven-track wide-band I tape recorder running at 120 and 15 in./s. Commercial anemometers were used in constant temperature mode without linearizers. The output voltages from the aspirating probe were low-pass filtered and were recorded on one head of the recorder to minimize phase shift problems. The analog data were then digitized at a rate of 120,000 samples/s for tape speed of 120 in./s. The data recorded at a tape speed of 15 in./s were digitized at 800 and 22,000 samples/s. The digitized data were then transferred to the computer for data reduction and analysis.

At cryogenic temperatures, nitrogen departs from ideal-gas behavior. The most obvious departure from ideal behavior is the existence of a "saturation boundary" in the P-T plane beyond which a real gas can condense and become a liquid. In addition to having a saturation boundary, both air and nitrogen depart from ideal-gas behavior due to thermal imperfections ($Pv \neq RT$, i.e., $Z \neq 1$) and caloric imperfections (specific heats not constant). However, studies have shown the real-gas effects on the isentropic flow relations to be extremely small, typically less than 0.2%.[9] Thus, even though the values of the compressibility factor Z and the ratio of specific heat γ for nitrogen depart significantly from their ideal-gas values at cryogenic temperatures, the isentropic flow relations used in Eq. (1) are insignificantly affected.

Experimental Observations and Discussion

Settling Chamber and Test Section Comparison

In this section some freestream data collected in the 0.3-m TCT settling chamber and test section are presented. Figure 5 is a comparison of the freestream stagnation pressure measured in the test section and settling chamber. The fluctuating stagnation pressure is much higher in the settling chamber than in the test section. Amplitudes of these fluctuations in rms values are 6 kPa ($P_T/P_{T\infty} = 3.7\%$) in the test section and 28 kPa ($P_T/P_{T\infty} = 17.5\%$) in the settling chamber.

A characterized frequency of about 830 Hz can be seen in Fig. 5 in the settling chamber data. This correlates exactly with the blade passing frequency of the driving fan. A frequency spectrum of the pressure data in Fig. 6 shows a distinct signal of about 830 Hz with second and third harmonics in the settling chamber. The test section frequency spectrum shows no distinct frequency content. The resolution is higher in the test section frequency spectrum than in the settling chamber because the same number of data points were used to perform a fast Fourier transform with data of different sampling rates.

Figure 7 compares test section and settling chamber stagnation temperature fluctuations. Stagnation temperature fluctuations are higher in the settling chamber than in the test section with rms values of 16 K ($T_T/T_{T\infty} = 12.3\%$) in the settling chamber and 11 K ($T_T/T_{T\infty} = 8.4\%$) in the test section. A characterized stagnation temperature fluctuation of about 830 Hz is apparent in the settling chamber, and no distinct fluctuations can be seen in the test section data. Figure 8 is a frequency spectrum of stagnation temperature in the test section and settling chamber. Again, there is an obvious signal at about 830 Hz in the settling chamber, but there are no apparent harmonics. Test section data have no characteristic frequency content.

The relatively high level of disturbance in the freestream of the tunnel can be due to the fact that the tunnel is a closely coupled fan-driven tunnel. Another source of these fluctuations may be due to flow separation in the high-speed diffuser.

The reason for the observed reduction in fluctuating stagnation pressure and temperature going from the settling chamber to the test section is not yet fully known. Kovaszney[10] has found that the disturbances in wind tunnels may be of three modes:

1) Vorticity fluctuations (turbulence).
2) Entropy fluctuations (temperature spottiness).
3) Sound pressure waves.

The vorticity and entropy fluctuations are convected along

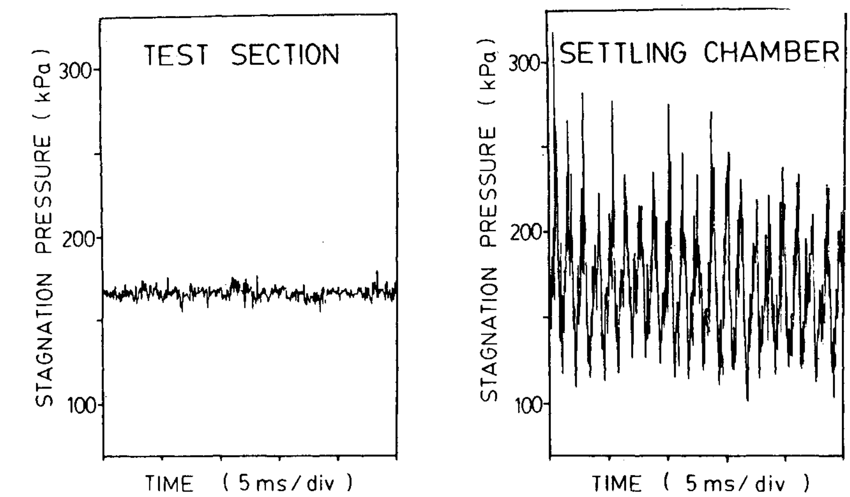


Fig. 5 Computation of test section and settling chamber stagnation pressure.

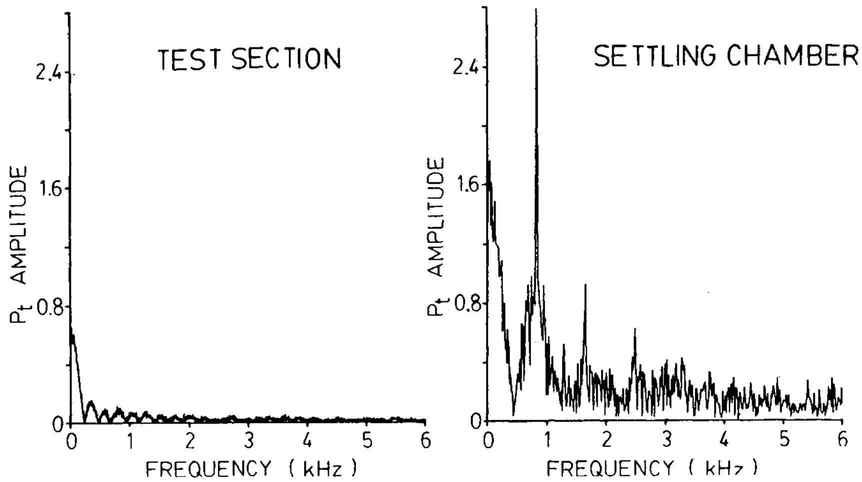


Fig. 6 Frequency spectrum comparison of stagnation pressure.

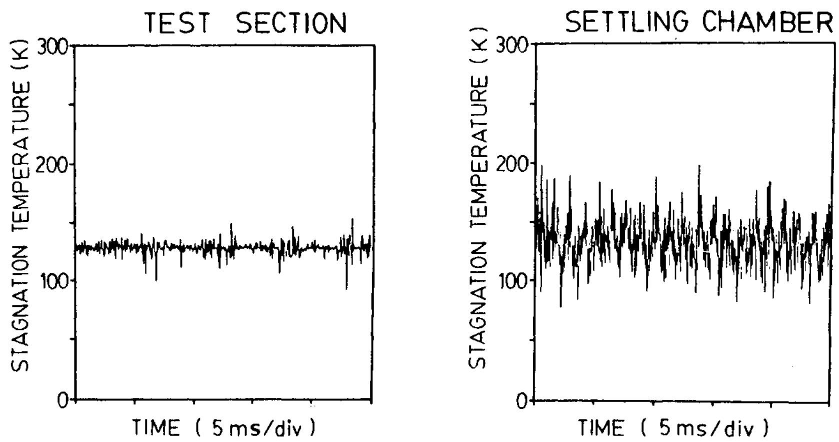


Fig. 7 Comparison of test section and settling chamber stagnation temperature.

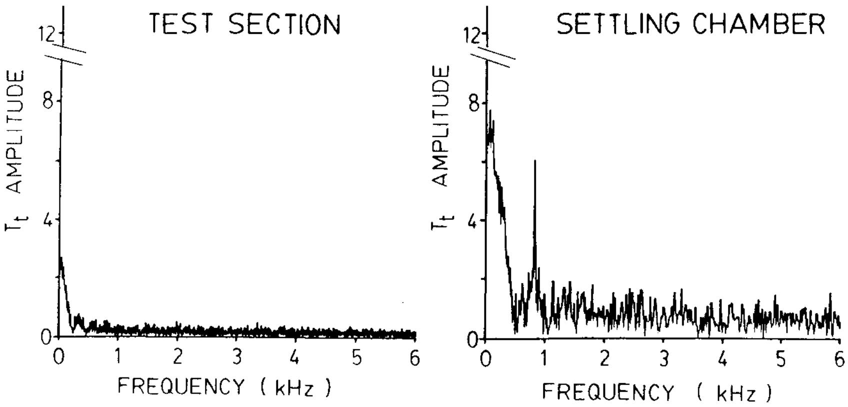
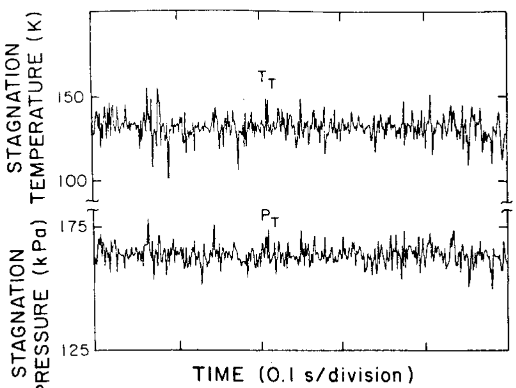
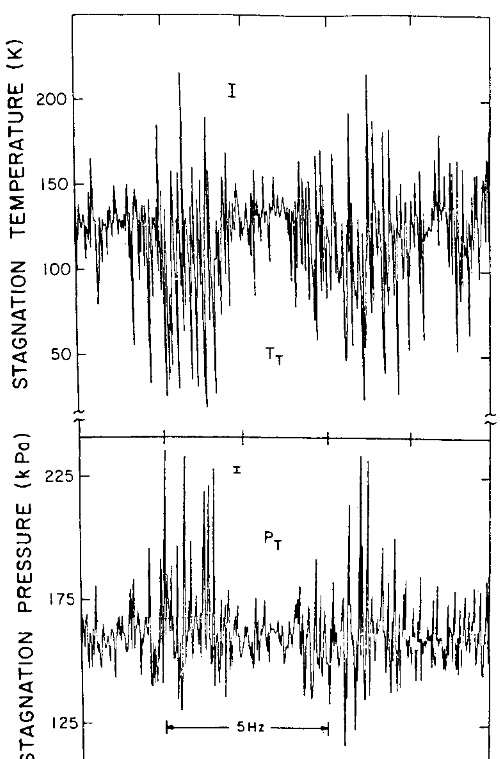


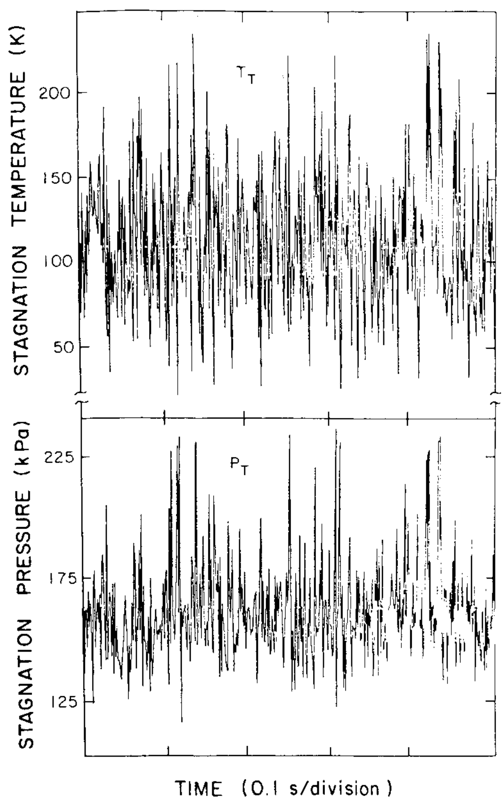
Fig. 8 Frequency spectrum comparison of stagnation temperature.



a) Freestream.



b) Approaching wake centerline.



c) Center of wake.

Fig. 9 Measured stagnation pressure and stagnation temperature.

streamlines and are traceable to conditions in the settling chamber that originate upstream. The sound disturbances can travel across streamlines and may originate either upstream or downstream of the test section or from the test section boundaries. The sound pressure waves travel at the speed of sound of the medium and, hence, may travel upstream.

Kovaszney[10] showed that if the intensities of the fluctuations are small, the three modes are independent. The velocity field can be split into a solenoidal and an irrotational field. The former corresponds to vorticity and the latter to sound waves. The static-pressure fluctuations belong to the sound-wave mode. The density and static-temperature fluctuations are split into an isentropic part that belongs to the sound-wave mode and a nonisentropic part that belongs to the entropy mode. Thus, the vorticity mode contains no static-pressure, static-temperature, or density fluctuations.

It has previously been shown that the velocity, density, and total temperature fluctuations in the 0.3-m TCT test section are mostly broadband with some discrete frequencies between 100 and 1000 Hz.[5] These disturbances were thought to be from upstream-moving sound waves. Also, previous settling chamber pressure measurements show distinct correlation of the blade passing frequency out to eight harmonics of the fundamental, whereas velocity fluctuations are of a much more random nature (no distinct peaks beyond the fourth harmonic). In the present investigation, the aspirating probe measures stagnation pressure and stagnation temperature. It is difficult to determine the effects of each disturbance mode from aspirating probe measurement alone. A future experiment is being planned in which the aspirating probe will be piggybacked with a high-frequency angle probe such that fluctuating velocity components can be measured as well. This may shed some light on the observed phenomenon.

Measurements Behind Oscillating Airfoil

Figure 9 is the measured stagnation pressure and temperature with the dual-wire aspirating probe in the test section of the tunnel. The airfoil is oscillating at a frequency of 5 Hz and at ± 0.75 deg about a mean angle of 1 deg. Figures 9a-c correspond to the probe in the freestream, approaching the centerline of the wake, and at the center of the wake, respectively. The 5-Hz oscillation can be readily seen in Fig. 9b, where the probe is near the centerline of the wake. However, when the probe is right at the center of the wake (Fig. 9c), the 5-Hz oscillation becomes very difficult to identify. Since the probe is about one chord downstream from the trailing edge of the airfoil, turbulent mixing may have hidden the 5-Hz oscillation. In the wake, fluctuating stagnation temperature of 42 K rms was observed. The high fluctuating stagnation may be caused by the unsteadiness due to the vortex shed from the airfoil. It is known that in an unsteady flow, where the static pressure is fluctuating with time, the stagnation temperature following a fluid particle is given by[11]

$$C_P \frac{DT_T}{Dt} = \frac{1}{\rho} \frac{\partial P}{\partial t} \tag{3}$$

where DT_T/Dt is the substantial derivative of stagnation temperature, ρ the fluid density, and C_p the fluid specific heat at constant pressure. Thus, it is possible to have large fluctuation in stagnation temperature in the wake. The data measured can be used as a basis for comparison with unsteady two-dimensional transonic viscous computer code.

Conclusion

A newly developed high-frequency response aspirating probe was used to make time-resolved measurements of stagnation temperature and pressure in a high-dynamic-pressure, transonic cryogenic wind tunnel. The data show a substantial decrease in fluctuating stagnation pressure from the settling chamber (28 kPa, rms) to the test section (6 kPa). The fluctuating stagnation temperature decreases from 16 K in the settling chamber to 11 K in the test section. The measurements in the settling chamber also exhibit a 830-Hz disturbance at the blade passing frequency of the driving fan. Measurements in the wake of the oscillating airfoil show fluctuating stagnation temperature of as much as 42 K in rms value. This high level of fluctuation may be caused by the unsteady static pressure in the wake.

Acknowledgments

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