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CHARACTERIZATION OF PARTICLES IN THE LANGLEY 0.3-METER TRANSONIC CRYOGENIC TUNNEL USING HOT WIRE ANEMOMETRY

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ABSTRACT

Hot-wire anemometry has been used to identify the nature of particles reportedly observed during free stream velocity measurements in the Langley 0.3-meter transonic cryogenic tunnel using a Laser Doppler Velocimeter. Since the heat-transfer process from the hot wire depends on the thermal conductivity and sticking capability of the particles, it was anticipated that the hot-wire anemometer response would be affected differently upon impaction by liquid droplets and solid aerosols in the test gas stream. Based on the measured time response of the hot-wire anemometer in the cryogenic tunnel operated in the 0.3-0.8 Mach number range, it is concluded that the particles impacting the hot wire are liquid in nature rather than solid aerosols. It is further surmised that the liquid aerosols are unevaporated liquid nitrogen droplets used for cooling the tunnel test gas.

INTRODUCTION

In recent Laser Doppler Velocimeter (LDV) studies in the Langley 0.3-meter transonic cryogenic tunnel (TCT), it was noted that strong forward-scattered light signals were observed without injecting particles normally needed for augmenting the existing Mie scattering material in wind tunnels.(1) It was postulated that the existing light scattering particles were unevaporated liquid nitrogen (LN_2) droplets injected to control the tunnel temperature. Apparently, some of the LN_2 droplets did not evaporate completely before entering the test section where LDV measurements were made. These LDV studies were made at tunnel pressures of 1.0-1.5 atmospheres (1 atm = 14.7 psi = 101 kpa), Mach numbers of 0.20-0.77 and total temperatures of 100-250 K.

If the background light scatterers in the tunnel are indeed unevaporated LN_2 droplets, the number of such surviving droplets in the test section is going to increase at higher tunnel pressures and at lower operating temperatures needed for higher Reynolds number aerodynamic studies. A high concentration of LN_2 droplets in the test section might result in wetting the model surface and hence changing its aerodynamic characteristics. It is therefore very

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important that the problem of the nature of the light scattering particles be resolved so that necessary steps may be taken to avoid vitiating the aerodynamic data obtained in the cryogenic tunnels. One of the methods that may help determine whether the light scattering particles observed in the Langley 0.3-meter TCT were liquid droplets or solid particles present in the nitrogen test medium is based on hot-wire anemometry characteristics. Essentially, the operating principle is based on the following arguments: If the light scattering particles present in the test medium are LN_2 droplets, they will tend to stick and cause the hot wire temperature to fall on impact. The solid particles, on the other hand, will tend to scatter off the hot wire. This will result in stressing the wire, thereby raising its resistance and hence the temperature. Thus the observation whether the current increases or decreases through the constant temperature hot-wire anemometer will help determine whether the striking particles are liquid drops or solid dust particles. The idea of using a heated filament to sample liquid particles was first suggested by Vonnegut and Neubauer(2) and later by Goldschmidt.(3) Goldschmidt and Householder(4) later used this principle to size-classify liquid aerosols.

A hot-wire anemometer was located just upstream of the 0.3-meter TCT test section and its output monitored as a function of the tunnel operating parameters. The results of these measurements and their implications in terms of the nature of the particles are discussed in the following sections.

DESCRIPTION OF THE EQUIPMENT

The Langley 0.3-meter TCT was used as the test facility in the present study. It is a continuous flow, fan driven tunnel with nitrogen as the test gas. The test gas is cooled by spraying LN_2 directly into the tunnel circuit. Figure 1 shows a schematic diagram of the tunnel.(5) The hot-wire probe is located just upstream of the test section. Figure 2 shows a schematic diagram of the hot-wire anemometer and associated equipment.

A standard constant temperature hot-wire anemometer was used in the present study. The sensing element was 4 μm diameter filament (platinum-coated tungsten) with an active length of 1.25 mm. The anemometer was located in the tunnel contraction cone just upstream of the test section. The anemometer was located there to avoid frequent wire breakages reported when it was used in the test section.(*) The inside diameter of the tunnel is approximately 1.2 m at the station where the probe is located. The probe was approximately 0.3 m from the tunnel wall. A 50 m cable was used to connect the probe to its associated bridge circuitry and was the limiting factor in the system time response. Overheat was set at approximately 1.4 with the tunnel cold (i.e., 105 K). At this overheat ratio,

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(*) Recently, Stainback et al(6) have reported measurements of velocity, density and total temperature fluctuations in the test section of the 0.3-meter TCT. However, these measurements were made at temperatures well above the condensation thresholds in order to avoid excessive aerodynamic loads associated with solid/liquid particle impacts.

$\Delta T \simeq 95^{o}C$, thus making the wire temperature 200 K. No attempt was made to hold the overheat constant when the tunnel temperature varied. Output of the constant temperature anemometer was monitored on a storage oscilloscope. Photographs of the anemometer response to the "particle" hits were made for permanent record.

The hot-wire anemometer system was calibrated for time response to impulse inputs by applying a low level 3 kHz square wave signal across the anemometer bridge. Response time of the system to the square wave input was about 20 microseconds (see figure 3).

EXPERIMENTAL RESULTS

Hot-wire anemometry measurements were made with a CAST-10 condensation model in the test section for various operating conditions summarized in Table I(a). Free stream Mach numbers in the test chamber ranged from 0.30 to 0.80, the temperature from 80 to 105 K and pressures from 1.2 atm to 5.0 atm. Corresponding values at the location of the hot-wire anemometer were as follows: Free stream Mach numbers 0.030 to 0.060; the temperature ranging from 79.4 K to 105.0 K and the pressures from 1.194 atm to 4.997 atm. These values are listed in Table I(b). As indicated earlier, the anemometer output was monitored on a storage oscilloscope. The oscilloscope was initially set in an automatic triggering mode for recording all anemometer signals. However, it proved to be very tedious to record the rather infrequent transient signals arriving at the oscilloscope. After several tunnel runs, it was decided to use the oscilloscope in the signal-triggering single sweep mode. Since almost all of the transients observed in free running time-base mode were initially positive-going, the single sweep trigger level was set at a positive bias of about twice the anemometer output resulting from carrier stream velocity fluctuations.(*) All subsequent data were recorded with the storage oscilloscope set in this externally-triggered single sweep mode.

The anemometer signals resulting from "particle" strikes are sharper and larger than those associated with carrier stream turbulence and would be the only ones recorded in the storage oscilloscope set in externally-triggered mode. (All signals arriving at the oscilloscope input during the sweep interval would, of course, be recorded once a strong positive-going anemometer signal triggers the oscilloscope.)

(*) Admittedly, positive biasing of the oscilloscope trigger rules out the recording of the negative-going signals expected to be associated with solid aerosols. However, no negative-going signals were observed during several tunnel runs under different operating conditions when the oscilloscope was operated in the free running mode and could accept signals of both polarity. Almost all of the signals observed during those runs were initially positive-going.

Data were recorded for several free stream velocities at each value of total tunnel pressure. Typical anemometer responses are illustrated in figures 4-6. Figure 4 shows anemometer output at a total tunnel pressure of 1.2 atm for test section Mach numbers of 0.6 and 0.8. (The corresponding Mach numbers at the anemometer station are 0.052 and 0.060.) Figure 5 shows the results at a total tunnel pressure of 3.0 atm for test section Mach numbers of 0.30 and 0.49. (The corresponding Mach numbers at the anemometer station are 0.030 and 0.046.) Figure 6 shows the results at 5.0 atm for test section Mach numbers of 0.30 and 0.65. (The corresponding Mach numbers at the anemometer station are 0.030 and 0.055.) It is noted that the anemometer output signals occur at higher temperatures as the carrier stream velocity goes up at all values of tunnel pressure.

DISCUSSION

Ideally, cryogenic tunnels should be operated at the lowest possible temperatures in order to maximize the Reynolds number for a given tunnel pressure. However, the minimum operating temperature is limited by the condensation effects that set in at low temperatures.(7) At low operating temperatures in tunnels using nitrogen as the test gas, one is faced with the possibility of encountering particles in the test section resulting from one or more of the following sources. (1) Dust particles present in the nitrogen test gas; (2) unevaporated LN_2 droplets from the cooling spray; (3) condensation of nitrogen molecules on pre-existing submicron aerosols in the test gas(7), and (4) homogeneous nucleation of N_2- molecules.(8) Particles of the type-1 are largely independent of the tunnel temperature. The remaining three types of particles are strongly temperature dependent--being more likely to exist at lower temperatures. Particles of types 3 and 4 are rather unlikely to occur at temperatures higher than the free stream saturation temperatures. It has been reported(9) that over the 1.2 to 4.5 atm total pressure range, low temperature nucleation effects are not observed until the total temperatures are 2 K or more <u>below</u> the free stream saturation temperatures in the cryogenic wind tunnels using nitrogen as the test gas. This leaves only particles of the types 1 and 2 as the possible candidates above free stream saturation temperatures in the 0.3-meter TCT. Efforts were therefore directed towards distinguishing between these two types of particles on the basis of their hot-wire anemometer responses as indicated earlier.

Table II summarizes the results obtained for several combinations of tunnel operating parameters. From these data, it has been generally noted that the voltage spikes in the anemometer output start appearing at higher temperatures as the tunnel pressure is increased. Similarly, the voltage spikes tend to appear at higher temperatures as the carrier stream velocity is increased at each of the three tunnel pressures tested. It was also observed that the amplitudes of the anemometer spikes were generally much larger at lower temperatures at all pressure levels in the tunnel. These features, coupled with the observations that no anemometer signals were recorded at temperatures much higher than free stream saturation values, suggest that the particles impacting the hot wire in the 0.3-meter TCT must be unevaporated LN_2 droplets. For example, at higher tunnel pressures, more of LN_2 would be needed to cool the tunnel gas to lower temperatures. Consequently, there is a greater chance of some LN_2 droplets surviving up to higher tunnel temperatures. Similarly, higher LN_2 injection rates needed for tunnel operation at higher Mach numbers at a given pressure in the tunnel increase the chances of survival of some of the droplets up to higher temperatures. If these deductions are correct, one would expect the survival chances of LN_2 droplets to be considerably higher at lower temperatures in the tunnel due to reduced evaporation rates. This would result in more numerous, and bigger anemometer signals at lower temperatures at all operating total tunnel pressures/Mach numbers as has indeed been observed.

CONCLUSIONS

It has been observed that particles in the 0.3-meter TCT striking the constant temperature hot-wire anemometer produce cooling of the wire resulting in positive voltage spikes at the anemometer output. These spikes appear at higher temperatures at higher tunnel pressures. At any given tunnel pressure, these voltage spikes tend to appear at higher temperatures as the carrier stream velocity is increased. These features suggest that the particles in the 0.3-meter TCT are unevaporated LN_2 droplets rather than solid aerosols. A further corroboration of this conclusion is provided by the observations that no signals were observed at temperatures much higher than the free stream saturation values and that the amplitude of the voltage spikes at the anemometer output were higher at lower temperatures at all tunnel pressures tested. If solid particles were present in the tunnel circuit, they would, of course, have been observed at all temperatures.

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Table I. Summary of Tunnel Operating Parameters

(a) Test Section

No.	Mach No. (m_∞)	Free Stream Temperature (T_t, K)	Total Pressure $(P_t, \text{atm})^{(*)}$
1	0.30	90.0	1.197
2	0.30	85.0	1.197
3	0.30	80.0	1.197
4	0.30	79.4	1.197
5	0.60	90.0	1.197
6	0.60	85.0	1.197
7	0.62	83.0	1.197
8	0.60	82.0	1.197
9	0.60	81.0	1.197
10.	0.60	80.0	1.197
11	0.70	90.0	1.197
12	0.70	85.0	1.197
13	0.70	83.0	1.197
14	0.70	81.5	1.197
15	0.70	80.0	1.197
16	0.80	95.0	1.197
17	0.80	90.0	1.197
18	0.80	85.0	1.197
19	0.80	84.1	1.197
20	0.80	83.5	1.197
21	0.80	83.0	1.197
22	0.80	82.0	1.197
23	0.80	80.0	1.197
24	0.80	79.0	1.197
25	0.30	100.0	3.000
26	0.30	95.0	3.000
27	0.30	92.0	3.000
28	0.30	90.6	3.000
29	0.30	89.0	3.000
30	0.50	100.0	3.000
31	0.50	95.0	3.000
32	0.49	91.7	3.000
33	0.50	91.0	3.000
34	0.50	90.1	3.000
35	0.50	89.0	3.000
36	0.70	100.0	3.000
37	0.70	95.00	3.000
38	0.70	92.0	3.000
39	0.70	90.5	3.000
40	0.70	89.5	3.000

Table I(a) Continued

No.	Mach No. (m_∞)	Free Stream Temperature (T_t,K)	Total Pressure (P_t,atm)$^{(*)}$
41	0.70	89.0	3.000
42	0.30	105.0	5.000
43	0.30	100.0	5.000
44	0.30	97.5	5.000
45	0.30	96.7	5.000
46	0.30	96.0	5.000
47	0.30	95.9	5.000
48	0.30	95.0	5.000
49	0.30	94.1	5.000
50	0.65	105.0	5.000
51	0.65	100.0	5.000
52	0.65	98.5	5.000
53	0.65	97.3	5.000
54	0.65	97.0	5.000
55	0.65	96.0	5.000
56	0.65	95.5	5.000

(*)1 atm = 14.7 psi = 101 KPa

Table I. Summary of Tunnel Operating Parameters
(b) Hot-Wire Anemometer Location

No.	Mach No. (M_∞)	Free Stream Temperature (T_t,K)	Tunnel Pressure (P_t, atm)*
1	0.030	90.0	1.196
2	0.030	85.0	1.196
3	0.030	80.0	1.196
4	0.030	79.4	1.196
5	0.052	90.0	1.195
6	0.052	85.0	1.195
7	0.053	83.0	1.195
8	0.052	82.0	1.195
9	0.052	81.0	1.195
10	0.052	80.0	1.195
11	0.057	89.9	1.194
12	0.057	85.0	1.194
13	0.057	83.0	1.194
14	0.057	81.5	1.194
15	0.057	80.0	1.194
16	0.060	94.9	1.194
17	0.060	89.9	1.194
18	0.060	84.9	1.194
19	0.060	84.0	1.194
20	0.060	83.4	1.194
21	0.060	82.9	1.194
22	0.060	81.9	1.194
23	0.060	79.9	1.194
24	0.060	78.9	1.194
25	0.030	100.0	2.998
26	0.030	95.0	2.998
27	0.030	92.0	2.998
28	0.030	90.6	2.998
29	0.030	89.0	2.998
30	0.046	100.0	2.996
31	0.046	95.0	2.996
32	0.046	91.7	2.996
33	0.046	91.0	2.996
34	0.046	90.0	2.996
35	0.046	89.0	2.996
36	0.057	99.9	2.993
37	0.057	94.9	2.993
38	0.057	91.9	2.993
39	0.057	90.4	2.993
40	0.057	89.4	2.993

Table I(b) Continued

No.	Mach No. (M_∞)	Free Stream Temperature (T_t, K)	Tunnel Pressure $(P_t, \text{atm})^*$
41	0.057	88.9	2.993
42	0.030	105.0	4.997
43	0.030	100.0	4.997
44	0.030	97.5	4.997
45	0.030	96.7	4.997
46	0.030	96.0	4.997
47	0.030	96.0	4.997
48	0.030	95.0	4.997
49	0.030	94.1	4.997
50	0.055	104.9	4.990
51	0.055	99.9	4.990
52	0.055	98.4	4.990
53	0.055	97.2	4.990
54	0.055	96.9	4.990
55	0.055	95.9	4.990
56	0.056	95.4	4.990

$^{(*)}$1 atm = 14.7 psi = 101 KPa

Table II. Summary of Highest Temperatures at Which the Anemometer Voltage Spikes Were First Observed for Various Values of Total Pressure and Free Stream Mach Numbers

No.	Total Pressure (P_t, atm)$^{(*)}$	Free Stream Mach Number in the Test Section (M_∞)	Total Temperature (T_t,K)$^{(**)}$
1	1.2	0.30	80.0
		0.60	82.0
		0.70	83.0
		0.80	84.1
2	3.0	0.30	90.6
		0.49	91.7
		0.70	91.5
3	5.0	0.30	96.7
		0.65	97.3

(*) 1 atm = 14.7 psi = 101 KPa

(**) No anemometer signals were observed at temperatures higher than those listed here. The solid particles, if present, should have been observed at all temperatures.

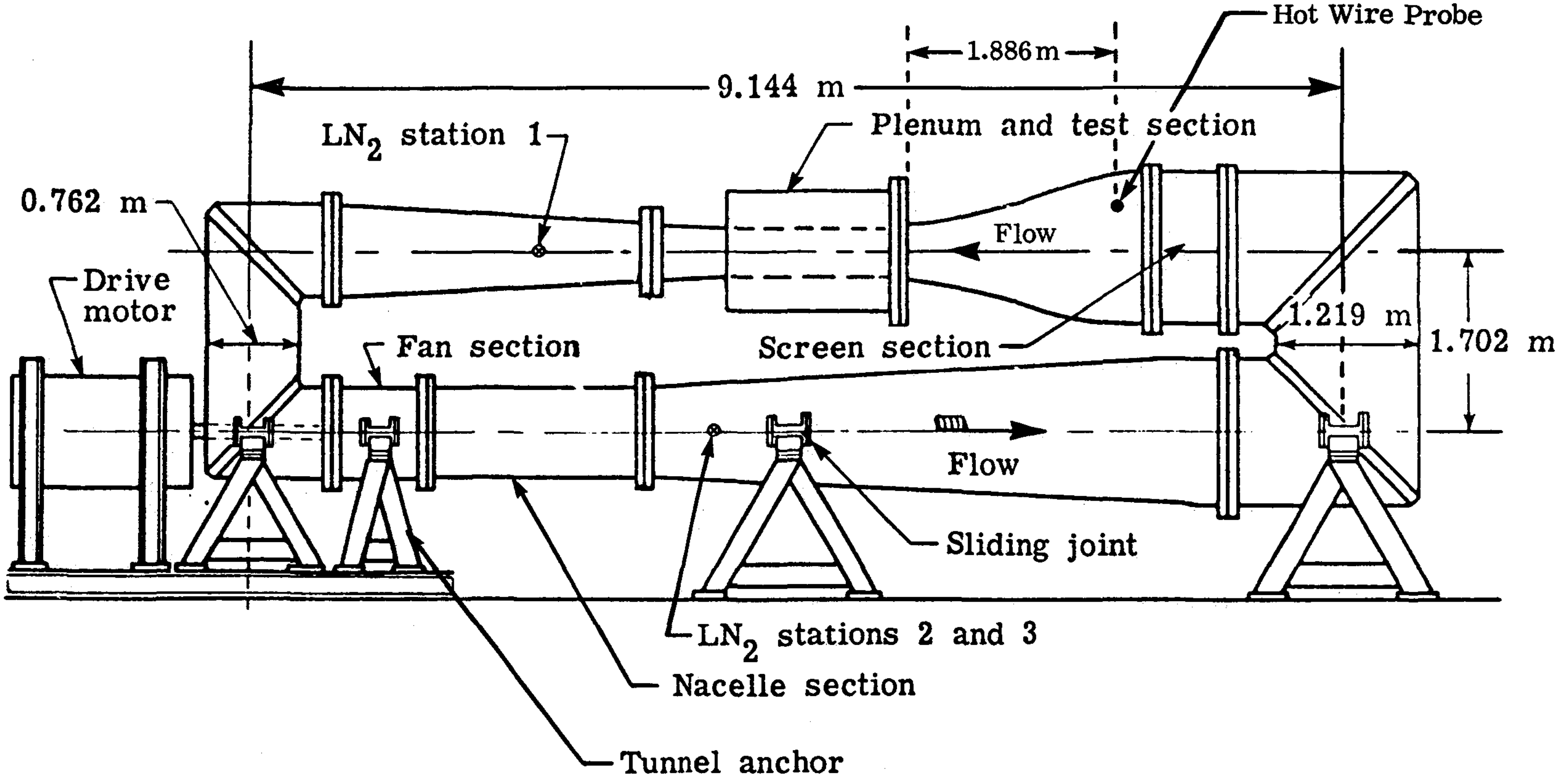


FIGURE I - SCHEMATIC DIAGRAM OF LANGLEY 0.3 METER TRASONIC CRYOGENIC TUNNEL.

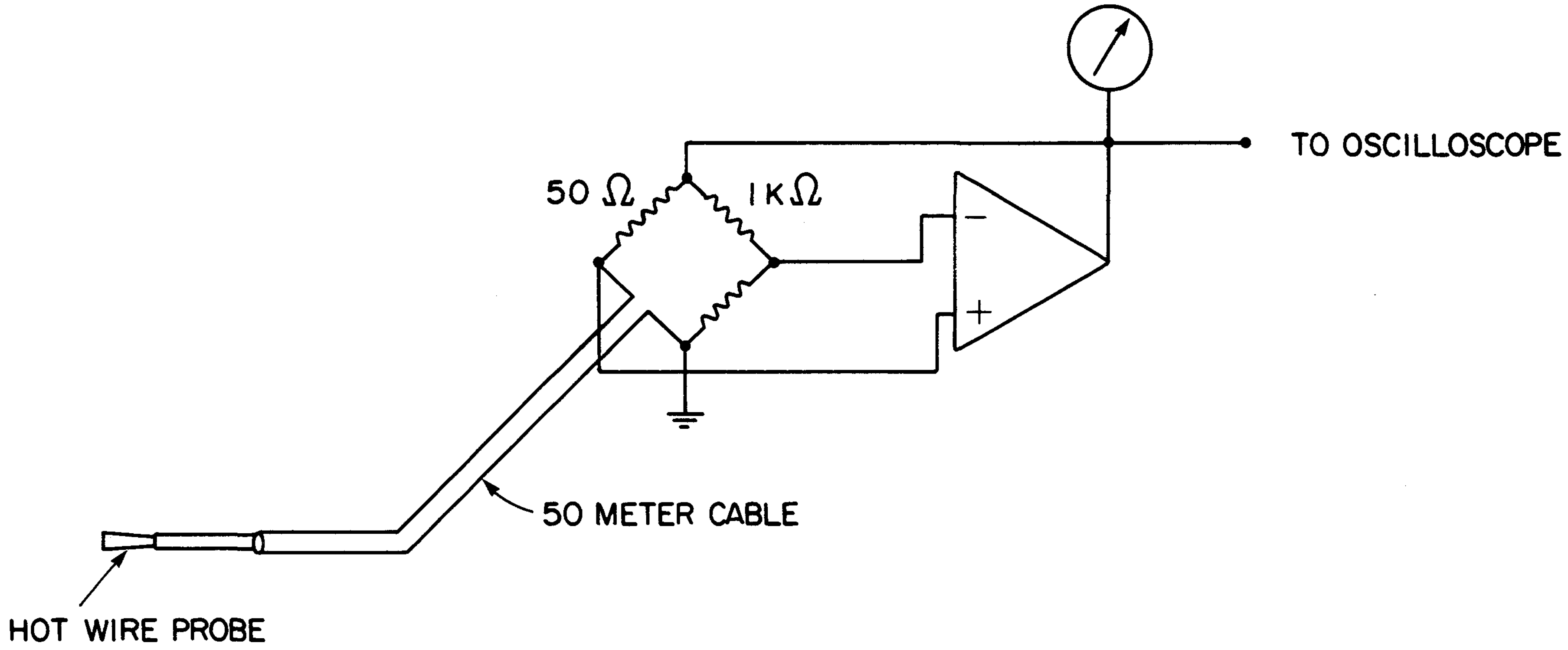


FIGURE 2 - SCHEMATIC DIAGRAM OF THE HOT-WIRE ANEMOMETER AND ASSOCIATED EQUIPMENT.

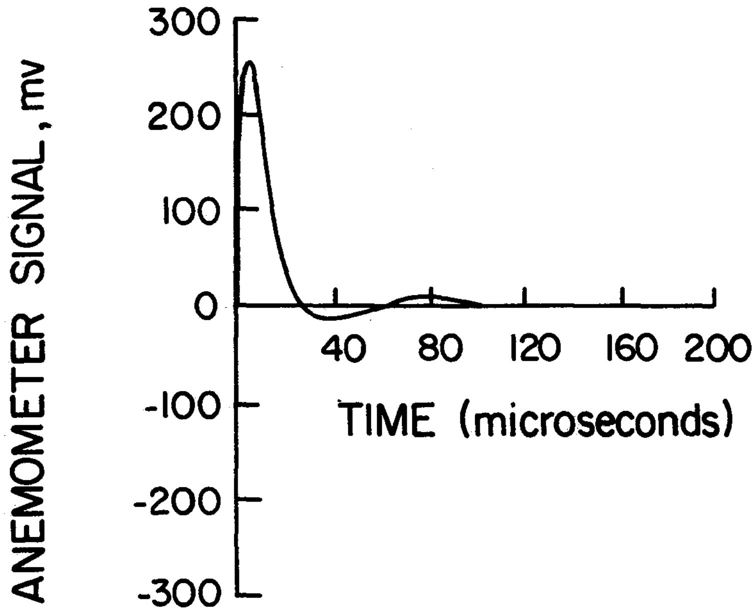


FIGURE 3 - HOT-WIRE ANEMOMETER RESPONSE TO A SQUARE WAVE INPUT.

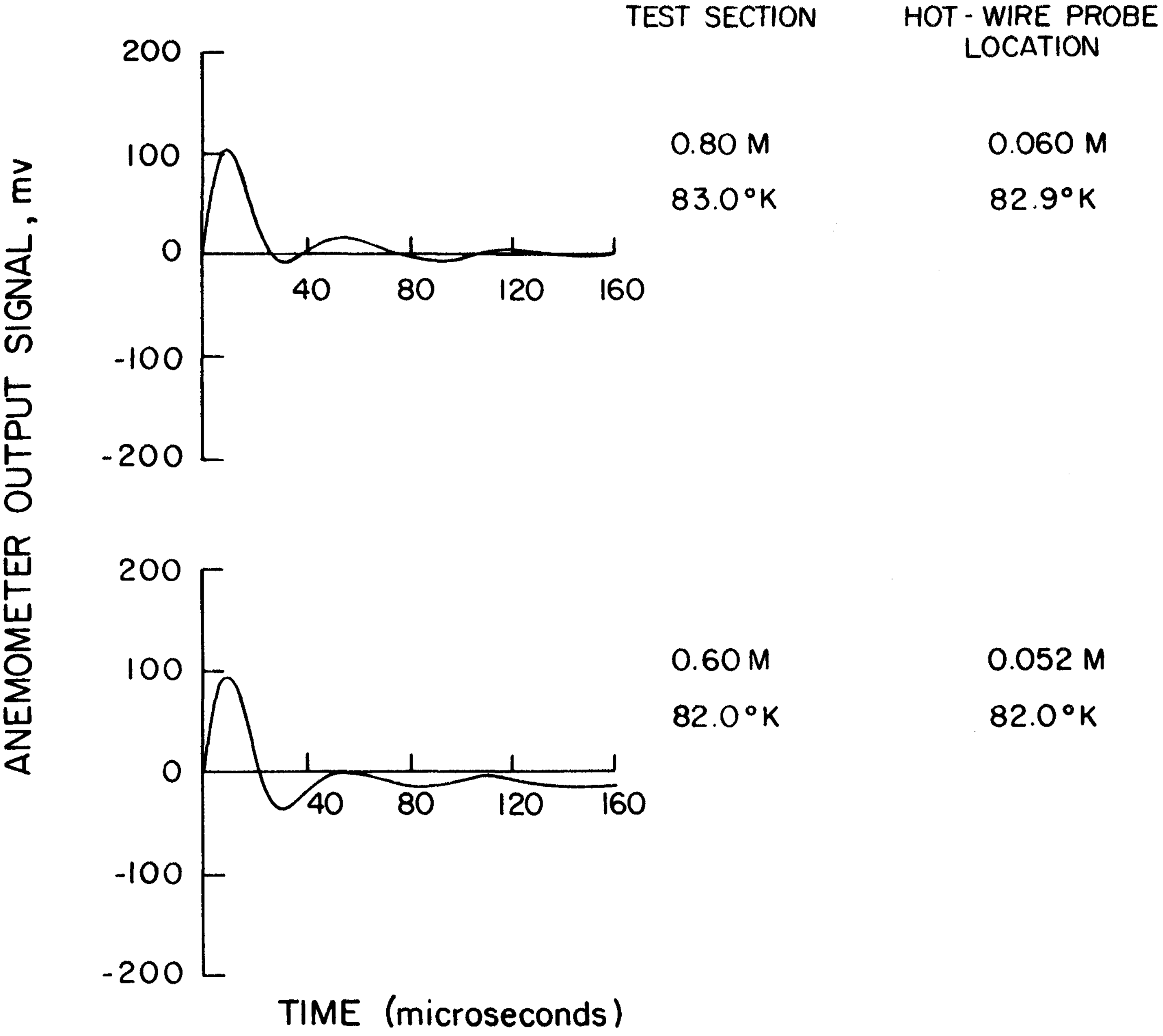
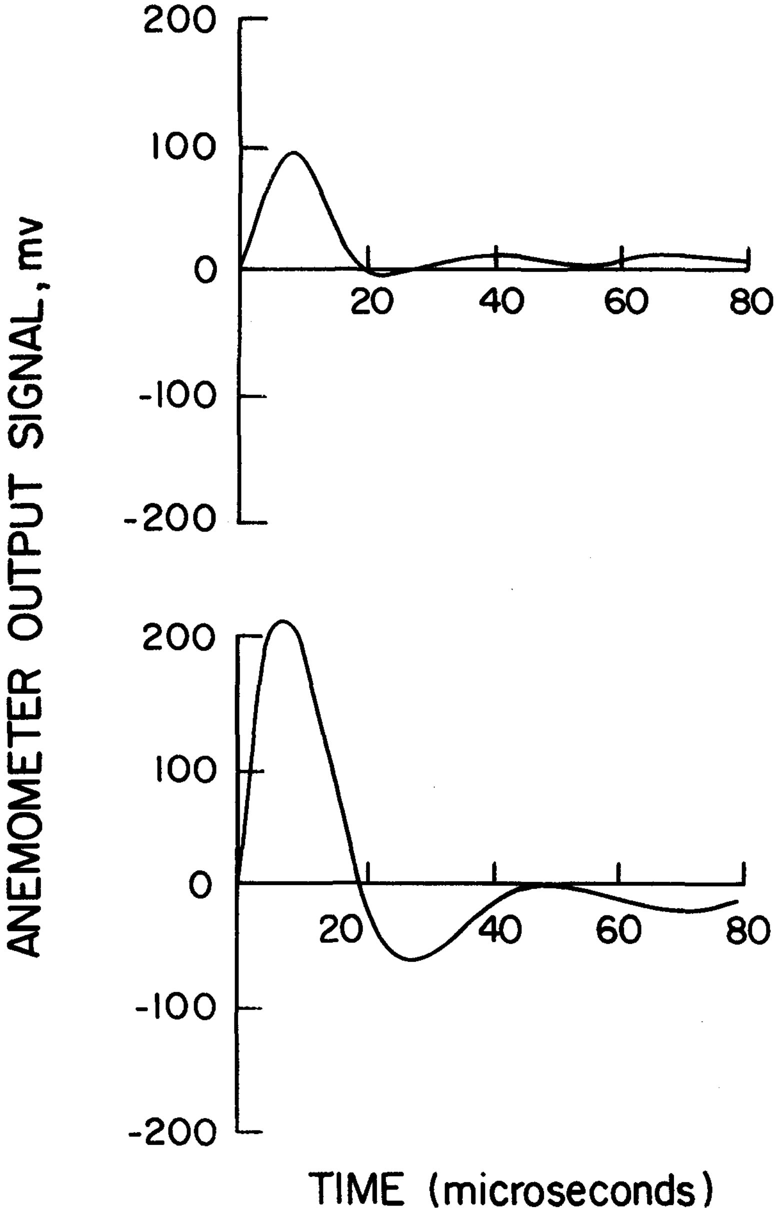


FIGURE 4 - HOT-WIRE ANEMOMETER RESPONSE TO PARTICLE STRIKES AT 1.2 atm FOR TWO VALUES OF CARRIER STREAM VELOCITY.



TEST SECTION	HOT-WIRE PROBE LOCATION
0.494 M 91.7°K	0.046 M 91.7°K
0.30 M 90.6°K	0.030 M 90.6°K

FIGURE 5 - HOT-WIRE ANEMOMETER RESPONSE TO PARTICLE STRIKES AT 3.0 atm FOR TWO VALUES OF CARRIER STREAM VELOCITY.

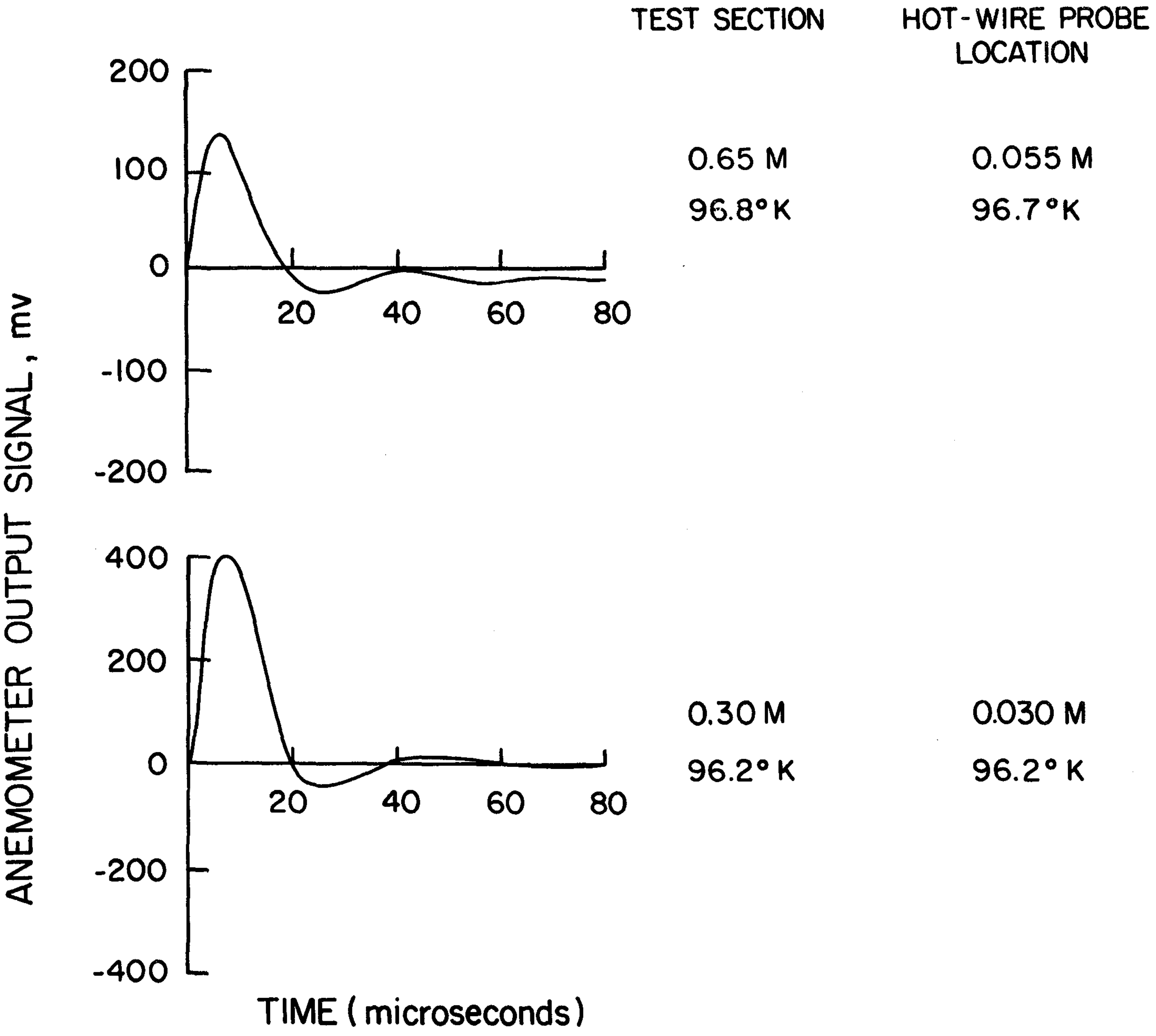


FIGURE 6 - HOT-WIRE ANEMOMETER RESPONSE TO PARTICLE STRIKES AT 5.0 atm FOR TWO VALUES OF CARRIER STREAM VELOCITY.

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15. Supplementary Notes

16. Abstract

Hot wire anemometry has been used to identify the nature of particles reportedly observed during free stream velocity measurements in the Langley 0.3-meter transonic cryogenic tunnel using a Laser Doppler Velocimeter. Since the heat-transfer process from the hot wire depends on the thermal conductivity and sticking capability of the particles, it was anticipated that the hot wire anemometer response would be affected differently upon impaction by liquid droplets and solid aerosols in the test gas stream. Based on the measured time response of the hot-wire anemometer in the cryogenic tunnel operated in the 0.3-0.8 Mach number range, it is concluded that the particles impacting the hot wire are liquid in nature rather than solid aerosols. It is further surmised that the liquid aerosols are unevaporated liquid nitrogen droplets used for cooling the tunnel test gas.

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