ENERGY AND COMFORT

Ventilation Test Instruments

Calibration of the CERTIFIER® Air Velocity Calibrator Using a Laser Doppler Velocimeter (LDV)

Application Note TI-130

Introduction

Traditionally a Pitot-static tube connected to a pressure transducer is used to make air velocity measurement. Lately, velocity transducers based on the principle of convective heat transfer have become popular. Both types of transducers need occasional calibrations. Also, several regulatory agencies require that the calibration of velocity transducers used in certain applications must be verified at regular intervals. While evaluating a velocity transducer calibration facility, one must consider two essential factors. One is the quality of air stream, and the other is the method used to establish the reference velocity in the calibration facility. A suitable calibration facility must provide a test section area large enough to avoid blocking effects, have good motor speed control, and provide an air stream with spatial uniformity and steadiness of flow. A well designed wind tunnel usually meets these requirements at velocities above 750 ft/min (FPM). However, to accomplish similar effects at lower velocities (30 to 750 FPM) is much more difficult.

A Pitot-static tube together with a well calibrated precision pressure transducer could be used to measure air velocities in wind tunnels, but the usefulness of this method is limited to velocities above 750 FPM. At the National Bureau of Standards, a laser Doppler velocimeter (LDV) is used to establish air velocity standard in the range of 10 to 1000 FPM (ref. 1).

TSI has developed a bench-top windtunnel (CERTIFIER® Model 8392) which can be used to calibrate velocity transducers in the range of 30 to 9000 FPM. The CERTIFIER® air velocity calibrator has a 4 inch × 4 inch square cross section and can accommodate velocity transducers up to 5/8 inch diameter without any blocking effect. It is a classical wind tunnel in the velocity range of 750 to 9000 FPM. However, steady and uniform velocities in the range of 30 to 750 FPM are established by using nozzle plates with multiple holes.

The wind tunnel has three modes of operation. In the first mode, no nozzle plate is inserted (open tunnel mode), in the second mode a nozzle plate with nine 0.656 inch diameter holes is inserted (No. 1 nozzle plate mode), and in the third mode a nozzle plate with nine 0.25 inch holes is inserted (No. 2 nozzle plate mode). The pressure transducer is connected between the inlet pressure tap and the test section pressure tap. For each mode of operation, there exists a relationship between the pressure transducer reading, ΔP, and the actual test point air velocity. (The test point is located at the middle of the test section and 2 inches downstream of the entrance to the clear Plexiglas section.) We used a laser Doppler velocimeter

(LDV) to establish this relationship. We also used the same LDV to study the spatial velocity uniformity inside the test section.

The Laser Doppler Velocimeter

LDV is the technique of measuring air velocity using a laser light (Ref. 2). A typical LDV consists of a laser, optics for beam transmission and scattered light collection, a photodetector tube to convert the light signal to electric signal, signal processor electronics to convert the electrical frequency signal to a digital number, and a microprocessor to store and analyze the data. We used a simple dual beam LDV (TSI Model 9100-3).

A coherent, monochromatic light beam form the laser enters the transmitting optics. The optics split the beam into two beams of equal intensity and cause the two beams to cross at the focal (measuring) point. At the focal pint the light beams cause constructive / destructive interference resulting in a "fringe" pattern. The fringe pattern consists of alternatively bright and dark lines parallel to the bisector of the beams.

As a particle passes through the light and dark regions, its scattered light generates a frequency signal in the photodetector, which is proportional to the velocity of the particle. If df is the spacing between fringes (the fringe spacing) and t is the time for the particle to pass through one fringe, then the particle velocity, V, is given by:

$$V = \frac{df}{t} = df \bullet F \tag{1}$$

where F is the frequency of the signal.

This simple model provides a correct expression for the fluid velocity. The signal processor accurately measures the frequency of the signal, F, generated at the photodetector. The other factor, df, is a function of the half angle, K, of the focusing lens. Accurate determination of K is therefore critical for the accurate fluid velocity measurement.

We use three independent methods to measure the half angle, K.

First, a rotating mirror mount calibrated to indicate degrees of rotation was placed at the focal point. Initially, one beam was reflected directly back upon itself and that point was used as a reference. Then the mirror was rotated until the other beam was reflected back upon itself and the angle between settings was noted. One half of this is the value of K. The second method involved shining the beams onto a wall perpendicular to the beam dissector. The distance between beam spots on the wall, and the distance from the wall to the point of beam crossing was measured accurately. The half angle, K, was calculated from these two distances. In the third method, the laser beams were carefully focused onto the edge of a rotating disk of precisely known diameter. The rotational speed of the disk was also precisely known, thus establishing a well-defined surface velocity at the circumference of the disk. The fringe spacing df (and the half angle, K), was calculated from the LDV reading and the actual surface velocity of the disk. The results of these three methods agreed with each other within 0.25 percent.

Once the half angle, K, is measured accurately, the LDV could be treated as a primary velocity standard. The dynamic range of the LDV easily encompassed the velocity range of the wind tunnel. Also, for LDV measurements no probes were inserted and the flow inside the wind tunnel remained undisturbed. For all our work, we used particles generated by atomizing a solution of water and glycerin as seed particles.

Comparison Between LDV, Pitot-static, and Bernoulli's Readings

The wind tunnel is equipped with a pressure tap at the inlet, and a pressure tap in the test section. An electronic pressure transducer is connected between the two pressure taps. In each of the three modes of operation, the pressure transducer reading, ΔP, is used to establish reference test section velocities.

At this point, it will be helpful to introduce the concept of "standard differential pressure reading" and "standard velocity". In all of the discussion which follows, the density of the air plays a significant role. The density of air significantly changes from day to day (often within hours) due to changes in barometric pressure, room temperature, and its moisture content. It is helpful to convert all data to standard conditions which could be viewed as the way the data would look if all experiments were conducted at barometric pressure of 29.92 inches Hg and room temperature of 70°F, and relative humidity of 0 percent. This eliminates the effect of density changes.

The actual differential pressure readings, ΔP, were converted to standard differential pressure readings, ΔP_s, using the following equation:

$$\Delta P_s = \Delta P\left(\frac{P}{29.92}\right)\left(\frac{530}{460+T}\right)(1-0.0004978\times e) \tag{2}$$

Where:

P = actual barometric pressure (inches Hg)
T = actual room temperature (°F)
e = vapor pressure of moisture (mm H_2O)

The actual measured velocities, V, were converted to standard velocities, V_s, using the following equation:

$$V_s = V\left(\frac{P}{29.92}\right)\left(\frac{530}{460+T}\right)(1-0.0004978\times e) \tag{3}$$

For the open tunnel mode, the test section velocities were measured by three independent methods. The first method was the LDV method described in The Laser Doppler Velocimeter section. In the second method, a Pitot-static tube was inserted at the test section and the difference between the impact pressure and the static pressure was measured by an electronic pressure transducer. The velocity, V, at the test section is given by:

$$V = \sqrt{2g\frac{\Delta P'}{\omega}} \tag{4}$$

Where:

g = acceleration due to gravity (ft/sec^2)
$\Delta P'$ = Pitot-static tube reading (lb/ft^2)
w = density of air (lb/ft^3)

The above equation reduces to:

$$V_{FPM} = 803.46\sqrt{\frac{\Delta P'_{Hg}}{\omega}} \tag{5}$$

Where:

V_{FPM} = velocity in feet per minute
$\Delta P'_{Hg}$ = Pitot-static tube reading in mmHg

A convenient expression for *w* is given by (Ref. 3):

$$\frac{1}{\omega}=\frac{0.754(460+\mathrm{T})}{\mathrm{P}}(1+0.0004978\times \mathrm{e}) \qquad (6)$$

In the third method, the air velocity in the test section was calculated from the pressure transducer reading, ΔP, using Bernoulli's equation, which is a statement of the principle of conservation of energy for fluid flow. The velocity, V, at the test section is given by:

$$\mathrm{V}=\sqrt{\left[\frac{2\mathrm{g}}{1-\left(\frac{\mathrm{A_T}}{\mathrm{A_I}}\right)^2}\right]\left(\frac{\Delta P}{\omega}\right)} \qquad (7)$$

Where:

A_T = area of the test section (ft^2)

A_I = area of the inlet (ft^2)

ΔP = differential pressure reading (lb/ft^2)

Before we undertook this work, we had calibrated four other wind tunnels using LDV and had observed that for a given standard differential pressure reading, ΔP_s, the measured standard velocity, V_s, did not vary significantly from tunnel to tunnel. By averaging the data of these four tunnels, we established a relationship between standard velocities and standard differential pressure readings which is given in Column 1 and Column 2 at the end of this Application Note. (We also established such a relationship for “with No. 1” and “with No. 2 nozzle plate mode”.) After taking room temperature, barometric pressure, and dew point, we calculated desired differential pressure, ΔP, which is given in Column 3 of Table 1. The relationship between ΔP and ΔP_s is given below:

$$\Delta \mathrm{P}=\Delta \mathrm{P_s}\left(\frac{29.92}{\mathrm{P}}\right)\left(\frac{460+\mathrm{T}}{530}\right)(1+0.0004978\times \mathrm{e}) \qquad (8)$$

Then the wind tunnel motor speed was adjusted until the pressure transducer connected to the wind tunnel pressure taps read the desired DP shown in Column 3. The actual LDV reading was taken and converted to standard velocity using equation (3). The actual and standard LDV velocities are given in Columns 4 and 5 in Table 1. All LDV velocities agreed with standard velocities within 1 percent. Because of the usual uncertainties associated with low differential pressure measurements, larger deviation at low velocities is understandable.

The LDV was removed and a Pitot-static tube was inserted into the wind tunnel. The tip of the Pitot-static tube coincided with the test point. A second pressure transducer was connected between the impact pressure and static pressure ports. The wind tunnel motor speed was adjusted so that the differential pressure transducer attached to the wind tunnel pressure taps read the desired ΔP given in Column 3, Table 2. (First three columns of Table 1, Table 2, and Table 3 are the same.) The Pitot-static tube differential pressure transducer was read and the readings are given in Column 4, Table 2. The actual velocities and standard velocities as read by Pitot-static tube were calculated using equations (5) and (8). Again except at the low velocity end, the measured Pitot-static velocities agreed with standard velocities within 1%. In the LDV measurement, only one differential pressure transducer measurement was involved, while in the Pitot-static tube measurement, two differential pressure transducers are involved. This perhaps explains the greater uncertainty at lower differential pressures.

The Bernoulli's velocities were calculated from desired differential pressure readings given in Column 3 by using equation (7), and the standard velocities were calculated using equation (3). The difference between standard velocities given in Column 2 and the Bernoulli's standard velocities given in Column 5 is a consistent 1.5 percent.

Higher Bernoulli's velocities (indicating that actual velocities are lower than theoretical velocities) were perhaps partly due to the fact that the test section pressure tap was located downstream of the test point, partly due to friction loses and partly due to imperfections in the pressure taps.

For lower velocities (with No. 1 and No. 2 nozzle plate mode), neither the Pitot-static tube measurement nor the Bernoulli's method is applicable. As discussed earlier, we had previously established a relationship between the standard velocity and standard differential pressure based on the calibration of four wind tunnels which is given in Columns 1 and 2 of Tables 4 and 5. The desired differential pressures were calculated using equation (8). The actual velocities were measured using LDV. The measured actual and standard velocities are shown in Columns 4 and 5. The measured standard velocities agreed with the standard velocities given in Column 1 within 2 percent.

Table 1: Comparison Between Pre-established Standard Velocities and LDV Measurement (no nozzle plate mode)

Pre-established Standard Velocity			LDV Measurement		
Standard Velocity (SFPM)	**Standard Differential Pressure (mm Hg)**	**Desired Differential Pressure (mm Hg)**	**Actual Velocity Reading (FPM)**	**Standard Velocity Reading (SFPM)**	**Difference Between 1 and 5 percent**
1	2	3	4	5	6
9000	9.56	10.05	9497	9036	+0.40
7500	6.64	6.98	7905	7521	+0.28
6000	4.25	4.47	6325	6018	+0.30
5000	2.95	3.10	5254	4999	-0.02
4000	1.89	1.99	4211	4007	+0.18
3000	1.06	1.11	3158	3005	+0.17
2500	0.739	0.777	2631	2503	+0.12
2000	0.476	0.500	2110	2008	+0.40
1500	0.271	0.285	1579	1502	+0.13
1000	0.119	0.125	1052	1001	+0.10
750	0.068	0.071	789	751	+0.13

Room Temperature = 78°F Dew Point = 52°F
Vapor Pressure = 9.85 mm H_2O Barometric Pressure = 29.04 in. Hg

Table 2: Comparison Between Pre-established Standard Velocities and Pitot-static Tube Measurement (no nozzle plate mode)

Pre-established Standard Velocity			Pitot-static Tube Measurement			
Standard Velocity (SFPM)	Standard Differential Pressure (mm Hg)	Desired Differential Pressure (mm Hg)	Measured Differential Pressure (mm Hg)	Actual Velocity Reading (FPM)	Standard Velocity Reading (SFPM)	Difference Between 1 and 5 percent
1	2	3	4	5	6	7
9000	9.56	10.05	9.76	9404	8948	-0.58
7500	6.64	6.98	6.78	7838	7458	-0.56
6000	4.25	4.47	4.35	6278	5973	-0.45
5000	2.95	3.10	3.00	5214	4961	-0.78
4000	1.89	1.99	1.93	4182	3979	-0.53
3000	1.06	1.11	1.08	3128	2976	-0.80
2500	0.739	0.777	0.750	2607	2480	-0.80
2000	0.476	0.500	0.476	2077	1976	-1.20
1500	0.271	0.285	0.265	1550	1475	-1.67
1000	0.119	0.125	0.116	1025	975	-2.50
750	0.068	0.071	0.063	756	719	-4.13

Room Temperature = 78°F Dew Point = 52°F
Vapor Pressure = 9.85 mm H_2O Barometric Pressure = 29.04 in. Hg

Table 3: Comparison Between Pre-established Standard Velocities and Bernoulli's Velocity (no nozzle plate mode)

Pre-established Standard Velocity			Bernoulli's Velocity		
Standard Velocity (SFPM)	Standard Differential Pressure (mm Hg)	Desired Differential Pressure (mm Hg)	Actual Velocity Reading (FPM)	Standard Velocity Reading (SFPM)	Difference Between 1 and 5 percent
1	2	3	4	5	6
9000	9.56	10.05	9601	9139	+1.54
7500	6.64	6.98	8006	7620	+1.60
6000	4.25	4.47	6404	6096	+1.60
5000	2.95	3.10	5334	5078	+1.56
4000	1.89	1.99	4270	4064	+1.60
3000	1.06	1.11	3196	3042	+1.40
2500	0.739	0.777	2666	2538	+1.52
2000	0.476	0.500	2133	2030	+1.50
1500	0.271	0.285	1602	1525	+1.67
1000	0.119	0.125	1070	1019	+1.90
750	0.068	0.071	806	768	+2.40

Room Temperature = 78°F Dew Point = 52°F
Vapor Pressure = 9.85 mm H_2O Barometric Pressure = 29.04 in. Hg

Table 4: Comparison Between Pre-established Standard Velocities and LDV Measurement (with no. 1 nozzle plate mode)

Pre-established Standard Velocity			LDV Measurement		
Standard Velocity (SFPM)	Standard Differential Pressure (mm Hg)	Desired Differential Pressure (mm Hg)	Actual Velocity Reading (FPM)	Standard Velocity Reading (SFPM)	Difference Between 1 and 5 percent
1	2	3	4	5	6
1500	8.24	8.60	1570	1500	0.0
1250	5.67	5.92	1302	1248	-0.2
1000	3.65	3.81	1049	1006	+0.6
750	2.04	2.13	785	753	+0.4
600	1.29	1.34	622	597	-0.5
500	0.897	0.935	523	502	+0.4
400	0.565	0.589	415	398	-0.5
300	0.314	0.328	311	299	-0.3
250	0.218	0.228	259	248	-0.8

Room Temperature = 73°F Dew Point = 47°F
Vapor Pressure = 8.23 mm H_2O Barometric Pressure = 28.94 in. Hg

Table 5: Comparison Between Pre-established Standard Velocities and LDV Measurement (with no. 2 nozzle plate mode)

Pre-established Standard Velocity			LDV Measurement		
Standard Velocity (SFPM)	Standard Differential Pressure (mm Hg)	Desired Differential Pressure (mm Hg)	Actual Velocity Reading (FPM)	Standard Velocity Reading (SFPM)	Difference Between 1 and 5 percent
1	2	3	4	5	6
250	8.31	8.68	259	248	-0.8
180	4.22	4.40	186	179	-0.6
120	1.86	1.94	124	119	-0.8
90	1.04	1.08	94.1	90.3	+0.3
60	0.480	0.500	63.2	60.7	+1.2
30	0.111	0.116	30.7	29.6	-1.3

Room Temperature = 73°F Dew Point = 47°F
Vapor Pressure = 8.23 mm H_2O Barometric Pressure = 28.94 in. Hg

Spatial Uniformity of the Velocity Within the Test Section

For the discussion regarding the spatial uniformity of the velocity within the test section, we will define VT as air velocity at the test point. The test point is located at 2 inches downstream of the entrance to the test section (Plexiglas section), and at the middle of the cross section (2 inches from either side, 2 inches from the top, 2 inches from the bottom). Air stream velocities, V, at various points within the test section were measured using LDV and normalized by dividing them by VT. Thus, the non-deviation of the ratio V/VT from unity is the indication of spatial uniformity. The velocity distribution across the cross section (top to bottom, left to right) for the three modes of operation are given in Figures 1 thru 3. These figures indicate good spatial uniformity. Compared to the "open tunnel mode" there is more data scatter with “No. 2 nozzle plate mode”. This is perhaps primarily due to the difficulties associated with low velocity measurement. Figures 4 through 6 show the velocity distribution along the longitudinal axis. The longitudinal velocity distribution in the open tunnel mode is very uniform. In the other two modes, this becomes non-uniform as we move nearer to the nozzle plates.

Conclusions

1. From this work it can be concluded that a relationship between standard velocities and standard differential pressure could be pre-established and this relationship does not vary from tunnel to tunnel. This assures that as long as the differential pressure transducer used is well calibrated, the results obtained using the wind tunnel will be accurate.

2. A LDV was used to establish the relationship between standard velocities and standard differential pressure. The LDV was calibrated with a rotating disc. Since the diameter and the rotational speed of the disc can be measured very accurately, it can be regarded as a primary standard.

3. A Pitot-static tube and a NIST traceable pressure transducer were used to independently check the velocity at the test point. The measured velocities agreed with the pre-established velocities within 1 percent.

4. The velocity profile within the wind tunnel is flat. This assures that the test probe will encounter a flat uniform velocity profile.

References

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