# Model 8390
# Bench Top Wind Tunnel

## Operation and Service Manual

September 1989

TSI Incorporated

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TSI Incorporated
P.O. Box 64394
500 Cardigan Road
Saint Paul, MN 55164
USA

Telephone 612-490-2888
FAX 612-490-2874

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Appendices:

Other manuals enclosed

(1) Dart Controls — Instruction manual for 250B variable speed control
(2) MKS Instruments, Inc. — Instruction manual for Type 223B pressure transducer (if model 8391 was purchased)
(3) MKS Instruments, Inc. — Instruction manual for PDR-D-1 power supply and digital readout (if Model 8391 was purchased)

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## SERVICE POLICY

Knowing that inoperative or defective instruments are as detrimental to TSI as they are to our customers, our service policy is designed to give prompt attention to any problems. If any malfunction is discovered, please contact your nearest sales office or representative, or call TSI's Customer Service department at (612)483-4711.

## 1 Introduction

The Model 8390 Bench-top Wind Tunnel is a conventional wind tunnel designed for laboratory and light industrial use. The tunnel can be used to calibrate a velocity transducer in the range of 30 FPM to 9000 FPM (0.15 m/s to 45 m/s). This broad range is made possible by using nozzles of various diameters to choke the flow. Adapters are provided to fit TSI velocity probes; other probes may be accommodated using the proper compression fitting with a 1/2-inch NPT male thread. A certificate of NBS traceability accompanies every unit.

A differential pressure meter of high accuracy is required when using the wind tunnel. TSI's Model 8391 is recommended and is available separately. A certificate of NBS traceability accompanies every Model 8391. The Model 8390 Bench-top Wind Tunnel, together with Model 8391, provides you with a complete calibration facility. All you need is to record the barometric pressure and the room temperature before you start calibration. You will also need a calculator to do some simple calculations.

The velocity in the wind tunnel was established by using a laser Doppler velocimeter (LDV) (see Appendix A) which can be regarded as a primary standard. The accuracy of the LDV was verified by a rotating disc. Thus the accuracy of the wind tunnel is traceable to the accuracy in measuring the diameter and rotational speed of the rotating disc. The diameter and the rotational speed of the rotating disc can be measured easily and accurately.

The air velocity in the wind tunnel was also checked by using a Pitot-static tube and an NBS traceable pressure transducer (see Appendix A, Section III). The LDV measurement and the Pitot-static tube measurement agreed very well, thereby establishing a trail for NBS traceability.

## 2 Unpacking and Inspection

Remove the Bench-top Wind Tunnel from its shipping container and thoroughly inspect it for shipping damage and to be certain that all the parts listed below were received. If damage exists, notify the carrier and contact your nearest TSI sales office for instructions. If the shipment was missing any of the below listed parts contact your nearest TSI sales office for instructions on obtaining them.

It is recommended that the original packaging be saved for any future storage or shipment.

Included with the wind tunnel is an accessory package that includes the following parts:

1 - Instruction manual
2 - Nozzle plates (each having different size nozzle holes)
1 - 6 feet of 0.25" [6.3 mm] O.D. pressure tubing
(replacement parts for future use)
*1 - Fitting assortment

*Refer to the illustrated parts list for specific fitting sizes.

## 3 Assembly

The wind tunnel comes preassembled. Figure 3.1 shows an assembled view of the wind tunnel. Use the following steps to make it operational.

(a) Set the Bench-top Wind Tunnel on a convenient work surface for ease of inspection and access. The Bench-top Wind Tunnel body is shipped assembled from the factory. If the Model 8391 pressure transducer was purchased with the wind tunnel it will already be mounted with the interconnecting tubing in place.

Be certain to remove any cardboard spacers placed around the fan motor at the end of the tunnel.

(b) Check that all fittings and hardware are present and are tight. Before shipping, the test section (the clear center section) was aligned with the two end sections providing a smooth transition and tight seal. If a misalignment is noticeable, contact TSI for instructions.

(c) Turn the control potentiometer on the motor controller fully counterclockwise. Make sure the power switch is off. Plug the controller into a 15 ampere service plug and connect the controller to the motor. Switch on the controller and slowly turn the control potentiometer clockwise until the fan begins to rotate. Listen for scraping sounds. If heard, refer to Troubleshooting, Section 7.

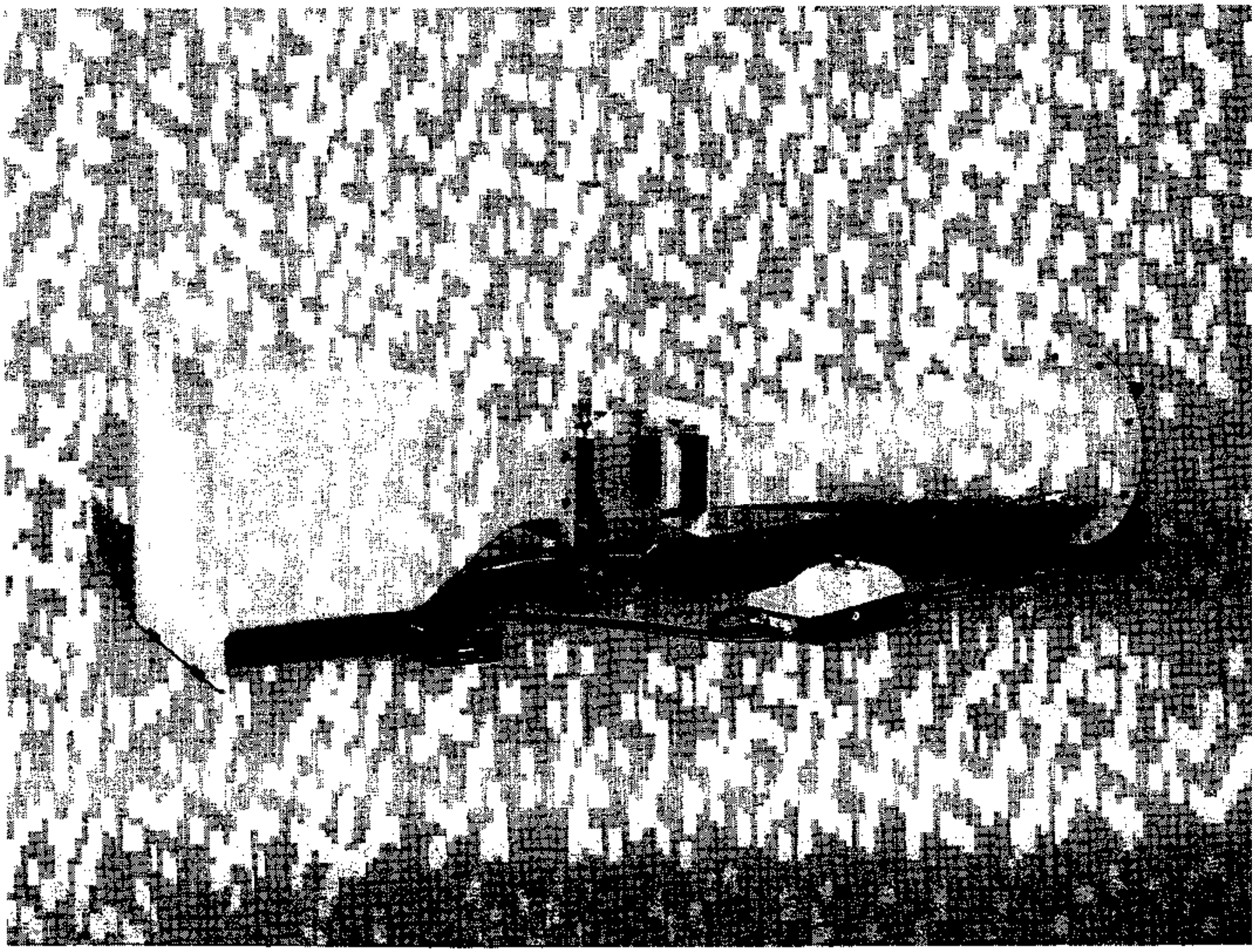


Figure 3.1. Assembled view of Bench-top Wind Tunnel

## 4 Setting it up

The accuracy and repeatability of the wind tunnel are adversely affected by air moving past the inlet. For this reason, it is important to observe the following four recommendations.

(a) Do not use the tunnel in small rooms or confined spaces; 1600 cubic feet is the minimum recommended room volume.

(b) Do not locate the tunnel near ventilation ducts, open windows, hallway doors or anything that produces significant air currents.

(c) Do not place objects near the tunnel inlet or allow persons to stand near the tunnel inlet when the wind tunnel is in operation.

(d) At high velocities, the wind tunnel will produce some air movement in most rooms. Try to minimize the resultant turbulence at the inlet by directing the exhaust air towards the greatest open air space.

# 5 Operating Instructions

## 5.1 Insertion of the Nozzle Plates

The wind tunnel can be used to calibrate a velocity transducer from 30 FPM to 9000 FPM (0.15 m/s to 45 m/s). This velocity range is covered through three modes, i.e., no nozzle plate; with a No. 1 nozzle plate inserted; and with a No. 2 nozzle plate inserted. (No. 1 nozzle plate has nine 0.656" diameter nozzle holes; No. 2 nozzle plate has nine 0.25" diameter nozzle holes.) The velocity range covered in each mode of operation is given in Table 1.

It is convenient to start with no nozzle plates inserted. However, if your velocity transducer needs to be calibrated at low velocities only, then insert the required orifice plate as follows:

(a) Unscrew the two thumbscrews at the rear of the test section and remove the rear test section cover.

(b) Carefully slide the required orifice plate into the test section. Make sure that the flow enters the nozzle holes through the rounded side. (Plates should be inserted so that the number 1 or 2 is toward the inlet and on top.)

(c) Replace the cover and the thumbscrews.

Table 1

VELOCITY RANGE FOR THE BENCH-TOP WIND TUNNEL

| Mode of Operation | Velocity SFPM | Range S m/s |
|---|---|---|
| No nozzle | 1500 - 9000 | 7.5 - 1.25 |
| With No. 1 nozzle | 250 - 1500 | 1.25 - 7.5 |
| With No. 2 nozzle | 30 - 250 | 0.15 - 1.25 |

## 5.2 Preparation of the Calibration Data Sheet

This manual assumes that you are calibrating thermal-type velocity transducers and you want to set the tunnel velocity in terms of standard velocities (also known as mass velocities).

(a) Make a copy of either the english or metric data sheets from Table 2.a (english) or 2.b (metric). (If a specific data sheet was provided with your tunnel, then use that data sheet.)

(b) Fill in the model number and serial number of the velocity transducer to be calibrated at the left-hand corner of the data sheet.

(c) Fill in the barometric and room temperature data at the right-hand corner of the data sheet. If a barometer is not available in your building, you could use local weather data (see Appendix B). However, for temperature you must use the actual temperature of the room where the calibration is being performed, not the outside temperature.

(d) Calculate the air density correction factor (K) using the equations given at the top of data sheet (see Appendix C for a more accurate K).

(e) Multiply the Column 2 value with the air density correction factor (K) and enter the result in Column 3.

## 5.3 Calibration

(a) Loosen the probe compression fitting and insert the velocity transducer into the test section. The shaft of the transducer must make a tight seal with the compression fitting. Several sizes of compression fittings are supplied to insure a good fit with a variety of probe sizes.

(b) Align the velocity transducer with the flow. If the velocity transducer has any directional sensitivity, make sure that it is positioned in its normal operating orientation with respect to the flow.

(c) Make sure that the high pressure side of the differential pressure meter is connected to the inlet pressure tap and the low pressure side is connected to the pressure tap on the test section. (The wind tunnel is shipped assembled this way if the Model 8391 pressure transducer and readout was purchased at the same time.) Check for any source of possible leaks in the pressure lines.

(d) Switch on the motor speed controller and turn the control knob clockwise until the motor starts. Slowly increase the motor speed until the differential pressure meter reading corresponds to the ΔP shown in the first row in Column 3 on your data sheet.

(e) Record the output of the velocity transducer being calibrated in Column 4.

(f) Decrease the motor speed until the differential pressure meter reading corresponds to the ΔP shown in the next row (Column 3) on your data sheet. Record the velocity transducer output in Column 4.

(g) Repeat the procedure until the calibration is finished. If necessary, insert the appropriate nozzle plates to obtain lower velocities (see section 5.1).

Table 2-A

## SAMPLE CALIBRATION DATA SHEET (ENGLISH)

Date ____________

Initials ____________

Model No. ____________

Barometric Pressure ____________

Serial No. ____________

Room Temperature ____________

---

Density Correction Factor:

$$K = \frac{29.92}{P} \times \frac{460 + t}{530}$$

t = temperature ($^{o}$F)
P = barometric pressure (inch of Hg)

or

Density Correction Factor:

$$K = \frac{760}{P} \times \frac{273.15 + t}{294.25}$$

t = temperature ($^{o}$C)
P = barometric pressure (mm of Hg)

---

**NO NOZZLE INSERTED**

| Standard Velocity SFPM | Standard P mm of Hg | Desired P (Column 2) x K mm of Hg | Velocity Transducer Output (volts or SFPM) |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 9000 | 9.56 | | |
| 7500 | 6.64 | | |
| 6000 | 4.25 | | |
| 5000 | 2.95 | | |
| 4000 | 1.89 | | |
| 3000 | 1.06 | | |
| 2500 | 0.739 | | |
| 2000 | 0.476 | | |
| 1500 | 0.271 | | |

**WITH NO. 1 NOZZLE PLATE (0.656" holes)**

| Standard Velocity SFPM<br>1 | Standard P mm of Hg<br>2 | Desired P (Column 2) x K mm of Hg<br>3 | Velocity Transducer Output (volts or SFPM)<br>4 |
|---|---|---|---|
| 1500 | 8.40 | | |
| 1250 | 5.76 | | |
| 1000 | 3.66 | | |
| 900 | 2.95 | | |
| 800 | 2.32 | | |
| 750 | 2.04 | | |
| 700 | 1.77 | | |
| 650 | 1.52 | | |
| 600 | 1.30 | | |
| 550 | 1.09 | | |
| 500 | 0.897 | | |
| 450 | 0.725 | | |
| 400 | 0.573 | | |
| 350 | 0.438 | | |
| 325 | 0.377 | | |
| 300 | 0.321 | | |
| 275 | 0.269 | | |
| 250 | 0.222 | | |

**WITH NO. 2 NOZZLE PLATE (0.25" holes)**

| Standard Velocity SFPM<br>1 | Standard P mm of Hg<br>2 | Desired P (column 2) x K mm of Hg<br>3 | Velocity Transducer Output (volts or SFPM)<br>4 |
|---|---|---|---|
| 250 | 8.71 | | |
| 225 | 7.01 | | |
| 200 | 5.50 | | |
| 180 | 4.42 | | |
| 150 | 3.04 | | |
| 120 | 1.93 | | |
| 100 | 1.32 | | |
| 90 | 1.06 | | |
| 80 | 0.826 | | |
| 70 | 0.625 | | |
| 60 | 0.454 | | |
| 50 | 0.312 | | |
| 40 | 0.199 | | |
| 30 | 0.111 | | |

Table 2-B

## SAMPLE CALIBRATION DATA SHEET (METRIC)

Date __________

Initials __________

Model No. __________

Barometric Pressure __________

Serial No. __________

Room Temperature __________

Density Correction Factor:

$$K = \frac{29.92}{P} \times \frac{460 + t}{530}$$

t = temperature (°F)
P = barometric pressure (inch of Hg)

or

Density Correction Factor:

$$K = \frac{760}{P} \times \frac{273.15 + t}{294.25}$$

t = temperature (°C)
P = barometric pressure (mm of Hg)

### NO NOZZLE INSERTED

| Standard Velocity S m/s | Standard P mm of Hg | Desired P (Column 2) x K mm of Hg | Velocity Transducer Output (volts or S m/s) |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 45.0 | 9.26 | | |
| 40.0 | 7.32 | | |
| 30.0 | 4.12 | | |
| 25.0 | 2.86 | | |
| 20.0 | 1.83 | | |
| 15.0 | 1.03 | | |
| 12.5 | 0.716 | | |
| 10.0 | 0.462 | | |
| 7.5 | 0.263 | | |

**WITH NO. 1 NOZZLE PLATE (0.656" holes)**

| Standard Velocity S m/s | Standard P mm of Hg | Desired P (Column 2) x K mm of Hg | Velocity Transducer Output (volts or S m/s) |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 7.5 | 8.14 | | |
| 6.5 | 6.05 | | |
| 5.5 | 4.30 | | |
| 5.0 | 3.55 | | |
| 4.5 | 2.86 | | |
| 4.0 | 2.25 | | |
| 3.5 | 1.71 | | |
| 3.25 | 1.47 | | |
| 3.00 | 1.26 | | |
| 2.75 | 1.05 | | |
| 2.50 | 0.869 | | |
| 2.25 | 0.702 | | |
| 2.00 | 0.555 | | |
| 1.75 | 0.424 | | |
| 1.50 | 0.311 | | |
| 1.4 | 0.270 | | |
| 1.3 | 0.233 | | |
| 1.25 | 0.215 | | |

**WITH NO. 2 NOZZLE PLATE (0.25" holes)**

| Standard Velocity S m/s | Standard P mm of Hg | Desired P (Column 2) x K mm of Hg | Velocity Transducer Output (volts or S m/s) |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 1.25 | 8.43 | | |
| 1.00 | 5.32 | | |
| 0.75 | 2.94 | | |
| 0.60 | 1.87 | | |
| 0.50 | 1.28 | | |
| 0.40 | 0.799 | | |
| 0.30 | 0.440 | | |
| 0.25 | 0.302 | | |
| 0.20 | 0.193 | | |
| 0.15 | 0.108 | | |

## 6 Determining velocities or pressures other than those supplied on the calibration data sheet

For $\Delta P$ at other velocities:

$$\Delta P_2 = \Delta P_1 \ (V_2/V_1)^2$$

where $V_1$ = known velocity

$\Delta P_1$ = differential pressure ($\Delta P$) for $V_1$

$\Delta P_2$ = unknown differential pressure

$V_2$ = desired velocity

For velocities at other $\Delta P$:

$$V_2 = V_1 \ (\Delta P_2/\Delta P_1)^{1/2}$$

where $V_1$ = known velocity

$\Delta P_2$ = differential pressure of interest

$V_2$ = unknown velocity

---

Note: The equations are valid for one mode (nozzle plate configuration) of operation only. For greatest accuracy, choose known velocity and pressure points as close as possible to the unknown value.

---

Example:

Case 1:

Note the pressure drop for 475 SFPM is not listed in Table 2. We can interpolate as follows:

$$\Delta P_2 = \Delta P_1 \ (V_2/V_1)^2$$

$$\Delta P_2 = .897(475/500)^2 = .810 \text{ mm of Hg}$$

Note that $V_1$ was selected as close to $V_2$ as possible. We could have used 450 SFPM instead of 500. Then, $\Delta P_2$ would be:

$$\Delta P_2 = .718(475/450)^2 = .800 \text{ mm of Hg}$$

The different answers are due to the fact that the nozzle coefficient was not taken into account. The error due to this is only about 0.6% of flow.

Case 2:

We want to find what is the velocity corresponding to $\Delta P$ = .805 mm of Hg (in the "with No. 1 Nozzle" mode):

$$V_2 = 500(.805/.897)^{1/2} = 473.7 \text{ SFPM}$$

or

$$V_1 = 450(.805/.718)^{1/2} = 476.5 \text{ SFPM}$$

## 7 Troubleshooting

| | Symptom | Solution |
|---|---|---|
| 1. | Scraping sounds at the fan | Realign fan. |
| 2. | The switch on control potentiometer is clockwise; no power to motor | Replace fuse in controller. See controller instruction manual.<br>Check that the power cord is plugged in and that the circuit or outlet is turned on |
| 3. | Inability to achieve specified velocity | Check that when the wind tunnel is running at maximum velocity the controller is receiving at least 115 VAC (220 VAC for the 220 AC model)<br>Clean flow straighteners and air filter. (see note 1. below) |
| 4. | Poor repeatability | Check for leaks in tunnel body and/or pressure hoses. Tunnel must not be operated in confined area. Room should have a minimum volume of 1600 cubic feet. |
| 5. | Poor accuracy | Check repeatability (see above). If the repeatability is good, check the accuracy of pressure transducer. |
| 6. | No reading or incorrect reading of pressure transducer and readout | Consult manufacturers manuals for pressure transducer and readout. |

Note 1. The honeycomb flow straighteners and filter can be removed for cleaning. A mild soap or detergent can be used. Do not use any solvents. Allow filter element to drip dry, do not wring it out.

## 8 Recommended calibration schedule

The wind tunnel is a mechanical fixture and needs no periodic calibration. The only component that needs periodic check is the pressure transducer. The Model 8391 pressure transducer is highly reliable and does not require periodic recalibration.

However, if you are required to maintain NBS traceability, then you should have the pressure transducers checked at least once a year. Such service is available from various local testing laboratories. You may want to send the pressure transducer to MKS Instruments, Inc., the manufacturer of the pressure transducer. Their address is:

MKS Instruments, Inc.
Six Shattuck Road
Andover, MA 01810

Telephone: (617) 975-2350
Telex: (617) 975-0094
FAX: (617) 975-0093

## 9 Maintenance

The wind tunnel will not require any maintenance if it is operated in a relatively clean environment. If it is operated in a dirty environment, then the honeycomb flow straighteners and the sponge filter (see page 21, Parts List) should be periodically checked and, if necessary, cleaned or replaced. The honeycomb flow straighteners and filter can be removed for cleaning. A mild soap or detergent can be used. Do not use any solvents. Allow filter element to drip dry, do not wring it out. Also, periodically check (and clean if necessary) the pressure tap holes.

The electric motor is a continuous duty type and requires no maintenance. In the event you encounter any problem with the electric motor, you should be able to buy a replacement locally (see Part 12, Parts List for description).

The 0.25 " outside diameter clear tubing connecting the pressure transducer and the pressure taps may need periodic replacement. Such tubing should be locally available.

<u>CAUTION</u>: Any leak in the lines connecting pressure taps and the pressure transducer will result in severe inaccuracy.

## 10 Safety notes

Follow all the safety rules that you will normally follow while operating any electrical equipment, specifically:

1. Do not operate the equipment in a wet environment.
2. Never operate the equipment if any of the electrical cable is damaged.
3. Do not open any enclosure without unplugging the power cords.
4. Never bring any part of your body close to the rotating motor. You should unplug the motor before doing any maintenance or cleaning of the motor.
5. Always use a grounded power source.

## 11 Specifications

| | | |
|---|---|---|
| Test section dimensions | 4 x 4" | 101.6 x 101.6 mm |
| Feed-thru hole | 1/2" NPT | |
| Overall size: | | |
| Length | 57" | 145 mm |
| Width | 17" | 43 mm |
| Height | 17" | 43 mm |
| Power | | |
| Model 8390 | 115V<br>60 Hz | |
| Model 8390-1 | 220V<br>50/60 Hz | |
| Fittings included for following probe diameters | 0.188"<br>0.25"<br>0.313"<br>0.375"<br>0.4"<br>0.5"<br>0.625" | 4.3 mm<br>6.3 mm<br>7.9 mm<br>9.5 mm<br>10.1 mm<br>12.7 mm<br>15.9 mm |

Accuracy

| | Velocity Range | | Nominal Pressure Drop Range | | Typical** Turbulence |
|---|---|---|---|---|---|
| Mode | FPM | m/s | mm of Hg | Accuracy* | Intensity |
| No nozzle | 1500-9000 | 7.5 - 45 | .25 - 9.5 | +/- 1% of reading & ±15 FPM (.075m/s) | .25% |
| With No. 1 Nozzle | 250-1500 | 1.25 - 7.5 | .2 - 8.5 | +/- 2.0% of reading & ±5 FPM (.025m/s) | 1.0% |
| With No. 2 Nozzle | 30- 250 | .15 - 1.25 | .1 - 8.5 | +/- 2.0% of reading & ±2 FPM (.01m/s) | 1.0% |

* Assumes use of TSI Model 8391 Pressure Transducer and readout or equivalent.

** Turbulence intensity is defined as the root mean square (RMS) of velocity fluctuations divided by the mean velocity.

## 12 Illustrated parts list

| QUANTITY REQUIRED | FSCM # IDENTIFICATION # | DESCRIPTION | ITEM # |
|---|---|---|---|
| 2 | 24575 SK8320-1 | Honeycomb flow straightener panel | 1 |
| 1 | 24575 SK8320-2 | Pad, filter | 2 |
| 1 | 24575-SK8320-3 | Inlet section, 4" wind tunnel | 3 |
| 1 | 24575-SK8320-4 | FTG 3/16 tubing 1/4 MPT thermocouple design nylon ferule | 4 |
| 1 | 24575 1601727 | FTG 1/4 tubing 3/8 MPT thermocouple design nylon ferule | 5 |
| 1 | 24575 1601796 | FTG 5/16 tubing 3/8 MPT thermocouple design nylon ferule | 6 |
| 1 | 24575 1601729 | FTG 3/8 tubing 3/8 MPT thermocouple design nylon ferule | 7 |
| 1 | 24575 1601797 | FTG 1/2 tubing 1/2 MPT thermocouple design nylon ferule | 8 |
| 1 | 24575 1601798 | FTG 5/8 tubing 1/2 MPT thermocouple desing nylon ferule | 9 |
| 1 | 24575 1601800 | FTG 1/4 FPT 1/2 MPT | 10 |
| 1 | 24575 1601799 | FTG 3/8 FPT 1/2 MPT | 11 |
| 1 | 24575 1601731 | FTG, reducer bushing 3/8 MPT to 1/4 FPT (Items 4 and 7 are used together) | 12 |
| 6 | 24575 SK8320-5 | Knurled thumb screw, #10-32 by .750" long | 16 |
| 1 | 24575 SK8320-6 | Cover, front, test section | 17 |
| 1 | 24575 SK8320-7 | Cover, rear, test section | 18 |
| 2 | 24575 SK8320-8 | Gasket, 4 X .375 X 1/16 inch | 19 |
| 12 | SK8320-9 | Cap screw, hex socket head, steel, #1/4-20 X 7/8" lg | 20 |
| 2 | 5155189 | Cap screw, hex socket head, steel, #1/4-20 X 2" lg | 21 |
| 1 | 24575 2601251 | Nozzle plate #2, .25 dia. | 22 |
| 1 | 24575 2601262 | Nozzle plate #1, .656 dia. | 23 |
| 2 | 24575 SK8320-10 | Gasket, 1/8" thick | 24 |
| 2 | 24575 SK8320-11 | Gasket, 1/8" thick | 25 |
| 1 | 24575 SK8320-12 | Diffuser section, 4" wind tunnel | 26 |
| 1 | 3306006 | DC variable speed control 1/4 - 1 HP, 115 VAC (Dart Controls Inc. Indianapolis, Indiana Model #253B-E) | 27 |
| 1 | SK8320-13 | Fan motor, 1 HP, 10000 RPM Dayton Model 2M191 115 VAC, 60 HZ | 28 |
| 1 | 24575 SK8320-14 | Motor mounting Brkt | 29 |

| QUANTITY REQUIRED | FSCM # IDENTIFICATION # | DESCRIPTION | ITEM # |
|---|---|---|---|
| 4 | 24575 SK8320-15 | Cap screw, hex socket head, steel, #1/4-20 X 1/2" lg | 30 |
| 1 | 24575 SK8320-16 | Fan blade | 31 |
| 1 | 24575 1601296 | FTG, br conn, 1/4 tu-1/8 MPT, nylon feral | 32 |
| 1 | 24575 1601589 | FTG, br insert 1/8 ID 1/4 OD tube | 33 |
| 1 | 24575 1206215 | Brkt, wind tunnel pressure transducer | 34 |
| 2 | 24575 5313010 | Hex nut, #1/4-20, stainless steel | 35 |
| 2 | 24575 5332031 | Washer, 1/4 X.47 OD internal tooth lock washer, zinc coated | 36 |
| 4 | 24575 5041090 | Screw, #4-40 X 7/16" lg pan head phillips, stainless steel | 37 |
| 1 | 24575 SK8320-17 | Test section assy | 38 |
| 6 ft | 24575 3001220 | Tygon tubing, 1/4 OD by 1/8 ID | 39 |
| 1 | 24575 839100 | Pressure transducer, 10 mm Hg, MKS brand | 40 |
| 4 | 24575 5305001 | Nut, #4-40 lock (kep) zinc coated | 41 |
| 1 | 24575 839101 | Pressure transducer readout | 42 |
| 1 | 24575 1605010 | Fuse, 1/8 amp (125 ma) for 115 VAC application | 43 |
| (1 alt) | 24575 (SK8320-18) | (Fuse, 1/16 amp (63 ma) for 220 VAC application) | (43) |
| 1 | 24575 1980004 | Manual, 8390 and 8391 | 44 |
| 1 | 24575 2670092 | Shipping/storage carton | 45 |

## 13 Preparation for reshipment or storage

The original shipping container is the recommended means for storage or shipment. If the original shipping container is not available suitable alternatives can be be provided. For storage either a sturdy container or protected surface may be used. The wind tunnel should be protected from moisture, excessive heat, dust and damage from contact with other items. For shipment a suitable container should be obtained which is large enough to hold, support and protect the assembled wind tunnel body from moisture, dust and physical damage. The motor speed controller, power supply/readout and miscellaneous fittings and hardware should be individually packaged. The individual packages should be suitably secured, if packaged within the wind tunnels' carton, as not to damage the wind tunnel during shipment. The wind tunnel and accessories should be wrapped in a protective wrapper if the packaging material is comprised of loose materials or expanding foam in place materials.

## 14 Customer service, repair or return

For any questions concerning operation, service, repair, replacement parts, calibration services or return of the wind tunnel contact TSI Inc. or its local representative. In the case of the pressure transducer and the power-supply/readout, contact either the original manufacturer or TSI Inc.

TSI Inc.
Attn. Customer Service
500 Cardigan Road
P.O. Box 64394
St. Paul, MN 55164

Phone: (612) 483-0900
Telex: 6879024
Fax: (612) 481-1220

(for the pressure transducer and readout/power-supply only)

MKS Instruments
Six Shattuck Road
Andover, MA 01810

Phone: (617) 975-2350
Telex: (617) 975-0094
FAX: (617) 975-0093

## 15 Performance verification

For calibration see section 8, Recommended calibration schedule.

For performance verification a NBS traceable Pitot-static tube connected to a calibrated pressure transducer , hot wire anemometer or laser Doppler velocimeter can be used. The velocity measuring device should be positioned in the center of the test section and should not introduce any leaks into the wind tunnel test section. Measurements should be converted to standard velocities before comparison. Pay special attention to the accuracy and resolution of the measuring technique when making comparisons. See APPENDIX A for a discussion on making the measurements and comparisons.

## APPENDIX A Calibration of a Bench-top Wind Tunnel Using LDV*

### I. 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 feet per minute (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 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 wind tunnel (TSI Model No. 8390) which can be used to calibrate velocity transducers in the range of 30 to 9,000 FPM. This wind tunnel has a 4" x 4" square cross section and can accommodate velocity transducers up to 5/8" diameter without any blocking effect. It is a classical wind tunnel in the velocity range of 750 FPM to 9,000 FPM. However, steady and uniform velocities in the range of 30 FPM 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" diameter holes is inserted (with No. 1 nozzle plate mode), and in the third mode a nozzle plate with nine 0.25" diameter holes is inserted (with No. 2 nozzle plate mode). A pressure transducer (TSI Model No. 8391) 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, ($\Delta P$), and the actual test point air velocity. (The test point is located at the middle of test section and 2 inches downstream of the entrance to the clear plexiglass 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.

*This section was written as a technical bulletin by TSI engineers.

## II. 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 electric frequency signal to a digital number, and a microcomputer to store and analyze the data. We used a simple dual beam laser Doppler velocimeter (TSI Model No. 9100-3).

A coherent, monochromatic light beam from the laser enters the transmitting optics. These 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 point 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 the fringes (the fringe spacing) and t the time for the particle to pass through one fringe, then the particle velocity, V, is given by

$$V = \frac{df}{t} = df \cdot F \qquad (1)$$

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 accurate fluid velocity measurement.

We used 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%.

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 measurement 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.

## III. 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, ($\Delta P$), 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 of Hg and room temperature of 70°F, and relative humidity of 0%. This eliminates the effect of density changes.

The actual differential pressure readings, $\Delta P$, were converted to standard differential pressure readings, $\Delta P_s$, using the following equation:

$$\Delta P_s = \Delta P \times \frac{P}{29.92} \times \frac{530}{460 + t} \times (1 - .0004978 \times e) \tag{2}$$

where: P = actual barometric pressure (inches of Hg)
t = actual room temperature (°F)
e = vapor pressure of moisture (mm of water)

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

$$V_s = V \times \frac{P}{29.92} \times \frac{530}{460 + t} \times (1 - .0004978 \times e) \tag{3}$$

For the open tunnel mode, the test section velocities were measured by three independent methods. The first method was the LDV method described in Section II. 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 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$^2$)

$\omega$ = 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

$\Delta P'_{Hg}$ is the Pitot-static tube reading in mm of Hg.

A convenient expression for $\omega$ is given by (Ref. 3):

$$\frac{1}{\omega} = \frac{.754\ (460 + t)}{P} \times (1 + .0004978 \times e) \tag{6}$$

In the third method, the air velocity in the test section was calculated from the pressure transducer reading, $\Delta P$, 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:

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

where $A_T$ = area of the test section (ft$^2$)
$A_I$ = area of the inlet (ft$^2$)
$\Delta P$ = 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, $\Delta P_s$, 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 of Table 1 at the end of this paper. (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, $\Delta P$, which is given in Column 3, Table 1. The relationship between $\Delta P$ and $\Delta P_s$ is given below, which is a restatement of equation (2).

$$\Delta P = \Delta Ps \times \frac{29.92}{P} \times \frac{460 + t}{530} \times (1 + .0004978 \times e) \qquad (8)$$

Then the wind tunnel motor speed was adjusted until the pressure transducer connected to the wind tunnel pressure taps read the desired $\Delta P$ 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%. Because of the usual uncertainty 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 $\Delta P$ 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 the 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 the standard velocities given in Column 1 and the Bernoulli's standard velocities given in Column 5 is a consistent 1.5%.

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 losses 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%.

Table 1. Comparison between pre-established standard velocities and LDV measurement — no nozzle plate mode

| Pre-established Standard Velocity | | | LDV Measurement | | |
|---|---|---|---|---|---|
| Standard Velocity SFPM 1 | Standard Differential Pressure mm of Hf 2 | Desired Differential Pressure mm of Hg 3 | Actual Velocity Reading FPM 4 | Standard Velocity Reading SFPM 5 | Difference Between 1 and 5 Percent 6 |
| 9000 | 9.56 | 10.05 | 9497 | 9036 | +.40 |
| 7500 | 6.64 | 6.98 | 7905 | 7521 | +.28 |
| 6000 | 4.25 | 4.47 | 6325 | 6018 | +.30 |
| 5000 | 2.95 | 3.10 | 5254 | 4999 | −.02 |
| 4000 | 1.89 | 1.99 | 4211 | 4007 | +.18 |
| 3000 | 1.06 | 1.11 | 3158 | 3005 | +.17 |
| 2500 | 0.739 | 0.777 | 2631 | 2503 | +.12 |
| 2000 | 0.476 | 0.500 | 2110 | 2008 | +.40 |
| 1500 | 0.271 | 0.285 | 1579 | 1502 | +.13 |
| 1000 | 0.119 | 0.125 | 1052 | 1001 | +.10 |
| 750 | 0.068 | 0.071 | 789 | 751 | +.13 |

Room Temperature = 78° F, Barometric Pressure = 29.04" of mercury

Dew point = 52° F (Vapor pressure = 9.85 mm of water)

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 1 | Standard Differential Pressure mm of Hf 2 | Desired Differential Pressure mm of Hg 3 | Measured Differential Pressure mm of Hg 4 | Actual Velocity Reading FPM 5 | Standard Velocity Reading SFPM 6 | Difference Between 1 and 6 Percent 7 |
| 9000 | 9.56 | 10.05 | 9.76 | 9404 | 8948 | -.58 |
| 7500 | 6.64 | 6.98 | 6.78 | 7838 | 7458 | -.56 |
| 6000 | 4.25 | 4.47 | 4.35 | 6278 | 5973 | -.45 |
| 5000 | 2.95 | 3.10 | 3.00 | 5214 | 4961 | -.78 |
| 4000 | 1.89 | 1.99 | 1.93 | 4182 | 3979 | -.53 |
| 3000 | 1.06 | 1.11 | 1.08 | 3128 | 2976 | -.80 |
| 2500 | 0.739 | 0.777 | 0.750 | 2607 | 2480 | -.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, Barometric Pressure = 29.04" of mercury

Dew point = 52° F (Vapor pressure = 9.85 mm of water)

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 1 | Standard Differential Pressure mm of Hf 2 | Desired Differential Pressure mm of Hg 3 | Actual Velocity Reading FPM 4 | Standard Velocity Reading SFPM 5 | Difference Between 1 and 5 Percent 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 | 0.0125 | 1070 | 1019 | 1.90 |
| 750 | 0.068 | 0.071 | 806 | 768 | 2.40 |

Room Temperature = 78° F, Barometric Pressure = 29.04" of mercury

Dew point = 52° F (Vapor pressure = 9.85 mm of water)

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 1 | Standard Differential Pressure mm of Hf 2 | Desired Differential Pressure mm of Hg 3 | Actual Velocity Reading FPM 4 | Standard Velocity Reading SFPM 5 | Difference Between 1 and 5 Percent 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, Barometric Pressure = 28.94" of mercury

Dew point = 47° F (Vapor pressure = 8.23 mm of water)

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 1 | Standard Differential Pressure mm of Hf 2 | Desired Differential Pressure mm of Hg 3 | Actual Velocity Reading FPM 4 | Standard Velocity Reading SFPM 5 | Difference Between 1 and 5 Percent 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, Barometric Pressure = 28.94" of mercury

Dew point = 47° F (Vapor pressure = 8.23 mm of water)

## IV. 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 $V_T$ as air velocity at the test point. The test point is located at 2" downstream of the entrance to the test section (plexiglass section), and at the middle of the cross section (2" from either side, 2" from the top, 2" from the bottom). Air stream velocities, V, at various points within the test section were measured using LDV and normalized by dividing them by $V_T$. Thus, the non-deviation of the ratio $V/V_T$ 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 Figure A1 thru A3. 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. Figure A4 thru A6 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.

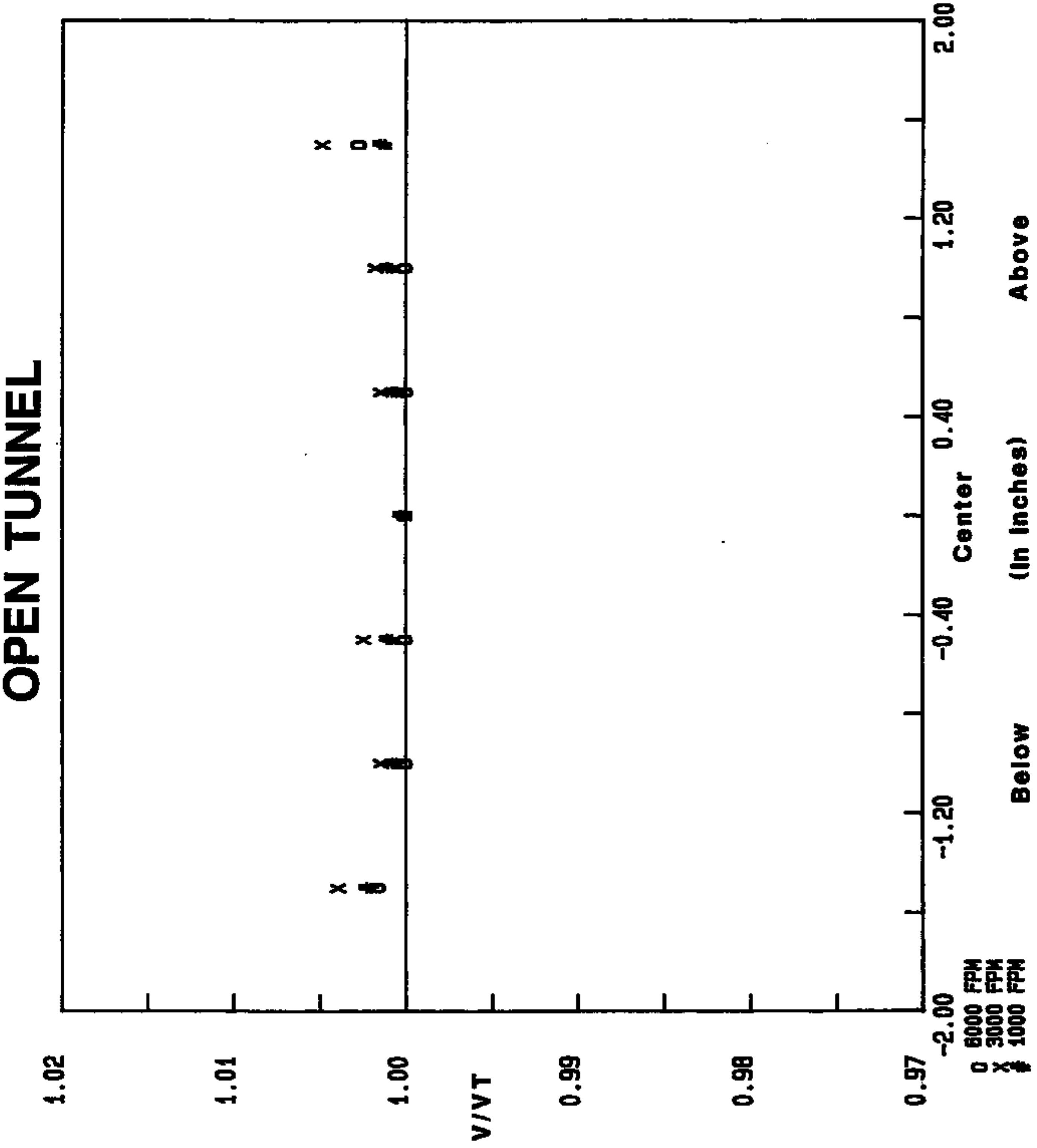

OPEN TUNNEL
V/VT
1.02
1.01
1.00
0.99
0.98
0.97
-2.00
-1.20
-0.40
0.40
1.20
2.00
Below
Center
(In Inches)
Above
0 6000 FPM
X 3000 FPM
# 1000 FPM

Figure A1 (a)

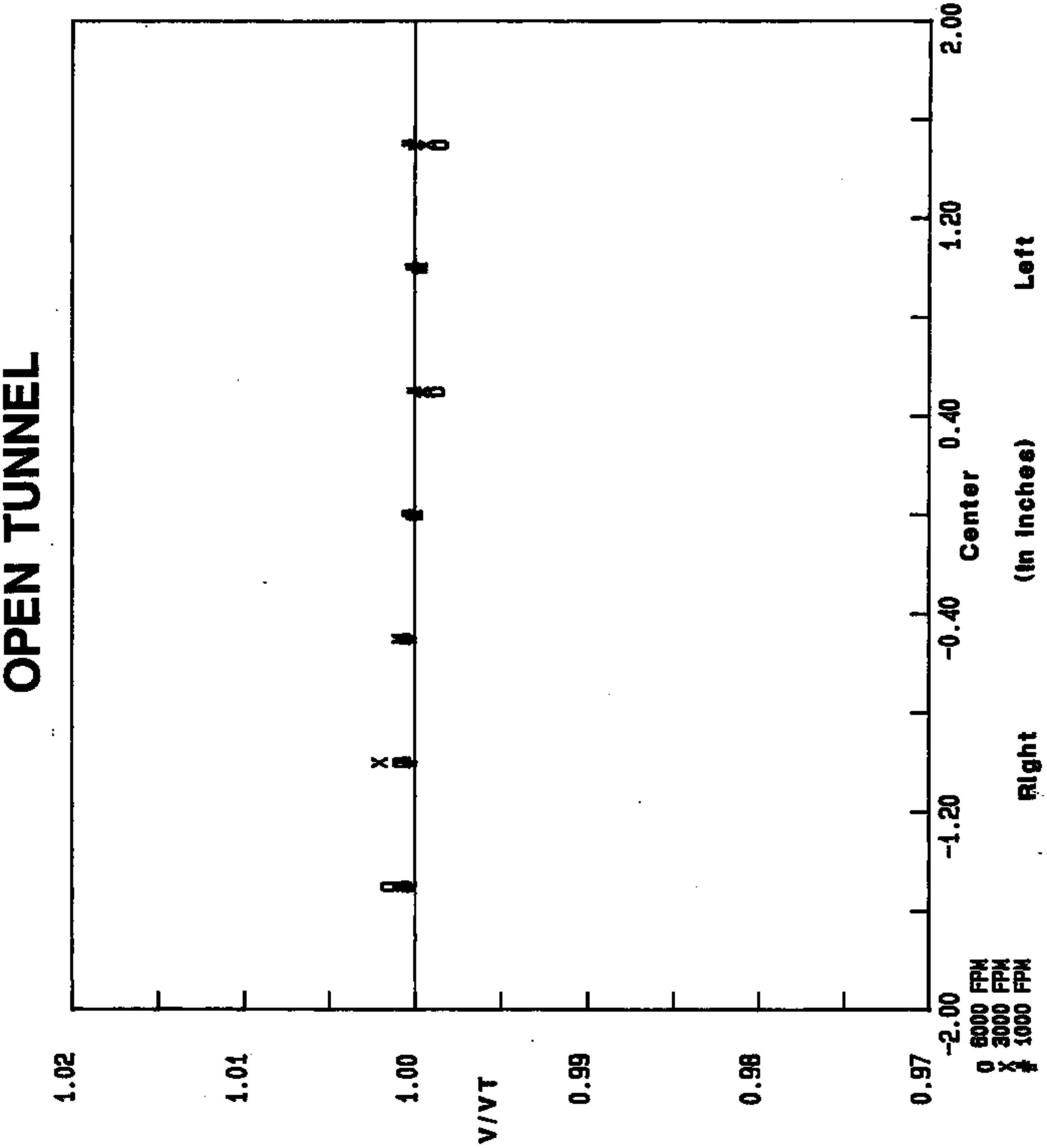

OPEN TUNNEL
V/VT
1.02
1.01
1.00
0.99
0.98
0.97
-2.00
-1.20
-0.40
0.40
1.20
2.00
Right
Center
Left
(In Inches)
0 6000 FPM
X 3000 FPM
# 1000 FPM

Figure A1(b)

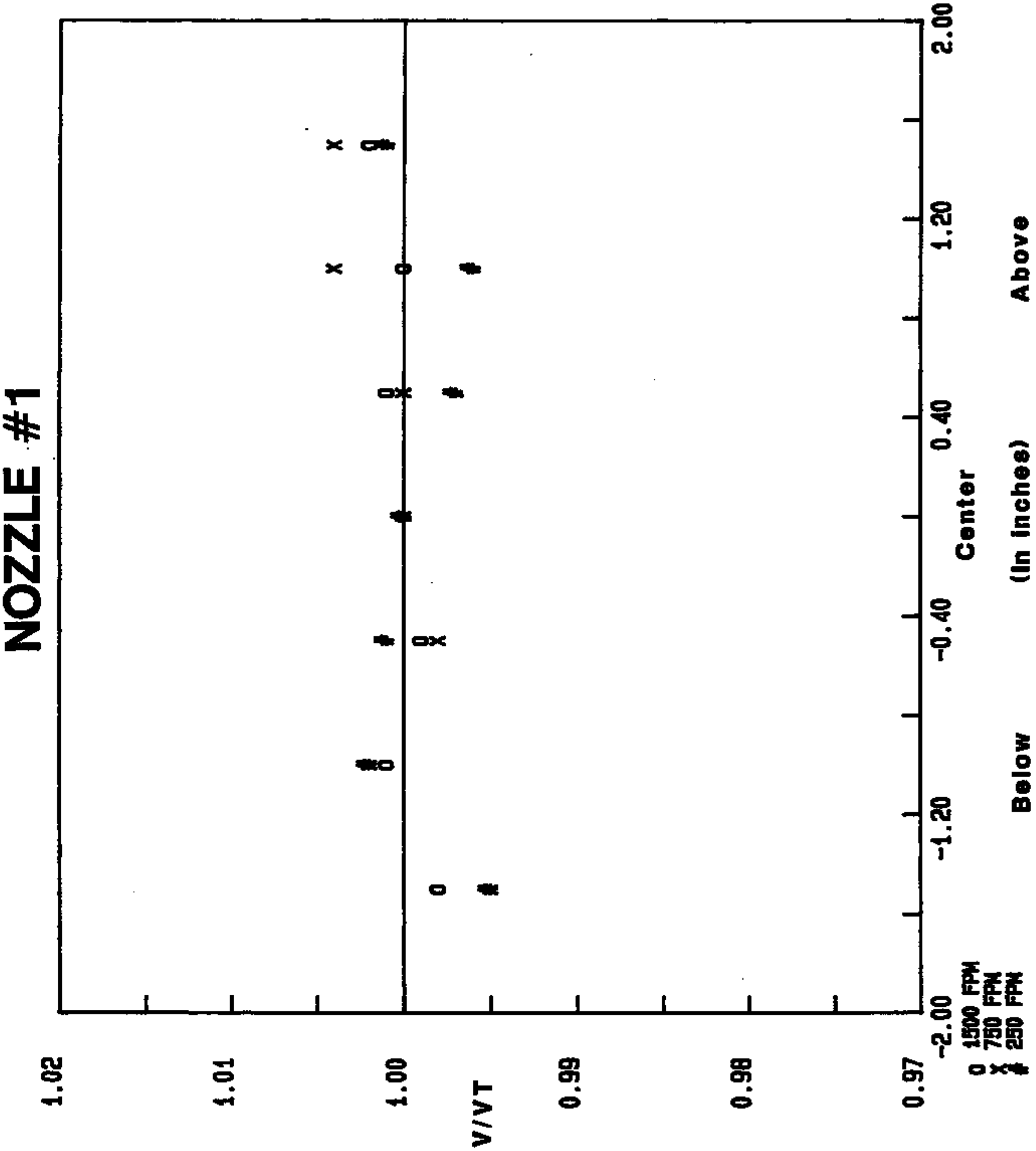

NOZZLE #1
V/VT
1.02
1.01
1.00
0.99
0.98
0.97
-2.00
-1.20
-0.40
0.40
1.20
2.00
Below
Center
Above
(In Inches)
o 1500 FPM
x 750 FPM
# 250 FPM

Figure A2(a)

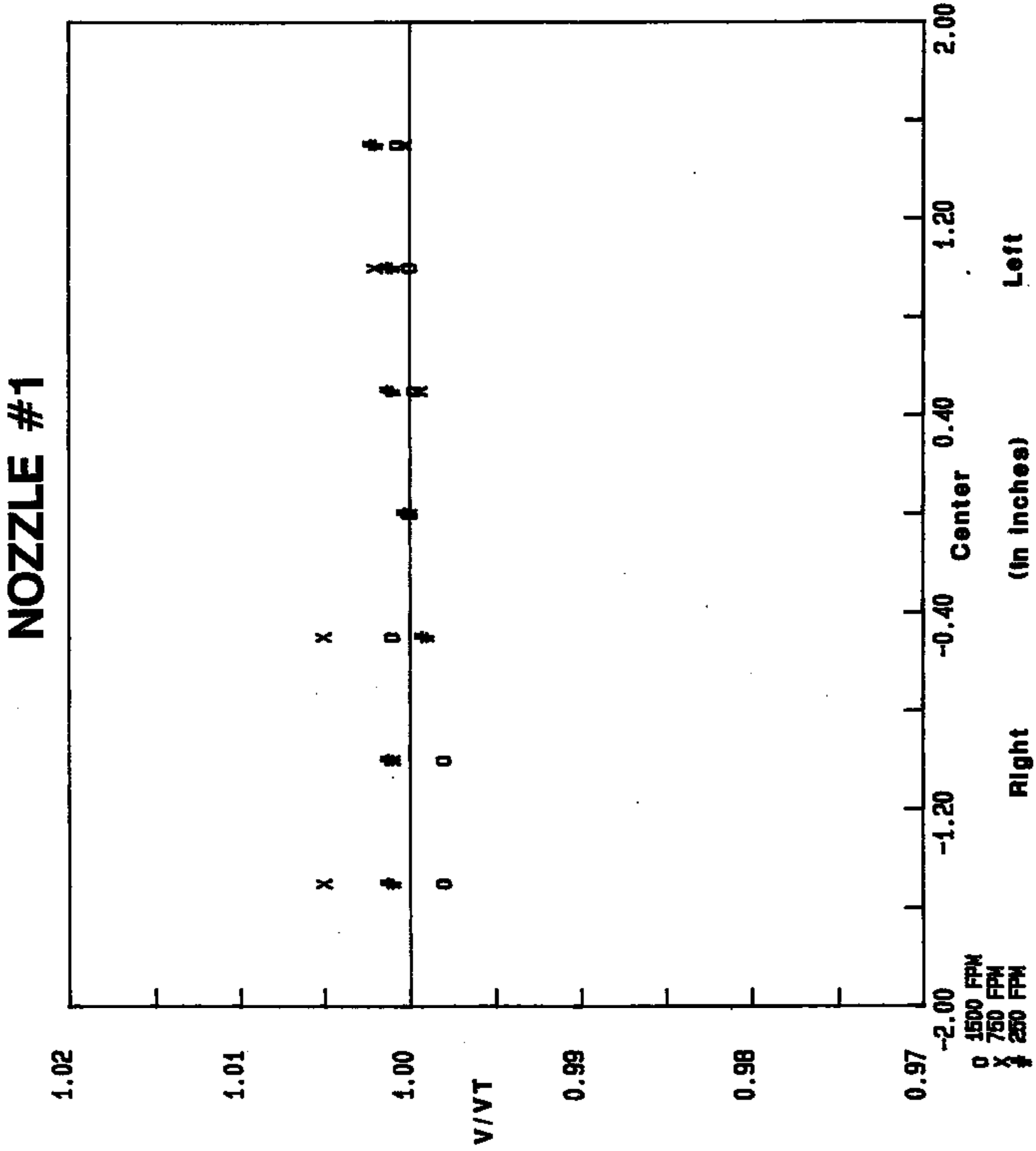

NOZZLE #1
V/VT
1.02
1.01
1.00
0.99
0.98
0.97
-2.00
-1.20
-0.40
0.40
1.20
2.00
Right
Center
Left
(in inches)
o 1500 FPM
x 750 FPM
# 250 FPM

Figure A2(b)

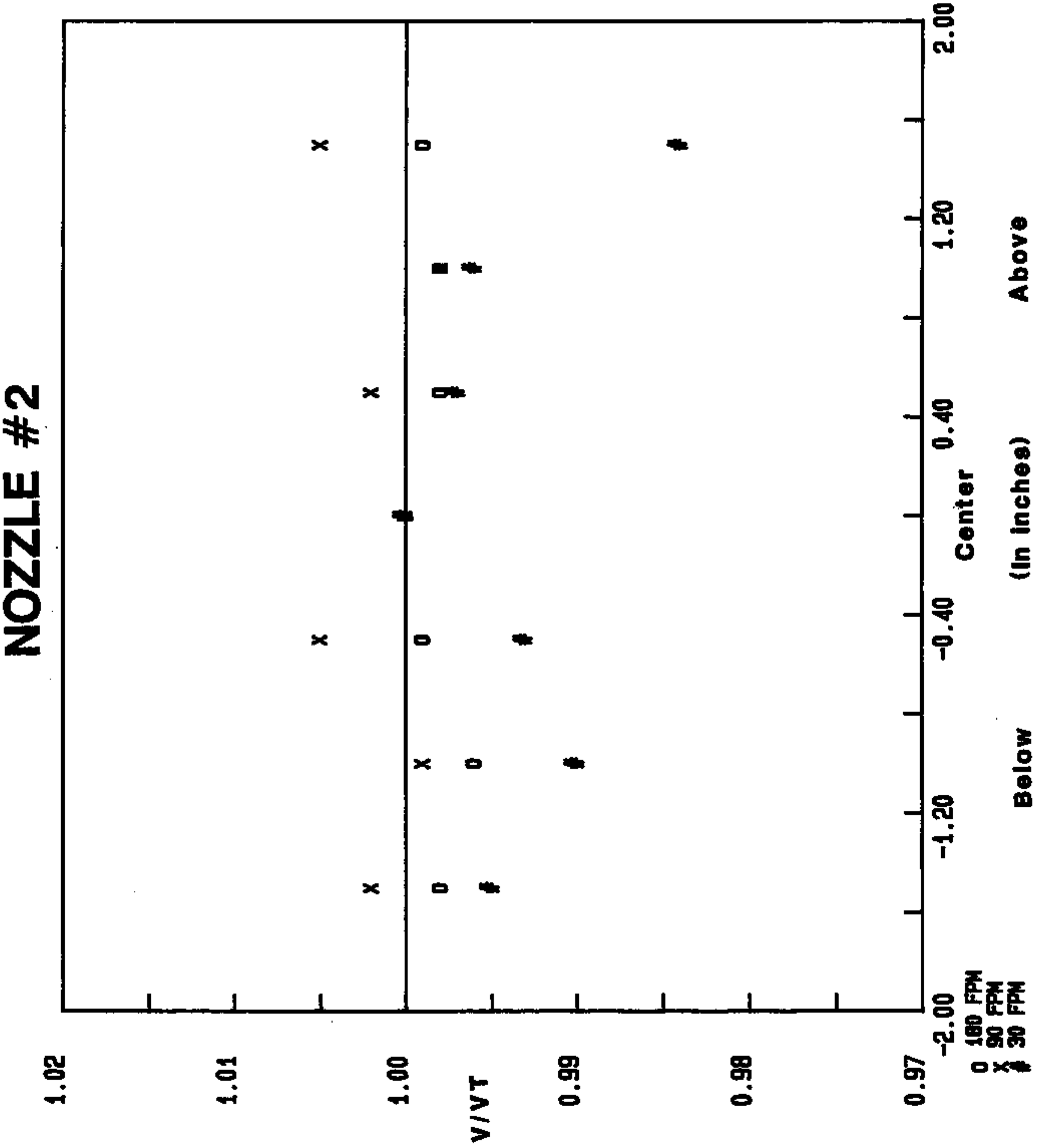
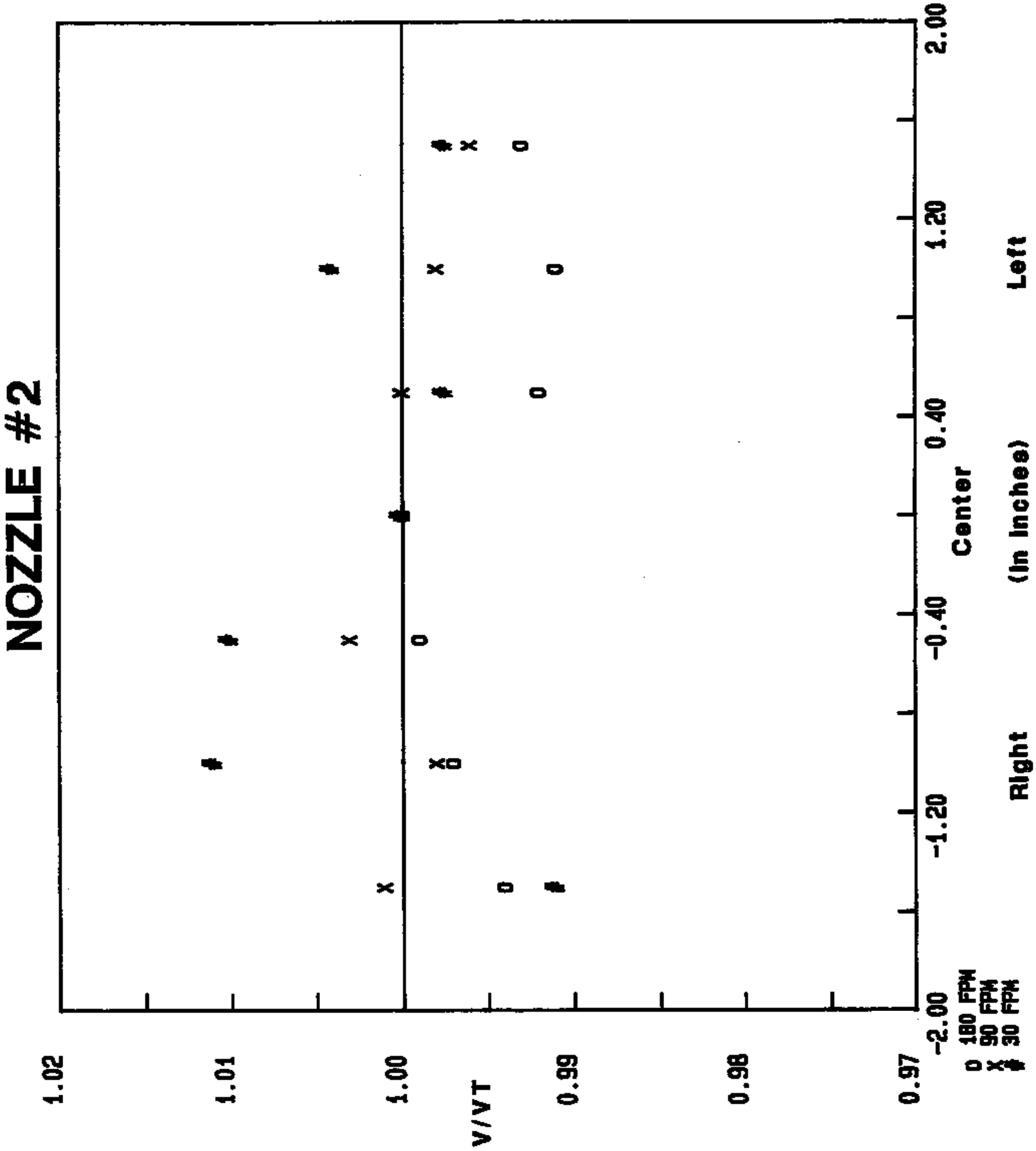

NOZZLE #2
V/VT
1.02
1.01
1.00
0.99
0.98
0.97
-2.00
-1.20
-0.40
0.40
1.20
2.00
Below
Center
Above
(In Inches)
0 180 FPM
X 90 FPM
# 30 FPM

Figure A3 (a)


NOZZLE #2
V/VT
1.02
1.01
1.00
0.99
0.98
0.97
-2.00
-1.20
-0.40
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2.00
Right
Center
Left
(In Inches)
0 180 FPM
X 90 FPM
# 30 FPM

Figure A3(b)

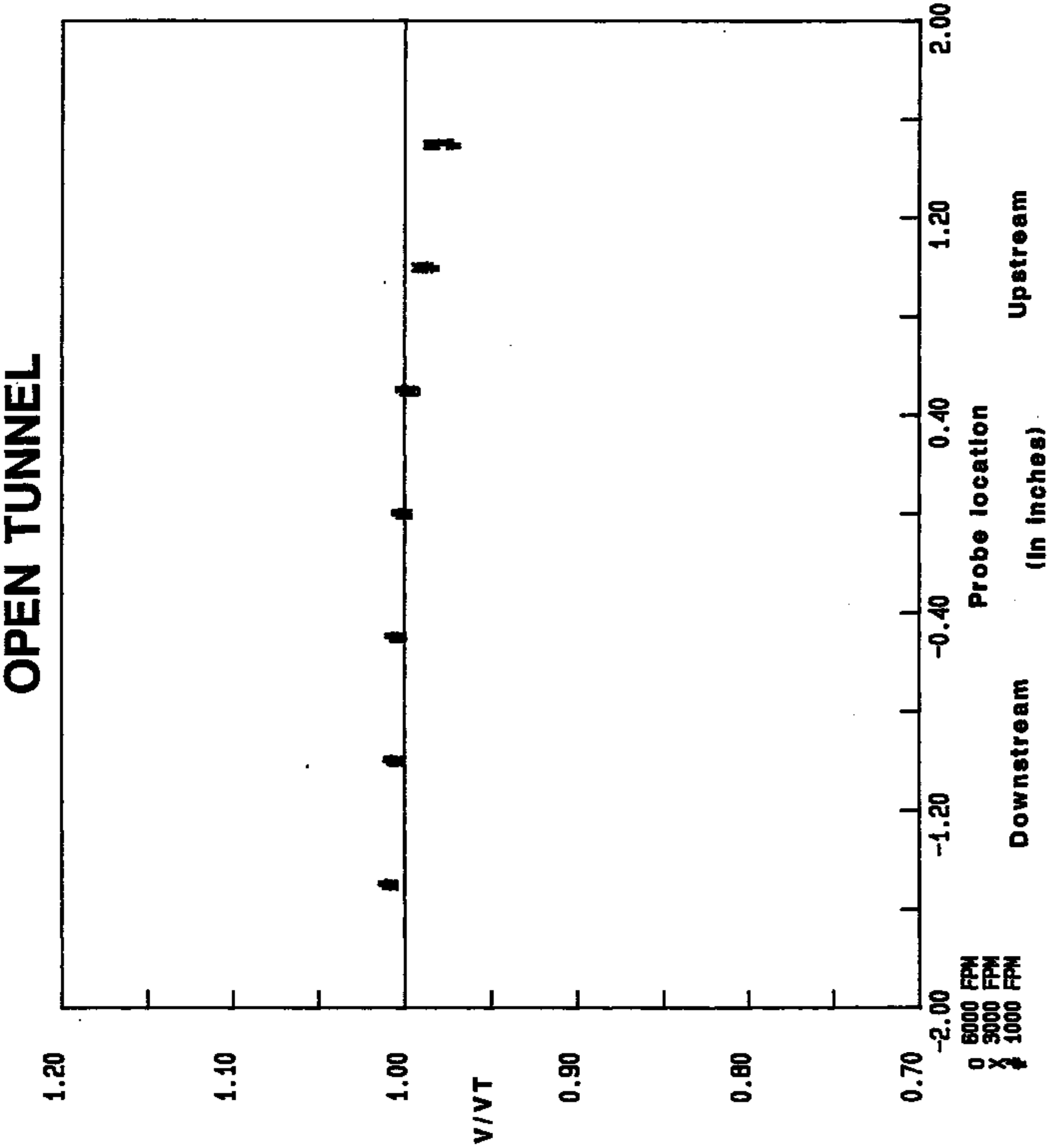
OPEN TUNNEL
V/VT
1.20
1.10
1.00
0.90
0.80
0.70
-2.00
-1.20
-0.40
0.40
1.20
2.00
Probe location
(In inches)
Downstream
Upstream
0 6000 FPM
X 3000 FPM
# 1000 FPM

**Figure A4**

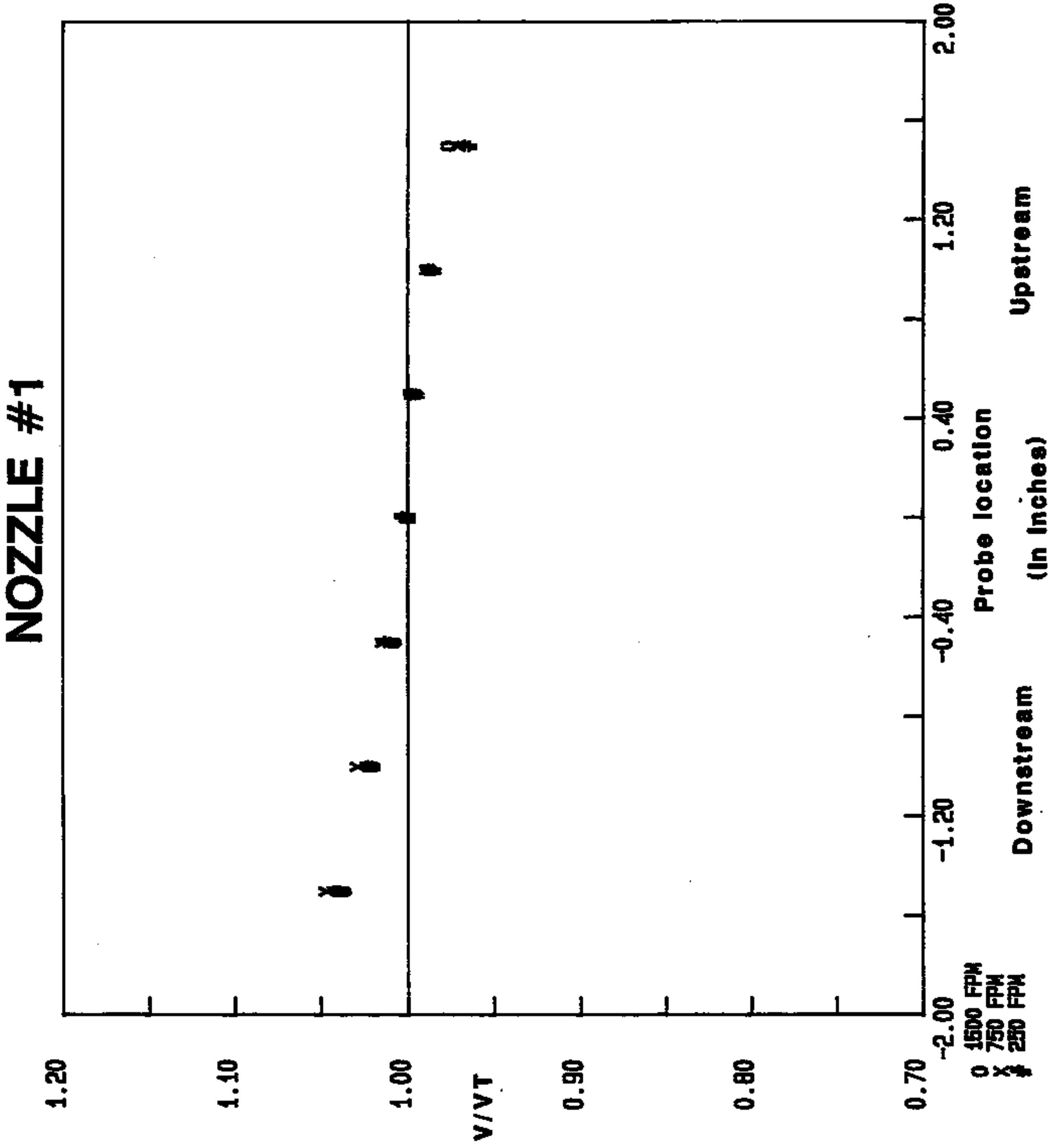
NOZZLE #1
V/VT
1.20
1.10
1.00
0.90
0.80
0.70
-2.00
-1.20
-0.40
0.40
1.20
2.00
Probe location
(In Inches)
Downstream
Upstream
0 1500 FPM
X 750 FPM
# 250 FPM

Figure A5

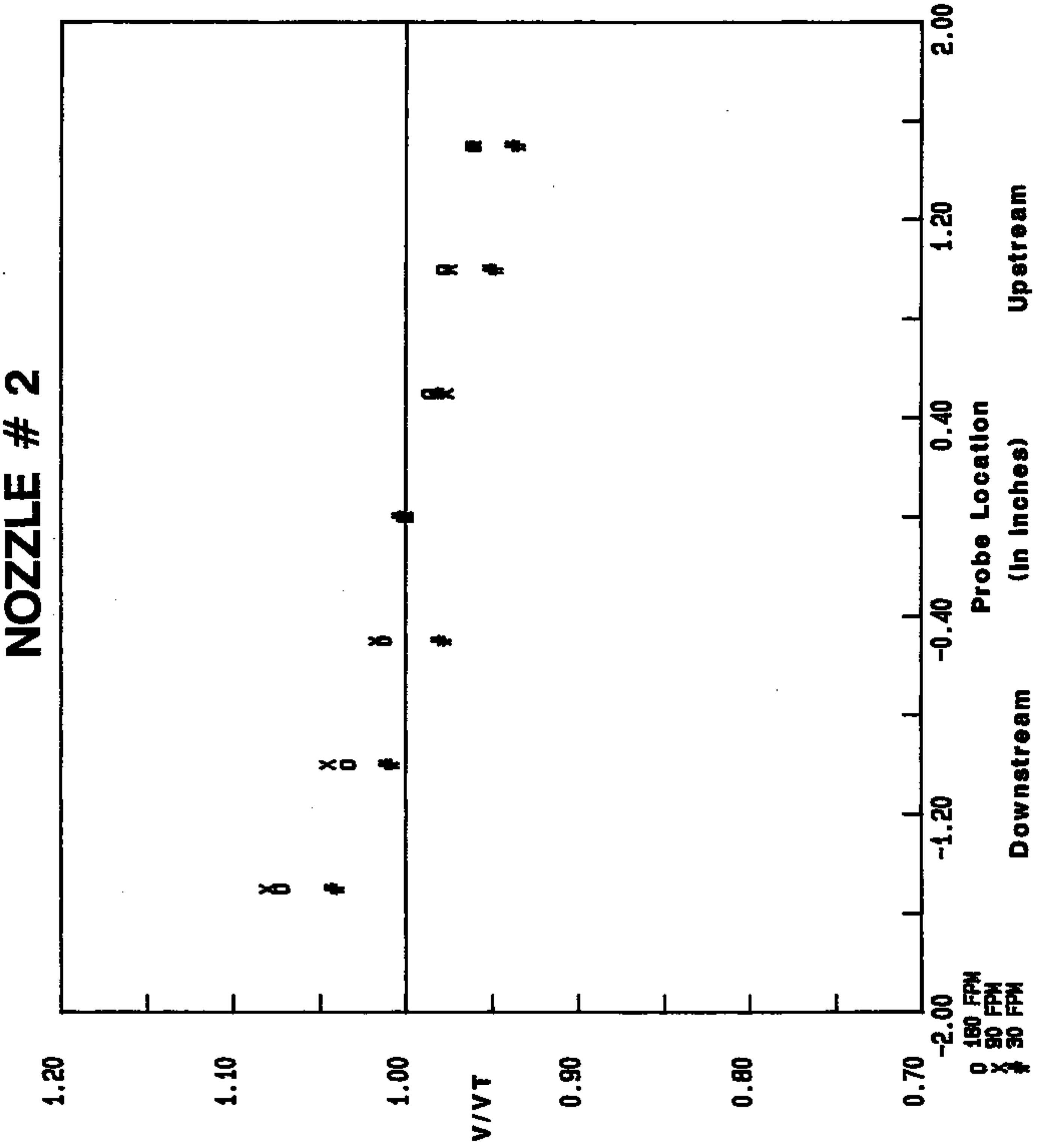
NOZZLE # 2
1.20
1.10
1.00
0.90
0.80
0.70
V/VT
-2.00
-1.20
-0.40
0.40
1.20
2.00
Probe Location
(In Inches)
Downstream
Upstream
0 180 FPM
X 90 FPM
# 30 FPM

Figure A6

## V. 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 NBS 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%.

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

## VI. REFERENCES

1. "A Low-Velocity Airflow Calibration and Research Facility," by L. P. Purtell and P. S. Klebanoff, NBS Technical Note 989, issued March 1979.

2. "Laser Doppler Velocimetry—Performance and Applications," Rajan Menon, American Laboratory, February 1982.

3. "Density of Moist Air," Handbook of Chemistry and Physics, R. C. Weast, editor, CRC Press.

## APPENDIX B Determining Barometric Pressure

For accuracy, you should use the actual barometric pressure inside your building. If you do not have a barometer in your building, you could use the barometric pressure given by a weather station. However, it is important to note that normally the weather stations give barometric pressure corrected to sea level ($P_{SL}$). For density correction, (see Appendix C), the actual barometric pressure, P, at your location (not sea level corrected) should be used.

$$P = P_{SL} - D$$

Where D is the sea level differential from table B1 or B2. The values of D given here are for 70° F. This is slightly different for other temperatures (see Handbook of Chemistry and Physics, R. C. Weast, editor, CRC Press)

TABLE B1. Values of D (Sea Level Differential)

| Elevation | Sea Level Differential D | | |
|---|---|---|---|
| Feet | in of Hg | mm of Hg | Millibar |
| 0 | 0.000 | 0.00 | 0.00 |
| 10 | .011 | .27 | .37 |
| 20 | .022 | .55 | .73 |
| 30 | .032 | .82 | 1.10 |
| 40 | .043 | 1.10 | 1.46 |
| 50 | .054 | 1.37 | 1.83 |
| 60 | .065 | 1.65 | 2.20 |
| 70 | .076 | 1.92 | 2.56 |
| 80 | .086 | 2.19 | 2.93 |
| 90 | .097 | 2.47 | 3.29 |
| 100 | 0.108 | 2.74 | 3.66 |
| 200 | .216 | 5.48 | 7.30 |
| 300 | .323 | 8.20 | 10.94 |
| 400 | .430 | 10.92 | 14.56 |
| 500 | .537 | 13.63 | 18.17 |
| 600 | .643 | 16.33 | 21.78 |
| 700 | .749 | 19.03 | 25.37 |
| 800 | .855 | 21.72 | 28.95 |
| 900 | .960 | 24.39 | 32.52 |
| 1000 | 1.066 | 27.07 | 36.08 |
| 2000 | 2.100 | 53.35 | 71.12 |
| 3000 | 3.105 | 78.86 | 105.13 |
| 4000 | 4.079 | 103.62 | 138.15 |
| 5000 | 5.025 | 127.64 | 170.18 |
| 6000 | 5.943 | 150.95 | 201.26 |
| 7000 | 6.833 | 173.56 | 231.40 |
| 8000 | 7.696 | 195.49 | 260.63 |
| 9000 | 8.533 | 216.74 | 288.97 |
| 10000 | 9.344 | 237.35 | 316.44 |
| 11000 | 10.130 | 257.31 | 343.05 |
| 12000 | 10.892 | 276.66 | 368.84 |

Table B2. Values of D (Sea Level Differential)

| Elevation | Sea Level Differential | | |
|---|---|---|---|
| Meters | in of Hg | mm of Hg | Millibar |
| 0 | 0.000 | 0.00 | 0.00 |
| 10 | .035 | .90 | 1.20 |
| 20 | .071 | 1.80 | 2.40 |
| 30 | .106 | 2.70 | 3.60 |
| 40 | .142 | 3.60 | 4.80 |
| 50 | .177 | 4.49 | 5.99 |
| 60 | .212 | 5.39 | 7.19 |
| 70 | .247 | 6.29 | 8.38 |
| 80 | .283 | 7.18 | 9.57 |
| 90 | .318 | 8.07 | 10.77 |
| 100 | 0.353 | 8.97 | 11.96 |
| 200 | .703 | 17.85 | 23.80 |
| 300 | 1.049 | 26.65 | 35.52 |
| 400 | 1.392 | 35.36 | 47.14 |
| 500 | 1.732 | 43.99 | 58.64 |
| 600 | 2.068 | 52.53 | 70.03 |
| 700 | 2.401 | 60.99 | 81.31 |
| 800 | 2.731 | 69.37 | 92.49 |
| 900 | 3.058 | 77.67 | 103.55 |
| 1000 | 3.381 | 85.89 | 114.51 |
| 2000 | 6.446 | 163.74 | 218.30 |
| 3000 | 9.218 | 234.14 | 312.17 |
| 4000 | 11.719 | 297.66 | 396.85 |

EXAMPLE:

The elevation of Minneapolis/St. Paul is 928 feet. The interpolated sea level differential (D) from Table B1 is .990. On a given day, the sea level corrected barometric pressure given by the weather station was 29.90 ($P_{SL}$). The actual barometric pressure P is given by:

$$P = P_{SL} - D$$

$$P = 29.90 - .990 = 28.91 \text{ in. of Hg.}$$

## APPENDIX C Density Correction Due to Moisture Content

Density of air depends primarily on temperature and atmospheric pressure. However, density of air also depends on its moisture content. For the same temperature and pressure, air becomes lighter as its moisture content increases.

An approximate equation to calculate the density of moist air, $\omega$, is given below:

$$\omega = \omega_a \, (1 - \phi \cdot B) \qquad \text{(C1)}$$

where $\omega_a$ = density of dry air

$\phi$ = relative humidity

B = Vapor pressure factor given in Table C-1

The density correction factor, K, used for calculating desired $\Delta P$ for Column 3, Table 2 is given by:

$$K = \frac{\omega_s}{\omega} = \frac{29.92}{P} \times \frac{(460 + t)}{530} \times (1 + \phi \cdot B) \qquad \text{(C2A)}$$

or

$$K = \frac{\omega_s}{\omega} = \frac{760}{P} \times \frac{(273.15 + t)}{294.25} \times (1 + \phi \cdot B) \qquad \text{(C2B)}$$

where $\omega_s$ = density of air at standard conditions

$\omega$ = density of air at test condition

P = barometric pressure [inches (or mm)] of mercury

t = temperature [°F (or °C)]

Note: $(1 - \phi \cdot B)$ in equation (C1) was replaced by $(1 + \phi \cdot B)$ in equation C2 because $(1 - \phi \cdot B)^{-1}$ is approximately equal to $(1 + \phi \cdot B)$.

Table C-1

| Temperature °C | Temperature °F | Vapor pressure factor B | Temperature °C | Temperature °F | Vapor pressure factor B |
|---|---|---|---|---|---|
| 10 | 50.0 | .0046 | 30 | 86.0 | .0158 |
| 11 | 51.8 | .0049 | 31 | 87.8 | .0168 |
| 12 | 53.6 | .0052 | 32 | 89.6 | .0178 |
| 13 | 55.4 | .0056 | 33 | 91.4 | .0188 |
| 14 | 57.2 | .0060 | 34 | 93.2 | .0199 |
| 15 | 59.0 | .0063 | 35 | 95.0 | .0210 |
| 16 | 60.8 | .0068 | 36 | 96.8 | .0222 |
| 17 | 62.6 | .0072 | 37 | 98.6 | .0234 |
| 18 | 64.4 | .0077 | 38 | 100.4 | .0247 |
| 19 | 66.2 | .0082 | 39 | 102.2 | .0261 |
| 20 | 68.0 | .0087 | 40 | 104.0 | .0276 |
| 21 | 69.8 | .0093 | 41 | 105.8 | .0291 |
| 22 | 71.6 | .0099 | 42 | 107.6 | .0307 |
| 23 | 73.4 | .0105 | 43 | 109.4 | .0323 |
| 24 | 75.2 | .0111 | 44 | 111.2 | .0340 |
| 25 | 77.0 | .0118 | 45 | 113.0 | .0358 |
| 26 | 78.8 | .0126 | 46 | 114.8 | .0377 |
| 27 | 80.6 | .0133 | 47 | 116.6 | .0397 |
| 28 | 82.4 | .0141 | 48 | 118.4 | .0417 |
| 29 | 84.2 | .0150 | 49 | 120.2 | .0438 |

The density correction discussed above is applicable for establishing the actual mass velocity in the wind tunnel. However, the thermal type velocity transducers are sensitive to the composition of air. Thus, as the moisture content of the air changes, a thermal type velocity transducer will give a different output for the same mass velocity. Fortunately, the density correction and error due to composition change compensate and reduce the net error. Table C2 gives typical errors due to density change and composition change. Column 2 shows the actual mass velocity calculated using the K given by equation C2A or C2B. Column 3 shows the apparent mass velocity calculated using the K given in Table 2A (or 2B). Column 4 shows the velocity indicated by a thermal type velocity transducer calibrated with dry air.

Thus, for practical purposes, one may ignore the density correction due to moisture content. However, if one is interested in establishing a velocity standard with better than 1% accuracy, one must take this into consideration.

Table C2. Error in thermal type velocity transducer due to composition change (dry air vs moist air)

Room Temperature 70° F

| Relative Humidity (Percent) 1 | Actual Mass Velocity 2 | Apparent Mass Velocity 3 | Indicated Velocity 4 |
|---|---|---|---|
| 0 | 100 | 100 | 100.00 |
| 10 | 99.95 | 100 | 100.17 |
| 20 | 99.90 | 100 | 100.34 |
| 30 | 99.85 | 100 | 100.51 |
| 40 | 99.80 | 100 | 100.68 |
| 50 | 99.75 | 100 | 100.85 |
| 60 | 99.70 | 100 | 101.02 |
| 70 | 99.65 | 100 | 101.19 |
| 80 | 99.60 | 100 | 101.36 |
| 90 | 99.55 | 100 | 101.53 |
| 100 | 99.50 | 100 | 101.68 |

**APPENDIX D**

**Conversion Factors**

| To convert from: | To: | Multiply by: |
|---|---|---|
| Velocity | | |
| Feet per minute (FPM) | Meters per second (m/s) | 0.00508 |
| | Miles per hour | 0.01136363 |
| | Kilometers per hour | 0.018288 |
| | Knots | 0.0098747 |
| Meters per second (m/s) | Feet per minute (FPM) | 196.85039 |
| | Miles per hour | 2.2369363 |
| | Kilometers per hour | 3.6 |
| | Knots | 1.9438445 |
| Pressure | | |
| Millimeters of mercury (mm of Hg) | Torrs | 1 |
| | Pounds per square inch | 0.0193368 |
| | Bars | 0.00133322 |
| | Atmospheres | 0.0013157895 |
| | Dynes per square centimeter | 1333.224 |
| | Pascal | 133.322 |
| | Inches of water | .53525 |
| | Inches of mercury | 0.03937 |

**TSI Incorporated**
**Industrial Test**
**Instruments Group**
*500 Cardigan Road*
*P.O. Box 64394*
*St. Paul, MN 55164*
*Telephone:* **1-800 876 9874**
*or 612 490 2888*
*Telex: 6879024*
*Fax: 612 490 2874*