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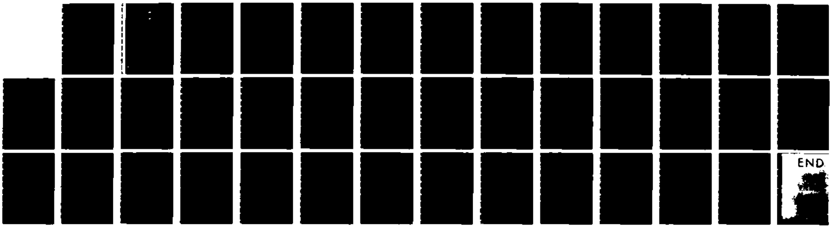

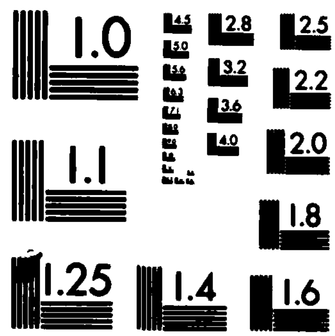

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CALIBRATION OF ENGINES LABORATORY AIR FLOW MEASURING DEVICES

by

S.J. Chiappetta

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
TECHNICAL NOTE 83-35

Canada

December 1983
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Energy Systems Section
Energy Conversion Division

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ABSTRACT

This note documents the calibration of the two air flow measuring instruments used in the DREO Engines Laboratory. It was found that the calibration performed agrees closely with the manufacturer's calibration. Functional relationships to acquire air flow from each instrument's output are suggested for use in computer programs.

RESUME

La présente note porte sur l'étalonnage des deux instruments de mesure du débit d'air utilisés dans les laboratoires des machines du Centre de recherches pour la Défense/Ottawa. On a trouvé que l'étalonnage réalisé correspond étroitement aux chiffres du fabricant. Voici des fonctions mathématiques pour calculer le débit de chacun par ordinateur.

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INTRODUCTION

In our laboratory, air flow is measured by two devices, a "turbine type" flow transducer and a flow nozzle. They are located in series on the engine intake air ducting, with the flow transducer being upstream of the flow nozzle, Figure 1. The maximum air flow to be measured is 50.0 cfm.

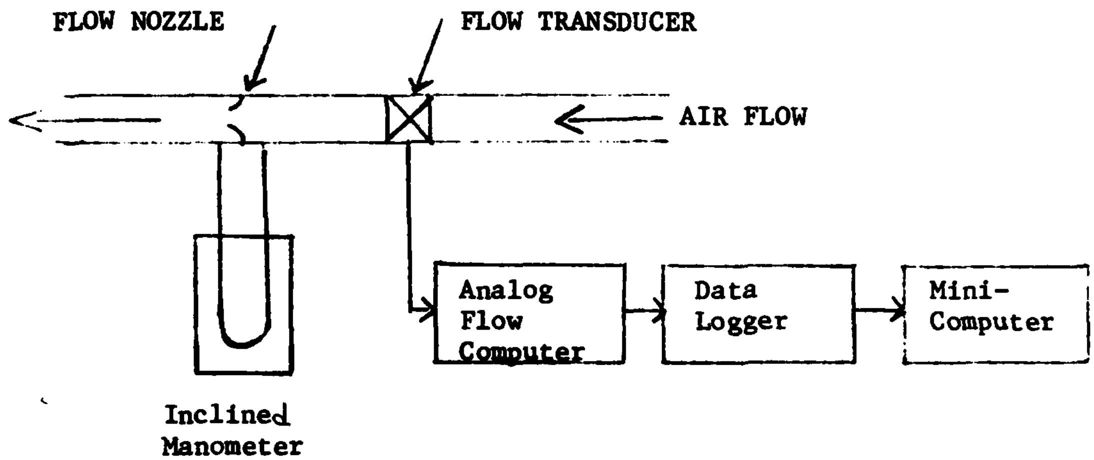


Figure 1: Schematic of Air Flow Measuring System.

The flow transducer produces a signal whose frequency is proportional to the volumetric flow rate. This signal is received by an Analog Flow Computer which displays either the frequency or the air flow on a digital readout. The flow computer also produces an analog potential (voltage) which is proportional to the values on the digital readout. This analog potential is fed to a data logger which is interfaced with a mini-computer.

The flow nozzle causes a static pressure drop in the air flow which is proportional to the volumetric flow rate. This pressure drop, as measured by an inclined manometer, is entered into the computer manually.

Conflicting flow measurements produced by these devices made it necessary to have them calibrated. Also discrepencies between indicated flow and the flow the computer used in calculations indicated the need for an investigation.

The calibration of the flow meters was performed by Consumer and Corporate Affairs, Legal Metrology Branch of the Canadian Federal Government. Subsequent to this an experiment was carried out to correlate the digital display of the flow computer to the analog potential it produces. Finally a functional relationship between the analog potential and actual flow was established for use by the computer. Also a relationship between actual flow and flow nozzle differential pressure was found.

EQUIPMENT TESTED

The turbine flow meter tested is a series 100A, Model 200F, Air Flow Transducer manufactured by Autotronics Controls Corporation, serial number 572. It was tested in conjunction with a Model 120C, Analog Flow Computer also manufactured by Autotronics Controls Corporation, serial number 107.

The flow nozzle tested is part of an M-5000 Air Fuel Meter system, serial number J12211. The nozzle diameter is 1.183 inches.

EXPERIMENTAL

The calibration performed by Legal Metrology determined the volumetric flow rate by measuring the time required to pass a known volume of gas at a constant rate. A statement of results (Annex I), was supplied which gives indicated flow (displayed by the flow computer) versus actual flow and flow nozzle differential pressure versus actual flow.

To correlate the digital display of the flow computer with the analog potential it produces, a separate test was performed, as illustrated in Figure 2.

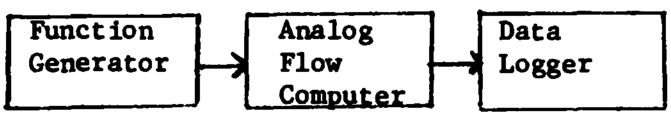


Figure 2: Schematic of test to correlate digital display of flow computer with analog potential.

The function generator produces a frequency signal which simulates the signal of the flow transducer. For various values of indicated flow, the values of analog potential were recorded along with the indicated frequency. The display of the Analog Flow Computer is controlled by a three position switch, positions marked "X1", "X2", and "ADJ". When the switch is in the "X1" position the frequency is displayed, in the "X2" position the frequency divided by two is displayed and in the "ADJ" position the volumetric flow in cfm is displayed. It should be noted that the analog potential produced by this device is different for each position of the switch.

The test data for this correlation test is given in Table I and a detailed description of equipment used is given in Annex II.

TABLE I

DATA TAKEN DURING THE CORRELATION TEST

ANALOG FLOW COMPUTER		FLUKE DATA LOGGER	
Frequency (Hz)*	Volume Flow (cfm)**	Potential (volts)*	Potential (volts)**
897	50.0	2.183	1.216
807	45.0	1.963	1.093
717	40.0	1.743	0.971
628	35.0	1.526	0.850
538	30.0	1.307	0.728
447	25.0	1.086	0.605
358	20.0	0.868	0.484
268	15.0	0.649	0.362
179	10.0	0.432	0.241
88	5.0	0.212	0.118
0	0.1	-0.004	-0.003

* - switch position "X1"

** - switch position "ADJ"

RESULTS AND DISCUSSION

FLOW TRANSDUCER

Table II summarizes the results obtained for the calibration of the flow transducer. Both the new calibration data (Legal Metrology results) and the older manufacturer supplied data is presented. An explanation for the new data will be given first.

TABLE II

FLOW TRANSDUCER CALIBRATION RESULTS

Indicated Flow (cfm)	Indicated Frequency (Hz)	Analog Potential (volts)	Actual Flow (cfm)	Predicted Flow (cfm)	Error (%)
0.1	0	-.004	0	-.02	-
22.0	394	.9559	22.2	22.15	-.23
30.0	538	1.3062	30.2	30.04	-.53
37.0	663	1.6127	37.2	36.86	-.92
42.0	753	1.8317	41.8	41.68	-.29
48.0	861	2.0944	46.8	47.41	1.29
52.0	933	2.2696	51.3	51.19	-.21
6.8	121	.2911	7.01	6.88	1.87
14.2	254	.6152	14.15	14.37	1.56
25.0	448	1.0880	24.84	25.14	1.19
50.7	909	2.2114	50.12	49.94	-.37

First data set new calibration points, second data set manufacturer supplied calibration points.

The indicated flow and actual flow is the data as supplied by Legal Metrology. The indicated frequency and analog potential is obtained from the indicated flow by a straight line relationship as developed from the data taken during the correlation test. Note that when analog potential is referred to, it is inferred that the switch is in the "X1" position. This is true throughout the report unless otherwise specified. It was decided that this is the best position for the switch as it produces larger values of analog potential.

The manufacturer supplied data is actual flow versus indicated frequency. The indicated flow and analog potential are also obtained by a straight line relationship developed from the correlation test data. See Annex III for sample calculations.

A functional relationship between actual flow and analog potential is required so that the computer can determine an actual flow rate from the analog potential values it receives from the data logger. It was decided to fit various polynomials, by the least squares technique, to the data (actual flow versus analog potential) and choose the most appropriate. Since the manufacturer supplied data agrees closely with the new calibration points (see Figure 3), both sets were used in the curve fitting. No correction for density is required as the effect of density on turbine type flow meters is small.

A second order polynomial was chosen,

$$Q_B = -.4346\, V_A^2 + 23.51\, V_A + .072, \quad SSE =^{*} .0808$$

where V_A = analog potential (volts)

Q_B = actual flow (cfm)

Equation is valid for V_A in the range 0 to 3 volts. A plot of the data and the equation is given in Figure 4.

---

* - sum of squared errors

The predicted flow in Table II is the flow predicted by the above equation at the listed analog potential. The percent error is the error between the predicted and actual flow.

Most predicted flow values agree with the ±.2 cfm tolerance Legal Metrology associates with their actual flow data. All but one of the new calibration points have errors of less than one percent. It was felt that closer agreement with the new calibration points, (rather than the manufacturer supplied points) is important.

FLOW NOZZLE

The calibration of the flow nozzle is summarized in the results supplied by Legal Metrology Branch (Annex I). A plot of the calibration points along with the manufacturer supplied curve is shown in Figure 5. The original manufacturer's data is given for dry air of density .07604 lbm/ft^3 and has been corrected to the density of .07372 lbm/ft^3 (Annex IV). The difference between the new calibration points and the manufacturers curve can be explained by the difference in flow conditions. The nozzle is intended for use as an intake from stagnation conditions rather than in a flowing stream.

To obtain a functional relationship between actual flow and differential pressure, polynomials of varying order were fitted to the data. The best curve was found to be a sixth order equation with no constant term. Note that this curve fits the data exactly as there are only six data points. The equation is,

$$Q_B = -.7870\ \Delta p^6 + 8.662\ \Delta p^5 - 37.37\ \Delta p^4 + 80.93\ \Delta p^3$$

$$-95.60\ \Delta p^2 + 74.11\ \Delta p$$

where Q_B = actual flow (cfm)

Δp = flow nozzle differential pressure inches water guage (in. w.g.)

Equation is valid in the range of pressure 0-3 in. w.g. The data points and equation are plotted in Figure 6.

If we consider as standard conditions, a flow medium with a density of .07372 lbm/ft^3 (the average conditions for the calibration), the actual flow at other conditions can be estimated with the following procedure:

1. The flow rate predicted by the above equation is found from the differential pressure measured.

2. A correction factor is calculated from the density of the flowing medium,

$$C_f = \sqrt{\frac{.07372}{\rho}}, \quad \text{where } \rho = \text{ density in lbm/ft}^3$$

(see Statement of Results in Annex II).

3. The correction factor is applied to the calculated flow rate to obtain the actual flow rate at the observed conditions.

A method for calculating air density suitable for use in a computer program has been outlined in Annex III.

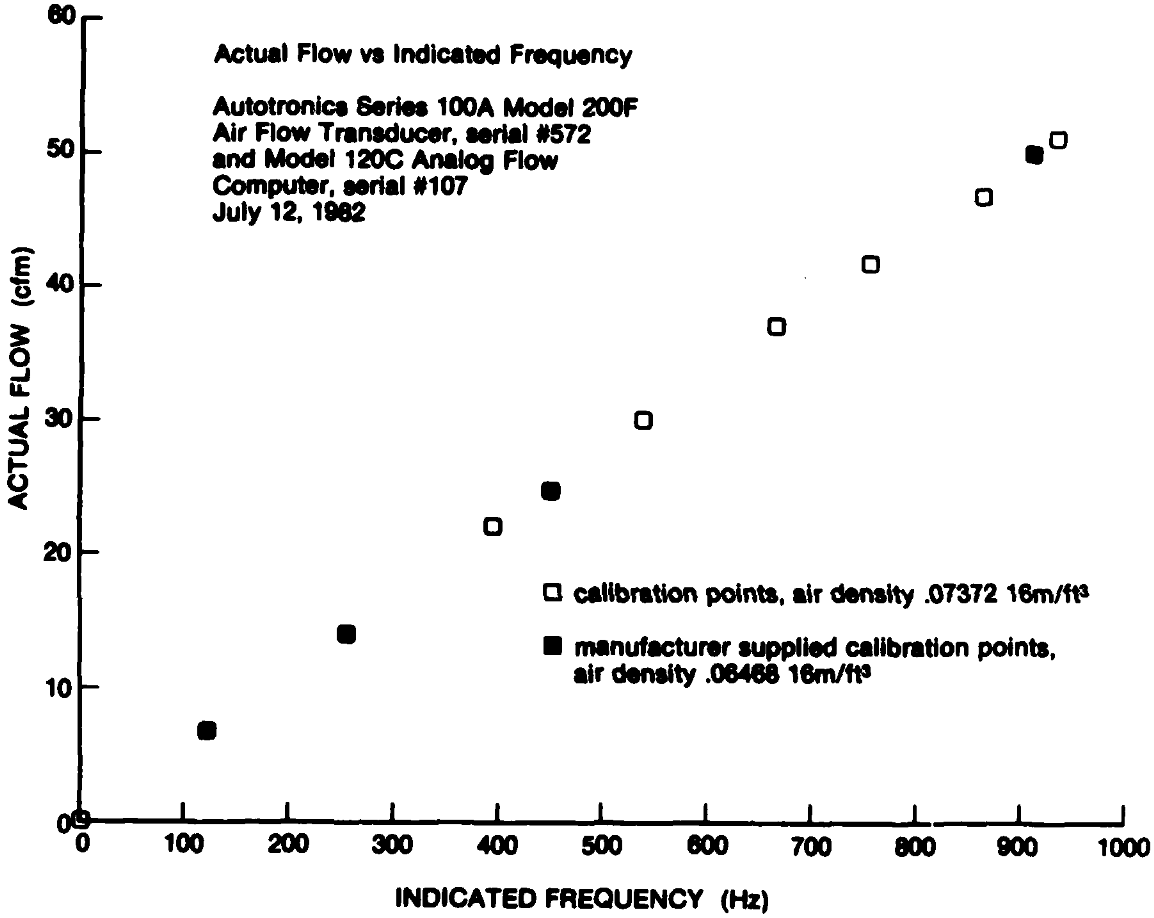


Figure 3. Actual Flow vs Indicated Frequency

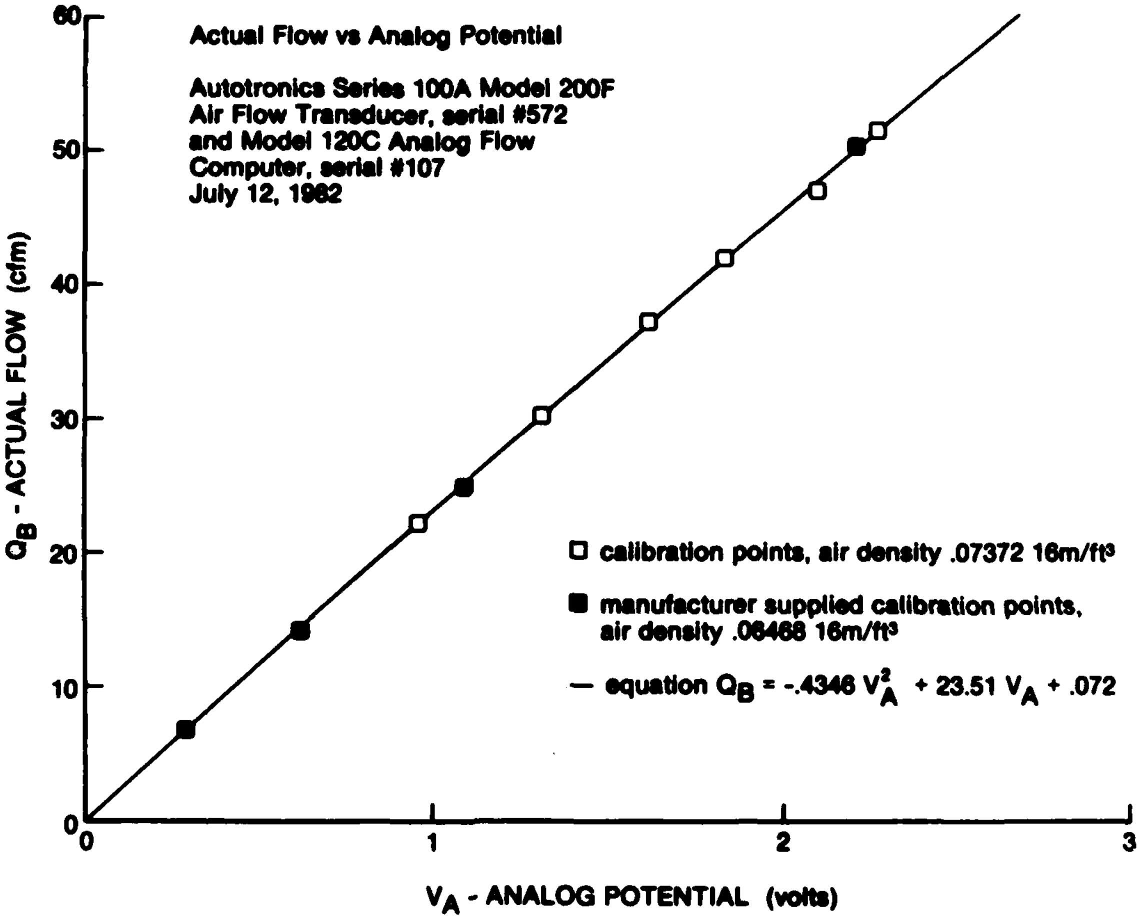


Figure 4. Actual Flow vs Analog Potential

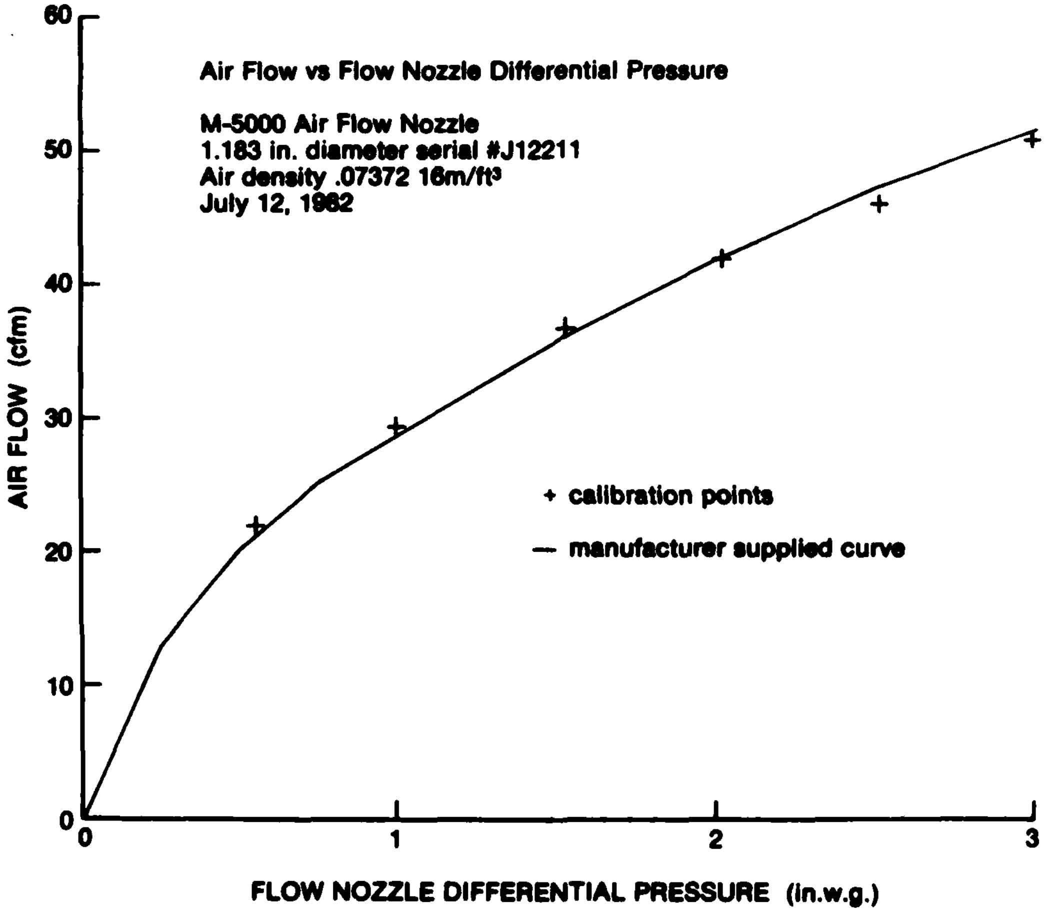


Figure 5. Air Flow vs Flow Nozzle Differential Pressure

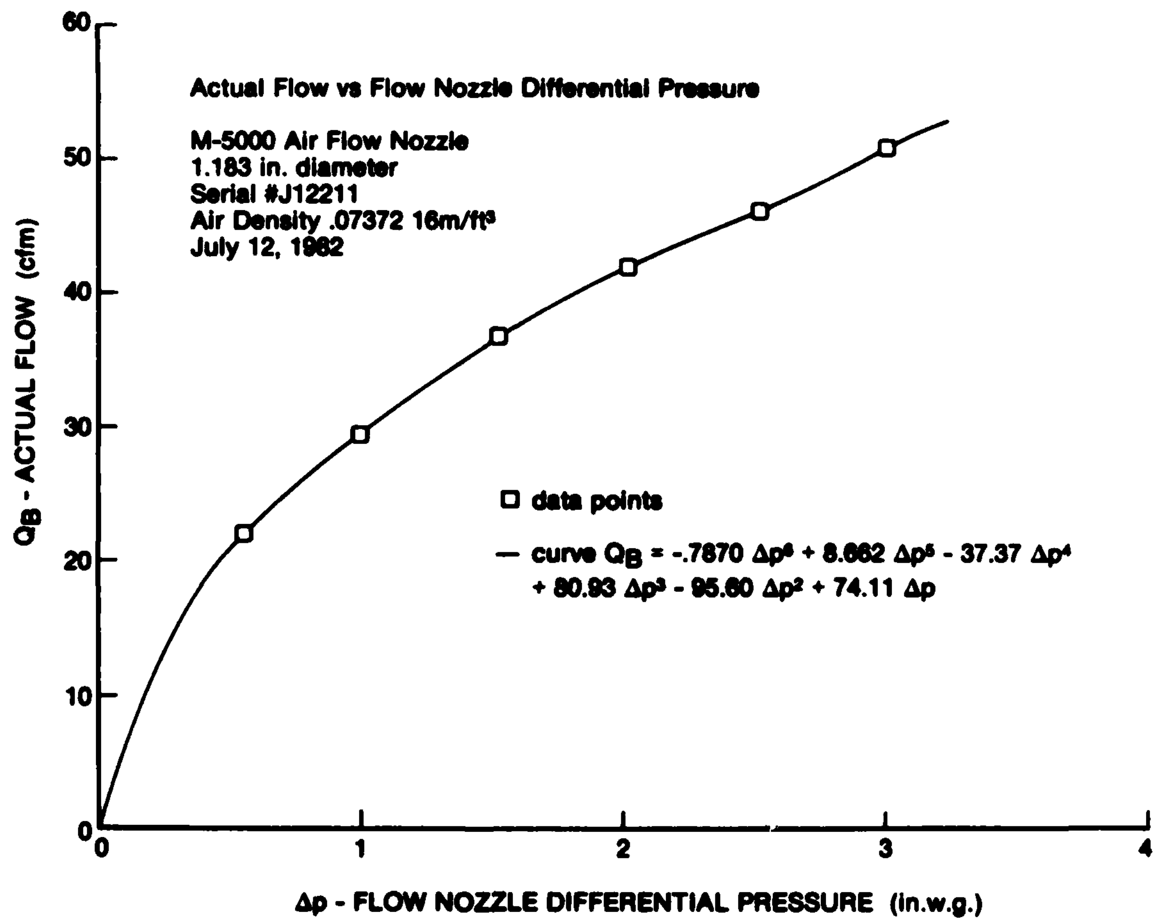


Figure 6. Actual Flow vs Flow Nozzle Differential Pressure

CONCLUSIONS AND RECOMMENDATIONS

Agreement between manufacturer's data and new calibration data suggests confidence in the calibration equations presented. Implementation of these equations should yield predicted flow rates with less than 1% error.

Calibration should have been performed to the analog potential rather than the indicated flow, as it is the analog potential which the computer uses in its calculations. This would make the correlation test unnecessary and eliminate any additional inaccuracies it introduces.

ANNEX I

Consumer and Corporate Affairs Canada | Consommation et Corporations Canada

Legal Metrology Branch
Legal Metrology Laboratories
Standards Building
Tunney's Pasture, Holland Ave.
Ottawa, Ontario
K1A 0C9

Project No.: I-1617

Date: July/82

Statement of Test Results

For

(a) Series 100A, model 200F Gas Turbine Meter S/N 572 (manufactured by Autotronic Controls Corporation) with model 120C Flow Computer, S/N 107,

and

(b) M-5000 Air Flow Nozzle with 1.183 inch diameter throat, S/N J12211.

Property of

Engines Testing Laboratory
Defence Research Establishment (Ottawa)
Department of National Defence

(a) Gas Turbine Meter used with Flow Computer.

Indicated Flow Rate ft^3/minute	True Flow Rate ft^3/minute
22.0	22.2
30.0	30.2
37.0	37.2
42.0	41.8
48.0	46.8
52.0	51.3

Notes:

1) All tests performed at the following average conditions, using laboratory air:

   (a) 68°F flowing/ambient temperature
   (b) 29.5 inches Hg (32°F) absolute pressure
   (c) 62% relative humidity
   (d) This translates to an average flowing meduim density of 0.07372 lbs/ft^3.
   (e) estimated reliability of results is ±0.2 ft^3/m.

(b) Flow Nozzle with Inclined Manometer.

True Flow Rate ft^3/m	Nozzle Differential Pressure Inches W.C. (60°F)
22.3	0.55
29.8	0.99
37.1	1.52
42.3	2.01
46.5	2.51
51.3	2.99

Notes:

1) All tests were performed using air of density 0.07372 lbs/ft^3.

2) (a) to determine the actual volume flow rate at existing flow conditions W.R.T. the observed differential pressure, the following generally Accepted relationship can be used:

$$Q\ \text{ACTUAL} = Q\ \text{STD} \times \sqrt{\frac{\rho\ \text{STD}}{\rho\ \text{ACTUAL}}}$$ where

Q ACTUAL = flow rate (ft^3/m) at existing flow conditions.

Q STD = flow rate (ft^3/m) at air density of 0.07372 lbs/ft^3
(as determined from statement of results above).

ρ STD = density of standard air (0.07372 lbs/ft^3)

ρ ACTUAL = density of existing air in lbs/ft^3.

(b) actual mass flow = Q ACTUAL x ρ ACTUAL x 60 lbs/hr.

3) estimated reliability of results, using the results and flow relationship above, is ±1%.

R. Drolet
Examiner R. Drolet

W. Hamilton
W. Hamilton
A/Head Gas Laboratory

Ref. No. G-6642-1

ANNEX II

EQUIPMENT LIST

DESCRIPTION	MANUFACTURER	SERIAL NUMBER
Air Flow Transducer Series 100A, Model 200F	Autotronics	572
Analog Flow Computer Model 120C	Autotronics	107
Flow Nozzle 1.183 in diameter	Go Power Systems	J1211
Data Logger Model 2240 B	Fluke	2136005
Function Generator Model 3311A	Hewlett Packard	1244A16317

ANNEX III

SAMPLE CALCULATIONS

SAMPLE CALCULATIONS

1. Calculations for Air Flow Transducer

a. From data in Table 3, fit a straight line to the indicated frequency versus the indicated flow:

$$f_i = 17.97\ Q_i - 1.5 \qquad (1)$$

where f_i = indicated frequency (Hz)
Q_i = indicated flow (cfm)
See Figure 7.

b. From data in Table 3, fit a straight line to the analog potential versus the indicated flow:

$$V_A = .04379\ Q_i - .00753 \qquad (2)$$

where V_A = analog potential (volts) switch on flow computer in the "X1" position for V_A.
See Figure 8.

c. From data in Table 3, fit a straight line to the analog potential versus the indicated frequency:

$$V_A = .002437\ f_i - .0038 \qquad (3)$$

where switch on flow computer in the "X1" position for V_A.
See Figure 9.

d. Data supplied by Legal Metrology Branch gives true flow and indicated flow. To change indicated flow to indicated frequency use equation (1), for $Q_i = 22.0$ cfm get,

$$f_i = 17.97\ Q_i - 1.5$$
$$= 17.97\ (22.0) - 1.5$$
$$= 394\ \text{Hz}.$$

Also need to change indicated flow to analog potential, use equation (2) for this. When $Q_i = 22.0$ cfm get,

$$V_A = .04379\ Q_i - .00753$$
$$= .04379\ (22.0) - .00753$$
$$= .9559\ \text{volts}.$$

e. Data supplied by manufacturer of flow transducer gives true flow and frequency. To change frequency to indicated flow use equation (1) solving for Q_i get,

$$Q_i = \frac{f_i + 1.5}{17.97}$$

For $f_i = 121$ Hz get,

$$Q_i = \frac{121 + 1.5}{17.97}$$
$$= 6.8\ \text{cfm}.$$

To change frequency to analog potential use equation (3), for $f_i = 121$ Hz get,

$$V_A = .002437\ f_i - .0038$$
$$= .002437\ (121) - .0038$$
$$= .2911\ \text{volts}.$$

f. By using least squares, polynomials of varying orders were fit to the data of actual flow and analog potential. After considering polynomials of order 1, 2, 3, 4 and 6, a second order polynomial was chosen on the basis of sum of the squared errors (SSE) and percent error with actual data. The polynomial chosen is

$$Q_B = -.4346\ V_A^2 + 23.51\ V_A + .07$$

$$SSE = .0808$$

The predicted flow is calculated using the above equation, for $V_A = .9559$

$$Q_B = -.4346\ (.9559)^2 + 23.51\ (.9559) + .07$$
$$= 22.15 \text{ cfm.}$$

$$\text{Percent error} = \left(\frac{22.15 - 22.2}{22.2}\right) \times 100$$
$$= -.23\% \ .$$

2. Calculations for Flow Nozzle

a. The data for actual flow versus differential pressure was fitted with a 6th order polynomial,

$$Q_B = 74.11\ \Delta p - 95.60\ \Delta p^2 + 80.93\ \Delta p^3 - 37.37\ \Delta p^4 + 8.662\ \Delta p^5 - .7870\ \Delta p^6$$

where Δp = differential pressure (in w.g.)
Q_B = actual air flow (cfm)

This equation is valid for Δp in the range 0-3 in w.g. and for air density of .07372 lbm/ft^3.

b. To correct data taken at other conditions, take the differential pressure and find Q_B as predicted by the above equation. This value for air flow must then be corrected by the following correction factor.

$$C_f = \sqrt{\frac{.07372}{\rho}}$$

where ρ is the density of the flowing medium. This correction factor applied to Q_B gives the actual air flow at the density ρ.

c. To calculate the density of air at measured conditions we must know the dry bulb temperature, the relative humidity and the absolute pressure. A knowledge of the saturation pressure of steam at various temperatures must also be available, this is usually found from steam tables. To easily incorporate this into a computer program a functional relationship between saturation pressure and temperature was found. A third order polynomial was fitted to a plot of saturation pressure versus temperature,

$$p_g = -.1200 + .009066\ T_d - 1.403 \times 10^{-4}\ T_d^2 + 1.561 \times 10^{-6}\ T_d^3$$

$$SSE = 1.37 \times 10^{-8}$$

where p_g = saturation pressure (p.s.i.a.)

T_d = dry bulb temperature (°F)

See Figure 10.

Now to calculate density we define the following variables,

p_t = total absolute pressure

ϕ = relative humidity

p_v = partial pressure of water vapour

p_a = partial pressure of dry air

R_a = gas constant for dry air

R_v = gas constant for steam

The density of the steam-air mixture is given by

$$p = \frac{p_a}{R_a T_d} + \frac{p_v}{R_v T_d}$$

By definition

$$p_v = \phi p_g$$

By Dalton's model of partial pressures

$$p_a = p_t - p_v$$

Saturation pressure (p_g) is calculated using the above polynomial.

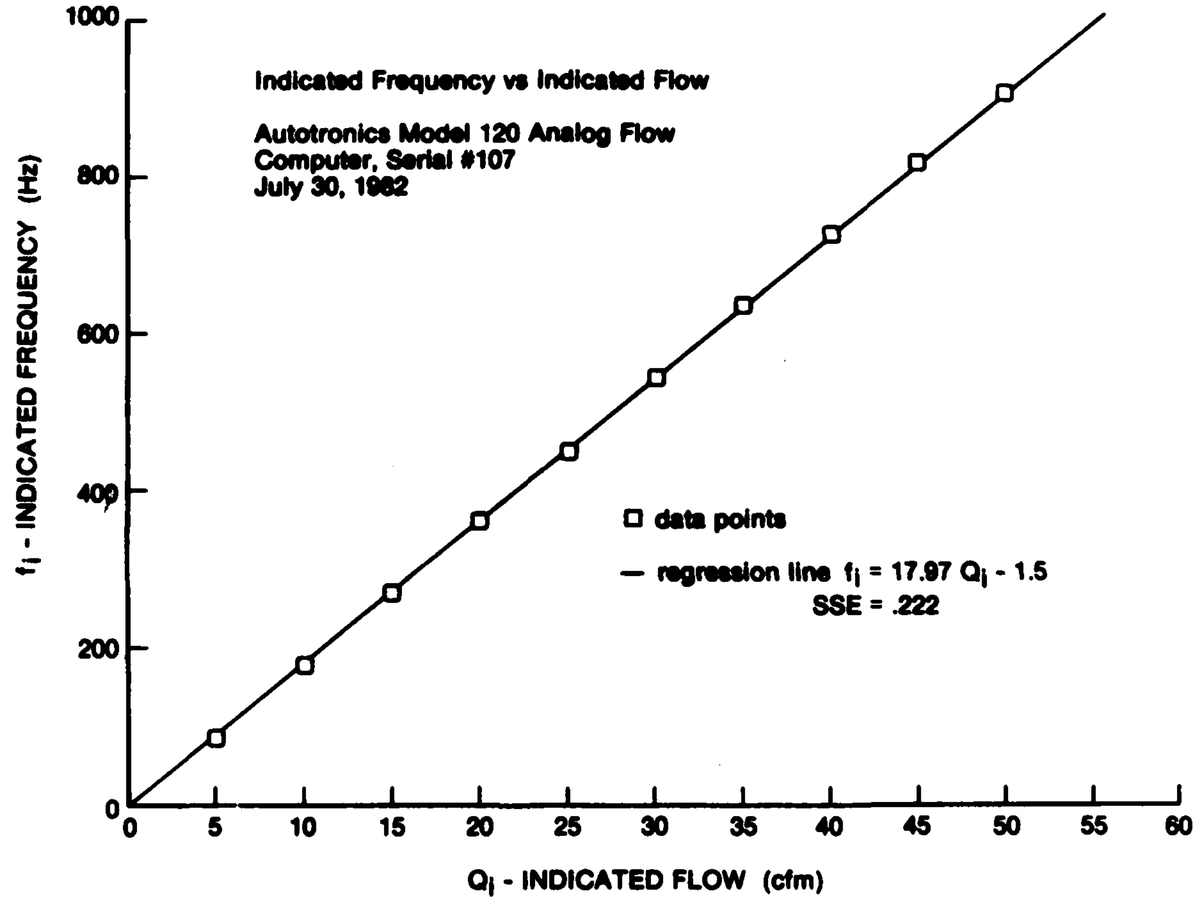


Figure 7. Indicated Frequency vs Indicated Flow

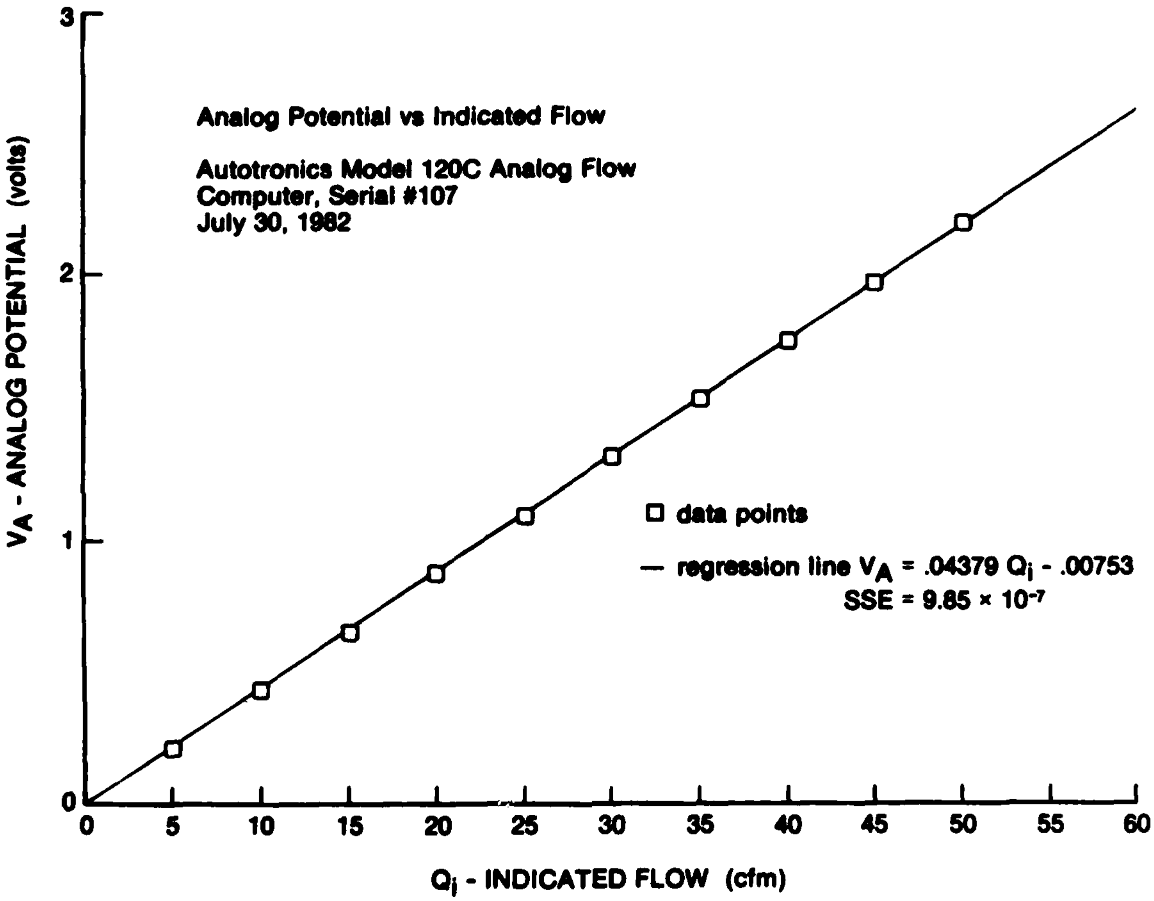


Figure 8. Analog Potential vs Indicated Flow

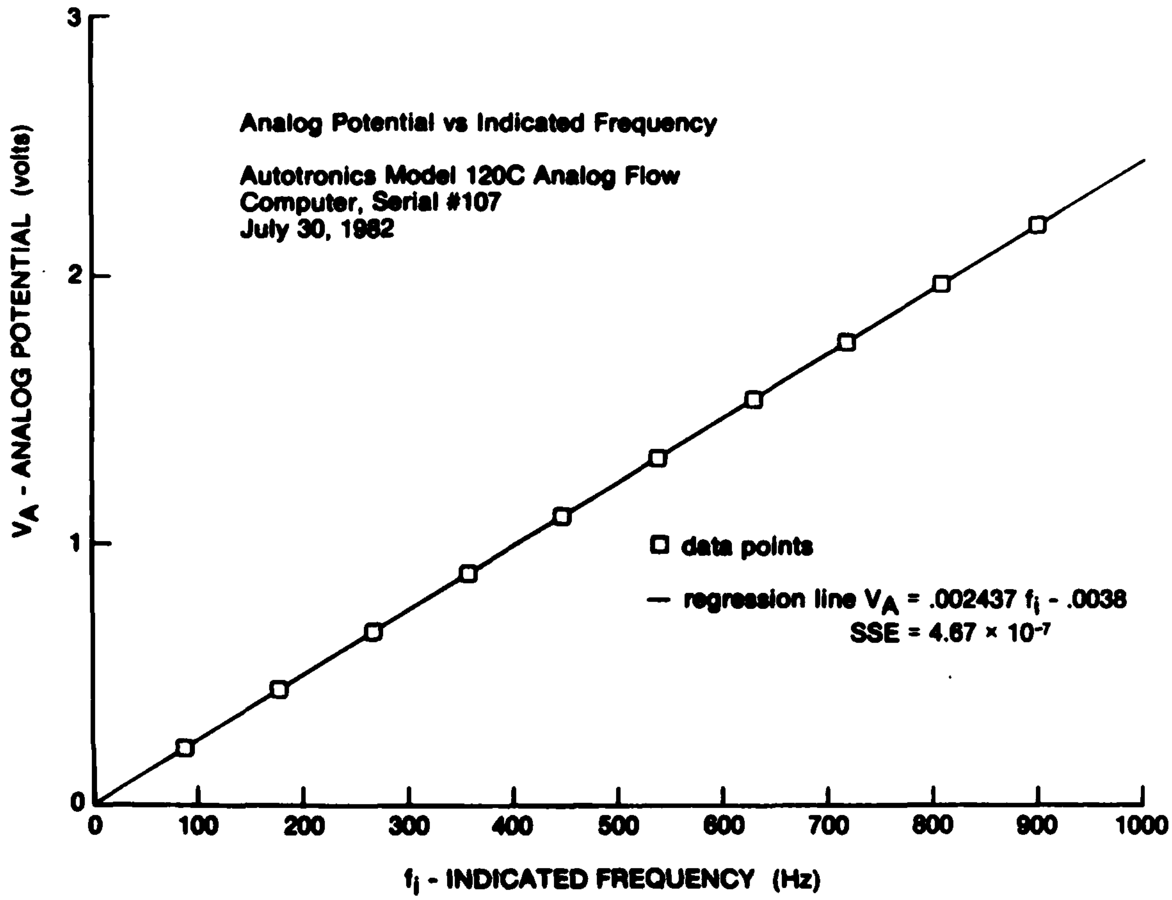


Figure 9. Analog Potential vs Indicated Frequency

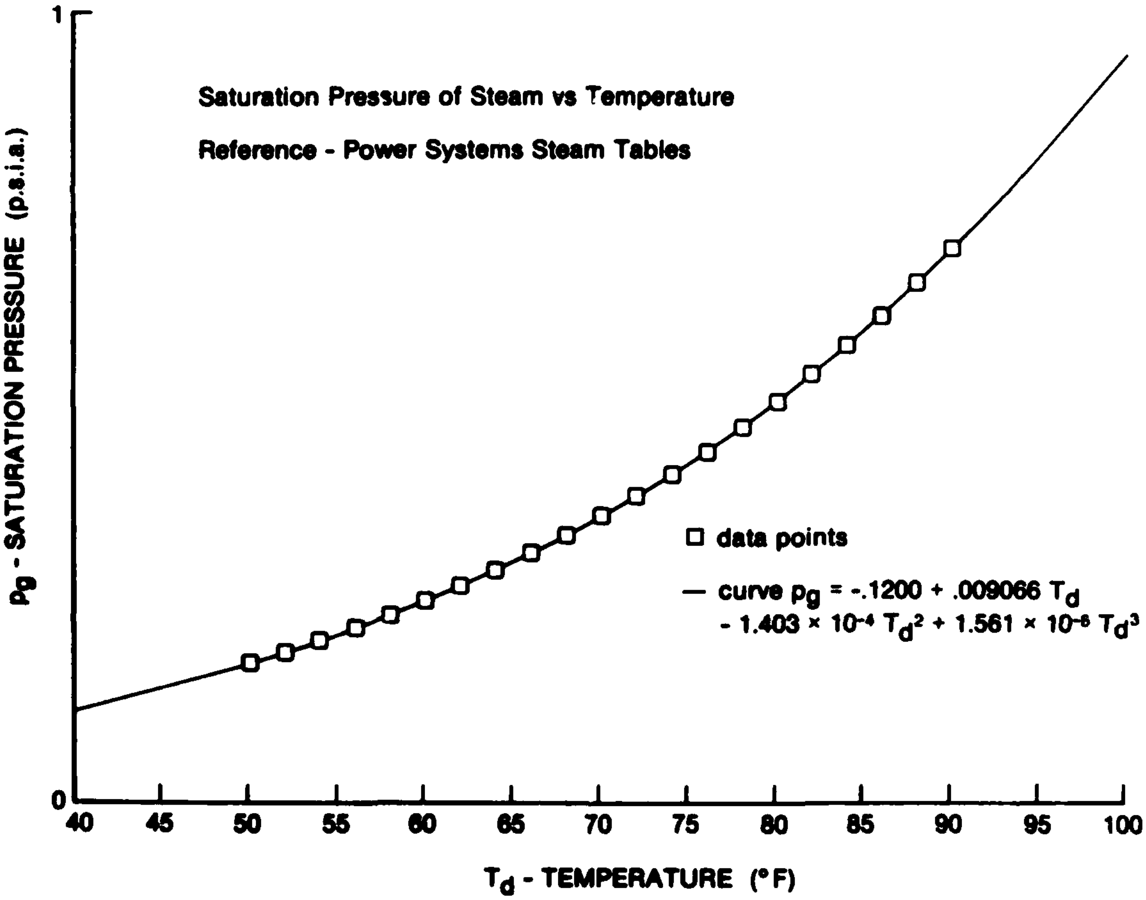
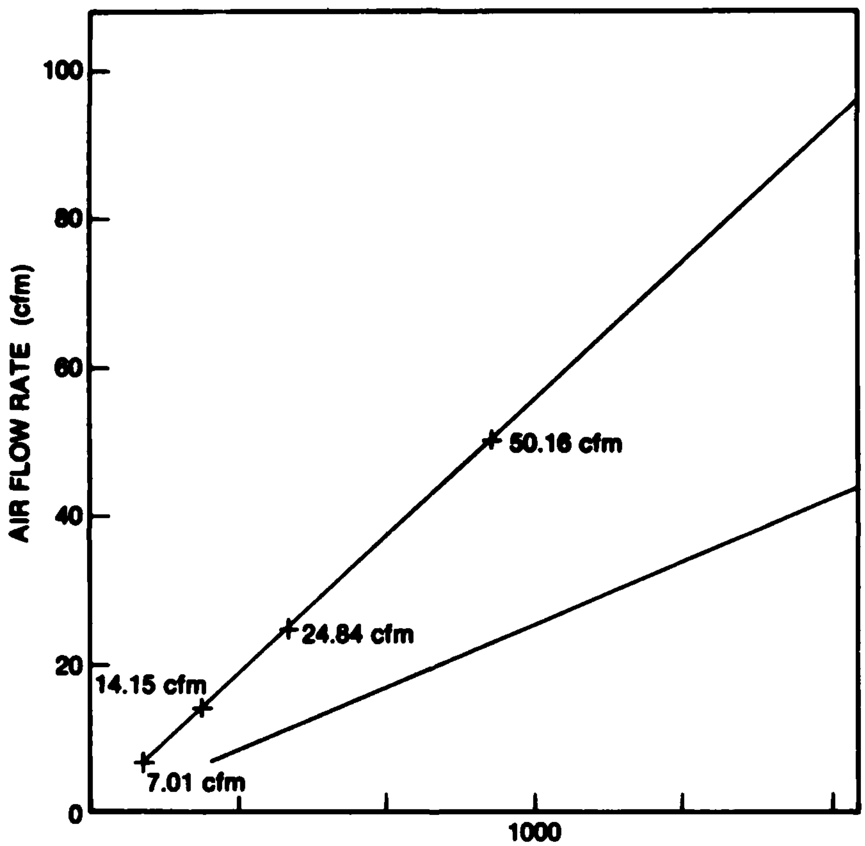
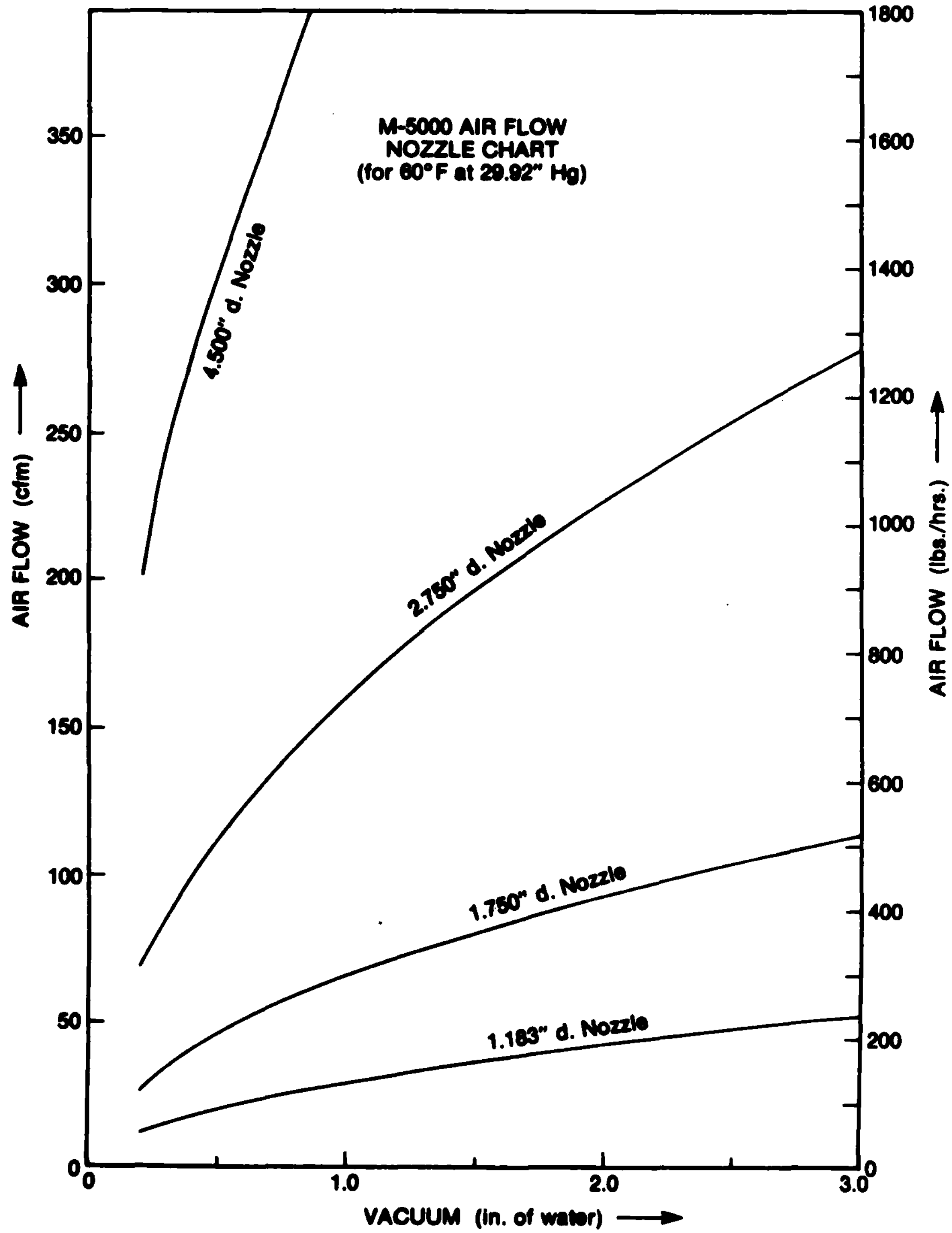


Figure 10. Saturation Pressure of Steam vs Temperature

ANNEX IV

MANUFACTURER SUPPLIED CALIBRATION DATA


AIR FLOW RATE (cfm)
100
80
60
40
20
0
1000
50.16 cfm
24.84 cfm
14.15 cfm
7.01 cfm



M-5000 AIR FLOW
NOZZLE CHART
(for 60°F at 29.92" Hg)
4.500" d. Nozzle
2.750" d. Nozzle
1.750" d. Nozzle
1.183" d. Nozzle
AIR FLOW (cfm)
AIR FLOW (lbs./hrs.)
VACUUM (in. of water)
0
50
100
150
200
250
300
350
1.0
2.0
3.0
200
400
600
800
1000
1200
1400
1600
1800

MANUFACTURERS SUPPLIED CALIBRATION DATA TAKEN FROM GRAPH ON PRECEDING PAGE, AND THIS DATA CORRECTED TO STANDARD CONDITIONS WITH DENSITY OF .07372 lbm/ft^3

DIFFERENTIAL PRESSURE (in. w.g.)	ACTUAL FLOW @ρ=.07604 lbm/ft^3 (cfm)	ACTUAL FLOW @ρ=.07372 lbm/ft^3 (cfm)
0	0	0
.25	13.04	13.24
.50	20.00	20.31
.75	25.22	25.61
1.00	28.70	29.15
1.25	32.17	32.67
1.50	35.65	36.21
1.75	38.70	39.30
2.00	41.74	42.39
2.25	44.35	45.04
2.50	46.96	47.69
2.75	49.13	49.90
3.00	51.30	52.10

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13. ABSTRACT

This note documents the calibration of the two air flow measuring instruments used in the DREO engines laboratory. It was found that the calibration performed agrees closely with the manufacturer's calibration. Functional relationships to acquire air flow from each instrument's output are suggested for use in computer programs.

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KEY WORDS

Air Flow
Calibration
Flow Nozzles
Turbine Flow Transducer

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