MEASUREMENT OF AIR FLOW AT VACUUM CONDITIONS USING SMALL VENTURIS

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SYMBOLS

A	Area at inlet
a	Area at throat
C	Discharge coefficient
C'	Flow coefficient, $C/\sqrt{1-\beta^4}$
D	Diameter at inlet
d	Diameter at throat
M	Mach number
m	Mass flow rate
p	Pressure
Δp	Differential pressure
R	Ideal gas constant
r	Ratio of pressure at throat to pressure at inlet
Re	Reynolds' number
q	Volume flow rate
T	Temperature
u_i	Internal energy
u_k	Kinetic energy
V	Velocity
v	Specific volume
Y	Expansion coefficient
β	Diameter ratio, d/D
γ	Ratio of specific heats
ϕ	Relative humidity
ρ	Density
μ	Viscosity

I. INTRODUCTION

Vacuum is used in the cigarette industry for various operations in the cigarette-making and packing machines. A typical operation is the use of suction to feed flat cigarette boxes to be folded and packed with cigarettes. Usually a central vacuum pump system supplies the vacuum for an entire factory.

This project developed as a result of the need to upgrade an old factory's vacuum system. At one time the system operated at 16-17 inches (406-437 mm) of mercury vacuum. Due to the addition of machinery over the years, the operating vacuum had dropped to 12 inches (305 mm) of mercury in many areas of the factory. This vacuum is considered marginal for proper operation of the machines.

It was possible to determine pump capacity requirements by using pump curves to compare existing flow rates to the flow rates required at higher vacuums. However, in order to determine adequate pipe sizes for the various areas, it was necessary to obtain flow requirements for each area of the factory.

Since modifications had been made to the machines over the years, nameplate data did not apply and it became necessary to measure the flows through the machines while they were in operation.

The pipe sizes supplying individual machines were 2 in.

(51 mm) and smaller. Contacts were made with various vendors concerning selection of flow measuring equipment. Most of the equipment available, such as rotometers, would cause large pressure drops, meaning a loss of vacuum at the machine.

Small Venturis appeared to be applicable. In discussions with manufacturers it was determined that curves for Δp versus flow were not readily available for vacuum conditions. Curves could be developed and supplied for each Venturi at an additional cost. Since there was a need to measure a wide range of flows at various vacuum conditions, it was decided to purchase the Venturis and develop the flow curves separately. The manufacturer agreed to supply the flow coefficients for each Venturi.

This report outlines the calculations used to develop the flow curves and the test procedure used to measure air flow at vacuum conditions. The charts developed will continue to be used in the future as part of a program to monitor the energy requirements of the cigarette-making and packing machines.

II. REVIEW OF LITERATURE

Differential pressure flowmeters are widely used in industry for measurement of compressible and incompressible flow. The primary elements most commonly used are the thin plate square-edged orifice, the flow nozzle, and the Venturi tube. Other differential pressure primary elements are linear resistance elements (capillary tubes), frictional resistance elements, and pipe elbows. These primary elements possess different characteristics, but in all cases a simple relationship can be made between pressure drop through the element and flow rate.

The equations for flow versus pressure drop for orifice plates and Venturis are found in most fluid mechanics textbooks (1,2). Flow rates are expressed as functions of pressure drop, fluid density, and the meter's discharge coefficient.

Most of the literature published on Venturis in recent years concerns standardization of Venturi geometry and the determination of discharge coefficients for those geometries. The American Society of Mechanical Engineers' "Research Report on Fluid Meters" (3) contains a complete treatment of Venturi meters, from derivation of the flow equations to standards for installation. This publication is used as a standard reference by companies such as Crane (4) to develop "shortcut formulas" and graphs for specific flowmeter applications.

Several papers have been published on methods for determining the discharge coefficient of Venturis used for compressible flow. Brain and Reid (5) and Watanabe and Komiya (6) used gravimetric methods to determine the discharge coefficients of small critical flow Venturi nozzles. Brain and Reid correlated their results with theoretical values developed from boundary layer theory.

In industrial applications, manufacturers usually supply flow curves for their Venturis, based on results of calibration tests. For example, the Venturis used in this project are shipped with standard flow versus Δp curves for water. The manufacturer also supplies correction factors for use when the flow is compressed air or steam. For other flows and conditions, curves are developed to meet the specific application. Manufacturers use publications and standards such as those previously mentioned to construct and calibrate their meters.

III. DESCRIPTION OF PROJECT

The objective of this project was to develop a simple, yet accurate method for measuring air flow rates through various cigarette-making machines to a central vacuum system. This information is needed to determine adequate pump capacities and pipe sizes for central vacuum systems. In addition, the information will be used to determine and monitor energy usage of the machines.

Flow tests must be run on machines that are in production. Since the machines require a minimum vacuum for proper operation, it is essential that the flow measuring device have a minimum pressure drop through it. Other constraints are that the device must be easily installed and removed, and be able to measure a wide range of flows.

Small Venturis met these requirements. Other flow elements considered include rotometers, annubars, and pitot tubes.

Preliminary calculations showed that a set of four Venturis, ranging in size from 1/2 to 1 1/4 in. (13 to 32mm) would meet the requirements. Their characteristics are shown in Table 1. The Venturis used are actually a combination flow nozzle-Venturi, manufactured by the Barco Division of Aeroquip Corporation.

At the pressures and flow ranges considered, flows were subsonic. Flows were characterized by Reynolds numbers of

TABLE 1

VENTURI CHARACTERISTICS

NOMINAL DIAMETER	DIAMETER RATIO, β	FLOW COEFFICIENT, C'*
½" (13 mm)	.323	.9167
1" (25 mm)	.567	1.046
1¼" (32 mm)	.588	1.002
1½" (38 mm)	.698	1.068

* Flow coefficients supplied by manufacturer

5×10^{3} to 1.5×10^{5} at the Venturi throat.

Theory

Flow versus Δp equations for the Venturi, flow nozzle, and orifice plate are obtained from the same theoretical considerations. Once a theoretical equation is obtained, a discharge coefficient, C, is introduced to relate actual flow to theoretical flow for that particular flow element (3).

In developing the flow equation for compressible flow through a Venturi, the following assumptions are made:

1. The flow is isentropic
2. The fluid performs no external work
3. Flow is steady
4. One dimensional flow (the velocity profile) at each section is relatively flat and normal to the pipe axis)
5. Ideal gas
6. Gravitational effects are neglected

Based on these assumptions, the following relationships apply:

1. Continuity

$$AV_1\rho_1 = aV_2\rho_2$$

2. Conservation of energy

$$(u_{k_2} + u_{i_2}) - (u_{k_1} + u_{i_1}) = p_1v_1 - p_2v_2$$

3. Isentropic flow

$$p_1v_1^{\gamma} = p_2v_2^{\gamma} = \text{constant}$$

4. Ideal gas law

$$p = \rho RT$$

Using these four equations a theoretical mass flow equation is developed (3):

$$m_t = a \left[\frac{2g_c(p_1 - p_2)\rho_1 r^{2/\gamma}(\frac{\gamma}{\gamma-1})(\frac{1-r^{(\gamma-1)/\gamma}}{1-r})}{1-\beta^4 r^{2/\gamma}} \right]^{1/2}$$

Usually this equation is simplified to

$$m_t = a \left[\frac{2g_c\rho_1(p_1 - p_2)}{1-\beta^4} \right]^{1/2} Y$$

where

$$Y = \left[r^{2/\gamma}(\frac{\gamma}{\gamma-1})(\frac{1-r^{(\gamma-1)/\gamma}}{1-r})(\frac{1-\beta^4}{1-\beta^4 r^{2/\gamma}}) \right]^{1/2}$$

For actual flow, the discharge coefficient, C, is applied:

$$C = \frac{\text{actual flow rate}}{\text{theoretical flow rate}}$$

The discharge coefficient accounts for departures from the ideal situations reflected in the assumptions. The actual flow equation then becomes

$$m_a = a(\frac{C}{\sqrt{1-\beta^4}})\{2g_c\rho_1(p_1-p_2)\}^{1/2} Y$$

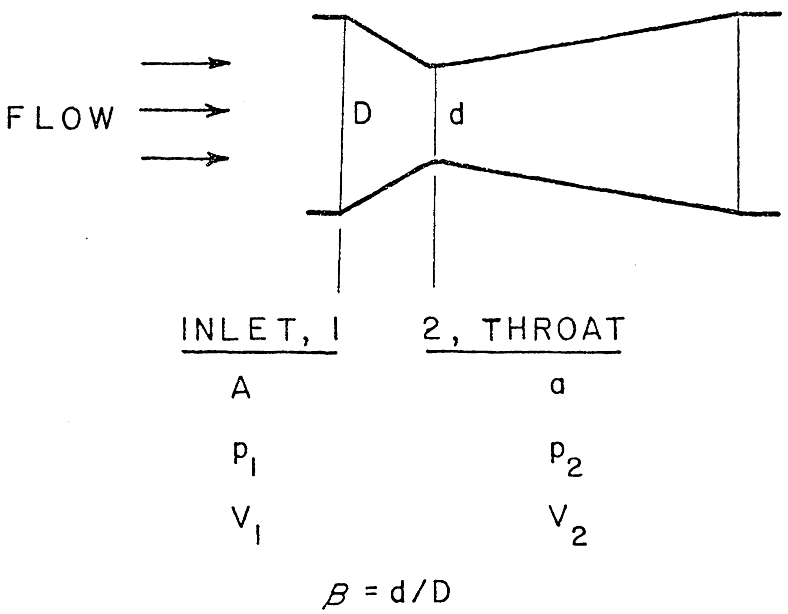


Figure 1- VENTURI

Letting $C'=C/\sqrt{1-\beta^4}$ and rearranging,

$$m_a=aC'Y\{2g_c\rho_1(p_1-p_2)\}^{1/2}$$

This equation is the basis for the flow calculations carried out in this project.

The product $C'Y$ is a function of fluid properties at the throat, and meter geometry: $C'Y=F(Re_d, \frac{1-r}{\gamma}, \beta, D)$. The expression $(1-r)/\gamma$ is called the acoustic ratio. It is related to the Mach number: $(1-r)/\gamma=M^2/2$. For subsonic flow through a Venturi, the effects of Reynolds number and acoustic ratio can be considered to be independent, such that $C'=G(Re_d, \beta, D)$, and $Y=H(\frac{1-r}{\gamma}, \beta)$ (3).

The maximum vacuum considered, 20 in. (508 mm) of mercury, falls within the classification of a "low vacuum" as defined by the American Vacuum Society (7). In this vacuum range, the normal fluid flow equations and properties described in this section are applicable. Rarefaction of the air is not a factor in the "low vacuum" range (8).

Computational Methods

A Texas Instruments "TI-58" programmable calculator with printer was used to develop the data for the charts. Several substitutions and simplifications were made to the flow equation in order to prepare the program. They are outlined on the following pages.

The parameters measured in the flow tests are:

p_1 = pressure (vacuum) at the inlet, in. (mm) of mercury

T_1 = temperature at the inlet, F (C)

Δp = pressure drop between inlet and throat, in. (mm) of water

The following are characteristics of the Venturi used:

D = inlet diameter, in. (mm)

β = diameter ratio, d/D

C' = flow coefficient

It is desirable to rearrange the flow equation so that volume rate of flow is expressed as a function of the measured variables and the meter characteristics:

$$q_1 = F(p_1, T_1, \Delta p, D, \beta, C')$$

In order to change the flow rate from mass flow to volume flow, the ideal gas law is applied:

$$m_a = (p_1 q_1)/RT_1$$

$$q_1 = \frac{RT_1}{P_1} m_a$$

$$q_1 = \left(\frac{RT_1}{p_1}\right)(aC')\left(2g_c\rho_1(p_1-p_2)\right)^{1/2} Y$$

Substituting $a=\pi d^2/4$, $\rho_1=p_1/RT_1$, and $d=\beta D$,

$$q_1 = (\pi/4)(C'Y\beta^2 D^2)(2g_c RT_1)^{1/2}\left(\frac{p_1-p_2}{p_1}\right)^{1/2}$$

After substituting constant values and unit conversion factors, the equation becomes

$$q_1 = 2.6262\beta^2 D^2 C' Y T_1^{1/2} R^{1/2}(1-r)^{1/2}$$

$$(q_1 = 1.11\text{x}10^{-3}\ \beta^2 D^2 C' Y T_1^{1/2} R^{1/2}(1-r)^{1/2})$$

where $r=p_2/p_1$, and the other variables have the following units:

β, Y; dimensionless

T_1; R (K)

R; $\dfrac{\text{ft-lb}_f}{\text{lb}_m\ \text{R}}$ $\left(\dfrac{\text{J}}{\text{kg-K}}\right)$

D; in. (mm)

q_1; ft^3/min (l/s)

The discharge coefficient, C', was provided by the manufacturer. This factor is relatively constant for Reynolds numbers greater than 10^4. In order to establish the accuracy of the results it is necessary to compute Reynolds number at the throat in each case; $Re_d=\rho_2 V_2 d/\mu$.

V_2 and Re_d are calculated using the results of the flow calculation. From continuity, $q_1=(\rho_2/\rho_1)V_2 a$. For isentropic flow, $\rho_2/\rho_1=r^{1/\gamma}$, therefore $q_1=r^{1/\gamma}V_2a$.

Substituting $a=(\pi\beta^2D^2)/4$ and solving for V_2,

$$V_2 = \frac{4q_1}{\pi\beta^2D^2r^{1/\gamma}} \quad .$$

Re_d is determined by substituting the expression for V_2 into $Re_d=(\rho_2V_2d)/\mu$:

$$Re_d = (\frac{4}{\pi})(\frac{1}{\mu})(\frac{p_1q_1}{RT_1\beta D})$$

Substituting the viscosity of air, $3.81\text{x}10^{-7}$ lb_f sec/ft^2 ($1.82\text{x}10^{-4}$ poise) at 73 F (22.8 C), and converting units,

$$Re_d = 5.6\text{x}10^4 \ (\frac{p_1q_1}{T_1\beta D})$$

$$(Re_d = 2.42\text{x}10^2 \ (\frac{p_1q_1}{T_1\beta D}\ )\ )$$

where p_1=psia (Pa) and the other variables have the units previously given.

Figure 2 is a flow chart of the program used. Input to the program consists of Venturi characteristics, inlet vacuum, inlet temperature, differential pressure increment, and maximum differential pressure. The program computes and prints the following results for each increment of differential pressure:

1. Flow, q_1
2. Expansion factor, Y
3. Velocity at the throat, V_2
4. Reynolds number at the throat, Re_d

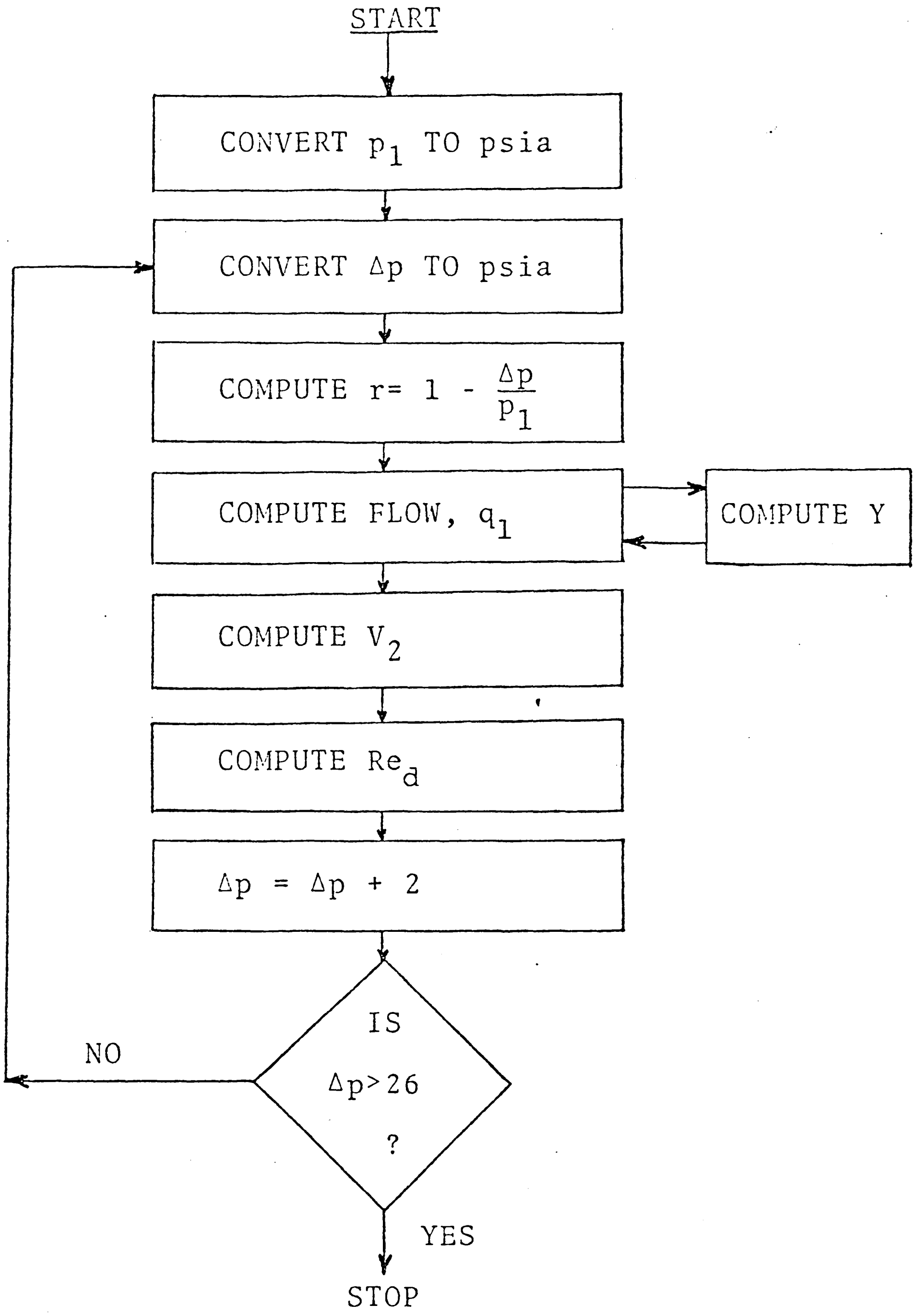


Figure 2 Flow Chart for Calculator Program

IV. RESULTS

Charts of Δp versus Flow

For each Venturi, flows were calculated at inlet vacuums from 8 to 20 in. (203 to 508 mm) of mercury. Differential pressures were varied from 2 to 26 in. (51 to 660 mm) of water. Inlet temperature used was 73 F (22.8 C).

From the calculated data, charts were developed. They are shown on Figs. 3 through 6. Data for the charts are included in the appendix.

Use of the Charts

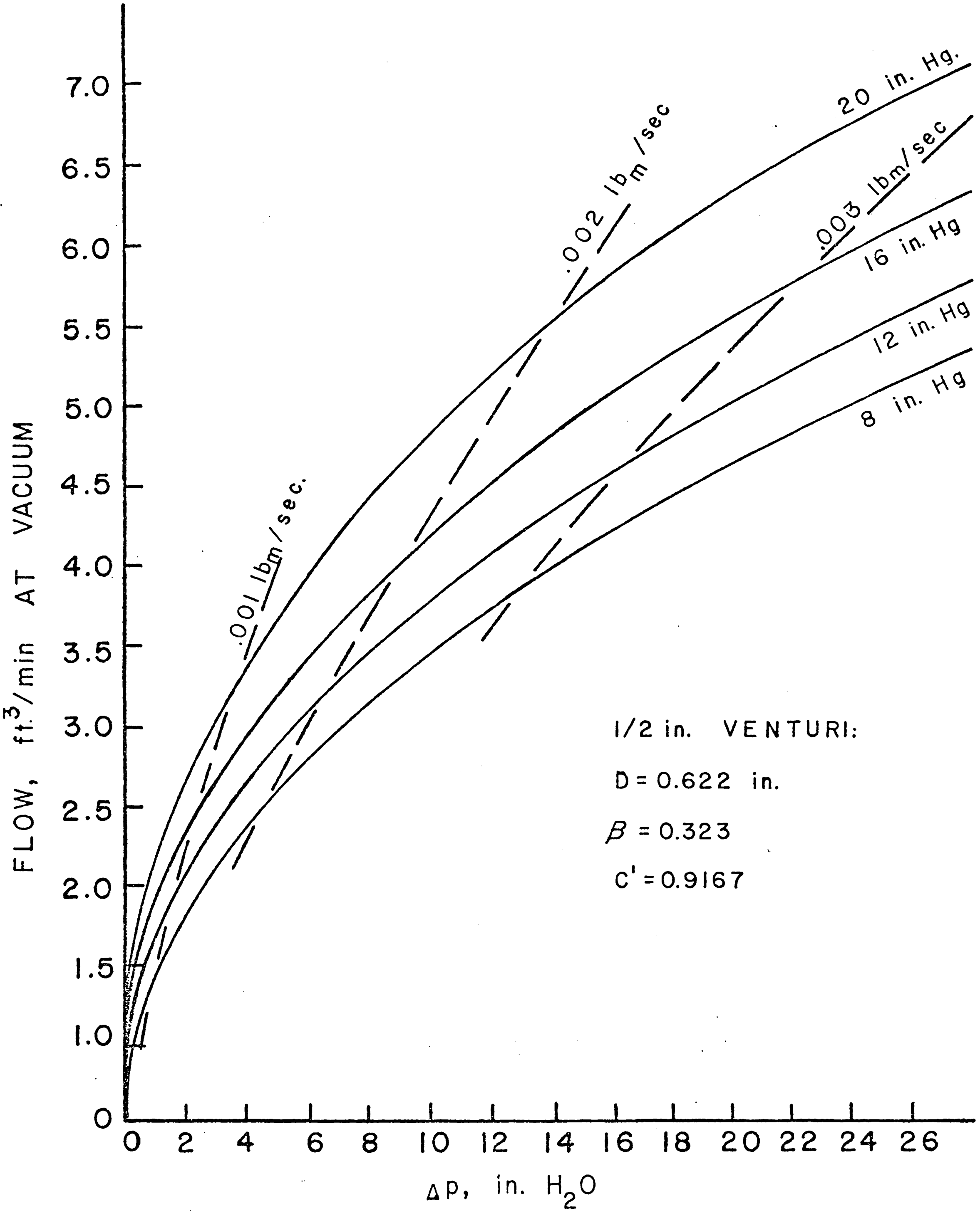
When tests are run, p_1 and Δp are measured with manometers. T_1 is measured with a thermocouple. Then by use of the appropriate chart, the flow rate can be determined without further calculation.

Although the temperature used to generate the charts was a constant 73 F (22.8 C), variations from this value do not have a significant effect on the result. The reasons for this are discussed in Section V.

Results of Field Tests

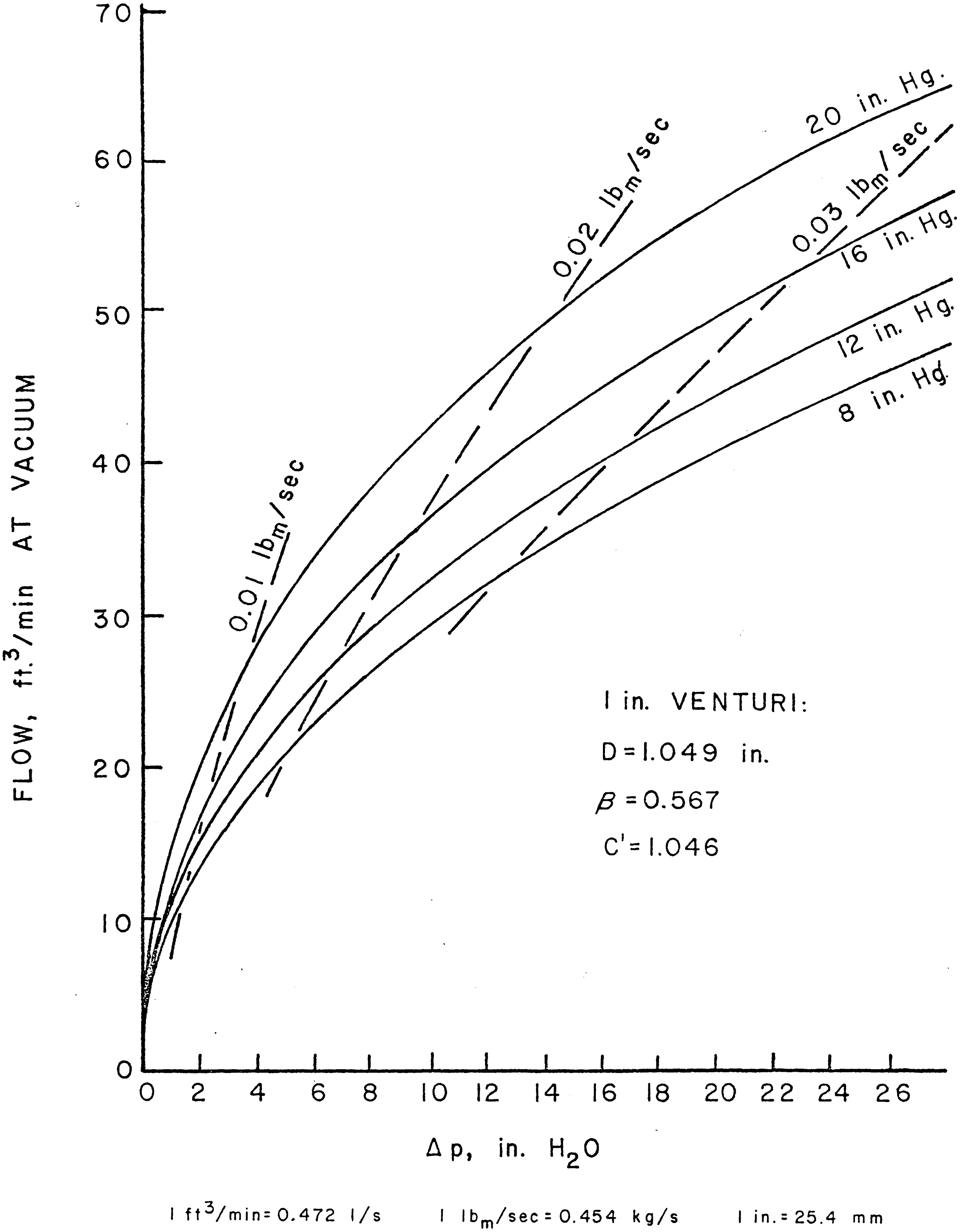
Tests were run on various production machines. The test set-up used is shown in Fig. 7. Differential pressures and vacuum were read, then the mercury manometer was removed and a thermocouple lead was inserted through the ¼ in. (6 mm) connection used for the mercury manometer.

Typical results are shown in Table 2. Using the test results it was possible to identify areas where the central vacuum system piping was inadequate for the flow to be handled. The results shown in Table 2 represent major categories of machines in the factory considered. Machine type A is the largest category. There are ninety-eight of these machines installed. Tests were run on four of them. Machines type B and C are new generation high-speed packing machines. They are operating on a separate vacuum pump since they cannot operate at vacuums less than 17 in. Hg. (432 mm Hg.).



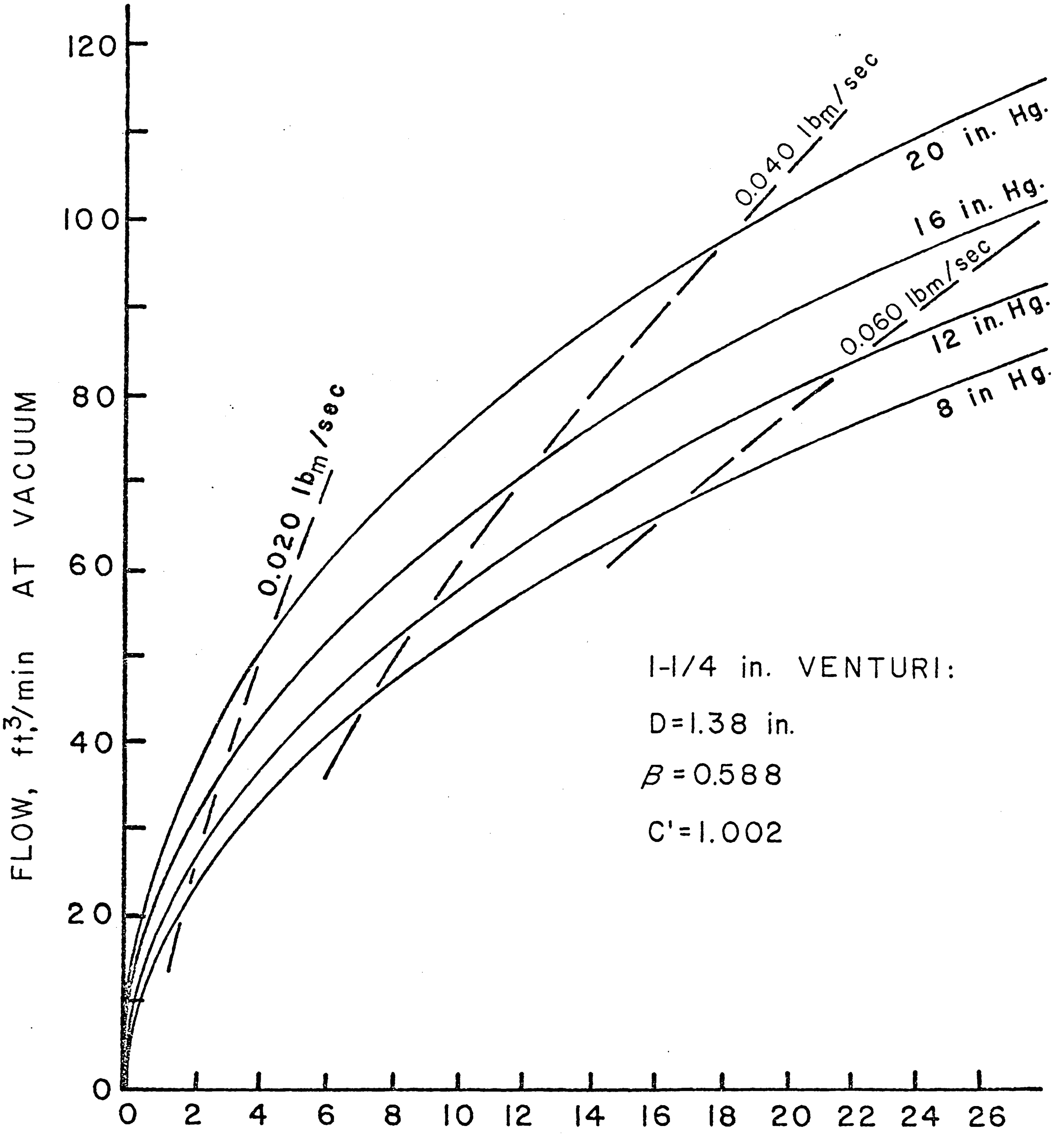
1 ft^3/min = 0.472 l/s 1 lb$_m$/sec = 0.454 kg/s 1 in. = 25.4 mm

Figure 3 - FLOW vs. Δp FOR 1/2 in. VENTURI



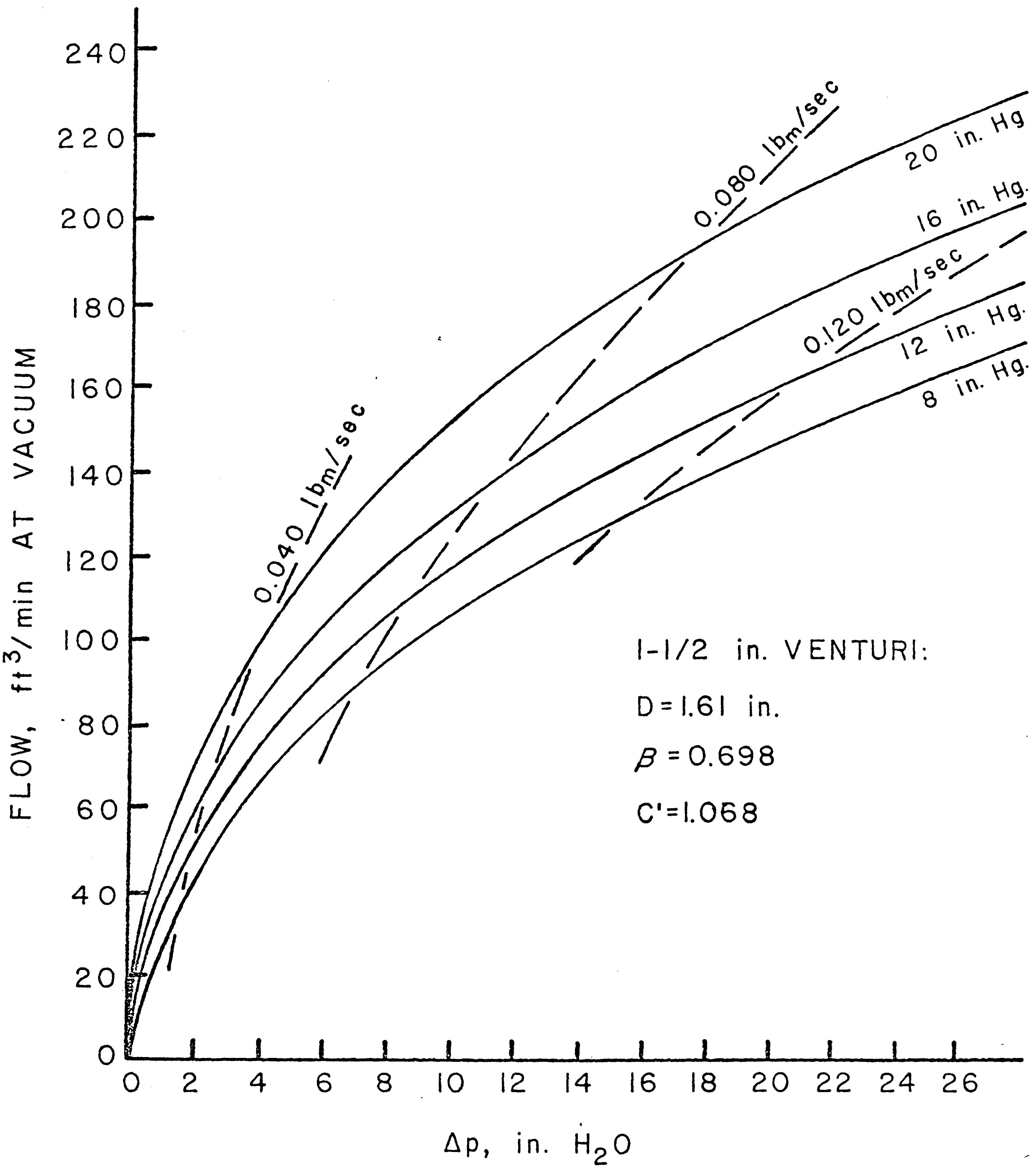
1 ft^3/min = 0.472 l/s   1 lb_m/sec = 0.454 kg/s   1 in. = 25.4 mm

Figure 4 - FLOW vs. Δp FOR 1 in. VENTURI



1 ft^3/min = 0.472 l/s 1 lb$_m$/sec = 0.454 kg/s 1 in. = 25.4 mm

Figure 5 - FLOW vs. Δp FOR 1-1/4 in. VENTURI



1 ft^3/min = 0.472 l/s 1 lb$_m$/sec = 0.454 kg/s 1 in = 25.4 mm

Figure 6 - FLOW vs. Δp FOR 1-1/2 in. VENTURI

TABLE 2

TYPICAL TEST RESULTS

Machine type	Venturi	Vacuum (p_1) in. Hg (mm Hg)	T_1 F (C)	Δp in. H_2O (mm H_2O)	FLOW ft^3/min (l/s)
A	1¼ in. (32 mm)	12.2 (310)	74 (23.3)	14.0 (356)	68 (32)
B	1 in. (25 mm)	22.0 (559)	73 (22.8)	4.5 (114)	30 (14)
C	1 in. (25 mm)	21.7 (551)	72 (22.2)	2.2 (56)	21 (10)

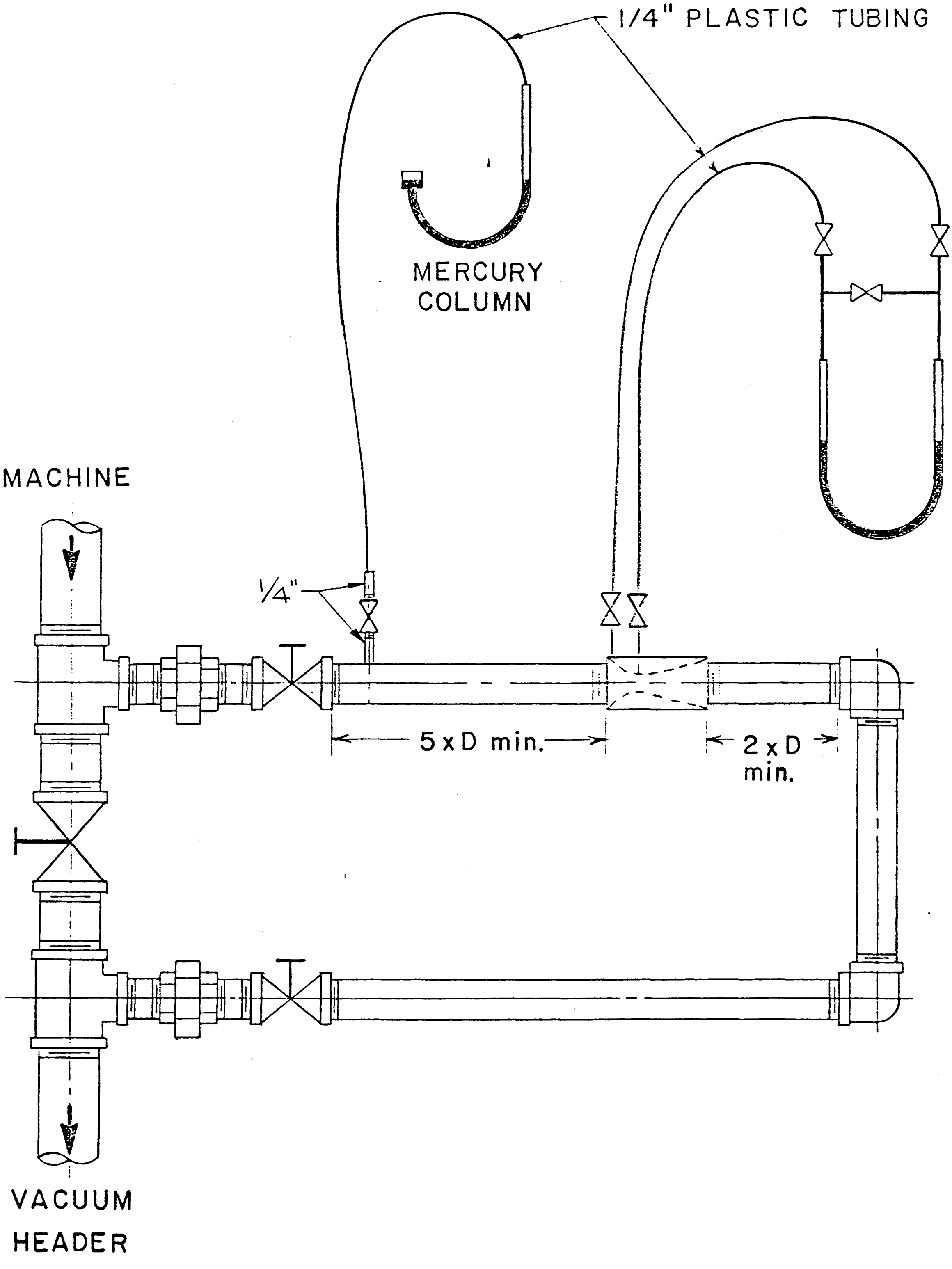


Figure 7- TEST INSTALLATION

V. DISCUSSION

Accuracy of Results

In order to evaluate the accuracy of the results it is necessary to consider each component of the flow equation and determine its contribution to the error in the final result. The equation used in the calculator program is

$$q = 2.6262\beta^2 D^2 C' T_1^{1/2} R^{1/2} (1-r)^{1/2} Y$$

In the following sections each component of this equation will be analyzed for its range of accuracy. The compound effect of all the errors will be analyzed using the methods described in references 9 and 10.

Venturi Inlet Diameter and Diameter Ratio, D and β

The accuracy of these numbers depends on the machining tolerances used by the manufacturer. In cases where extreme temperatures are involved, it is necessary to make corrections for metal expansion (3). In this project this type of correction was not necessary. A range of ±1% in the values of d and D is considered accurate to cover production tolerances. Since $\beta = d/D$, the range of error for β is ±2%.

Discharge Coefficient, C'

The discharge coefficients for the four Venturis were supplied by the manufacturer. They are accurate within ±5% over the range of Reynolds numbers calculated, 5×10^3 to 1.5×10^5.

Temperature, T_1

In the tests, a "Digimite" temperature sensor was used to measure the air temperature at the inlet to the Venturi. A type J thermocouple was the sensing element. The device provides a direct digital readout of temperature, with an accuracy of ±.2 F.

At high velocities, (above 200 ft/sec (61 m/s)), a thermometer's reading is affected by the impinging air (3). The temperature indicated tends to approach the stagnation temperature, rather than the static temperature (the temperature that the thermometer would read if it were moving with the stream). The relationship between static and stagnation temperatures is (1):

$$T_{static} = T_{stagnation} - \left(\frac{\gamma-1}{2}\right)\left(\frac{V^2}{R}\right)$$

Using this relationship, a range of temperatures can be established using the extremes of temperatures measured and velocities from 200 ft/sec (61 m/s) to the maximum calculated, 633 ft/sec (193 m/s). The range of temperatures measured is 70 to 75 F (21.1 to 23.9 C).

Using 70 F (21.1 C) and 633 ft/sec (193 m/s) produces the lowest static temperature, 483 R (262.5 K), while 75 F (23.9 C) and 200 ft/sec (61 m/s) produces the highest static temperature, 531 R (294.5 K). Based on these results, the temperature range can be stated as 507 R ±5% (281.2 K ±5%).

Gas Constant, R

The flow measured in the tests is room air which has entered the system. This air contains water vapor. The gas constant for the mixture will depend upon the proportion of water vapor contained in the mixture.

Room conditions in the production areas are maintained at 76 F ±2 F (24.4 C ±1.1 C), and 56% ±1% relative humidity. The value of R for the mixture can be determined using thermodynamic principles. Both the air and the water vapor can be considered ideal gases at the temperatures and pressures involved (11). The Gibbs-Dalton Law states that each component of the mixture behaves as if it existed at the temperature of the mixture and filled the same volume occupied by the mixture (11). Therefore,

$$\rho_{mixture} = \frac{m_{air} + m_{vapor}}{\text{Volume}} = \rho_{air} + \rho_{vapor}$$

Using the ideal gas law for the mixture, at atmospheric conditions (i.e., in the room):

$$p = \rho_{mixt} R_{mixt} T$$

$$p = (\rho_{air} + \rho_{vapor}) R_{mixt} T$$

$$p = \left(\frac{p_{air}}{R_{air}T} + \frac{p_{vap}}{R_{vap}T}\right) R_{mixt} T$$

Substituting $p_{air} = p - p_{vap}$ and rearranging,

$$R_{mixt} = \frac{R_{air}}{1 + \frac{p_{vap}}{p}\left(\frac{R_{air}}{R_{vap}} - 1\right)}$$

Using the values of $R_{air} = 53.35 \frac{ft\text{-}lb_f}{lb_m\ R}$ $(287 \frac{J}{kg\ K})$, $R_{vap} = 85.6 \frac{ft\text{-}lb_f}{lb_m\ R}$ $(462 \frac{J}{kg\ K})$, and the definition of relative humidity, ϕ =pressure of vapor/saturation pressure of vapor (10), the values of R_{mixt} can be calculated for the range of temperatures and relative humidities encountered in the room. The extremes of these values are shown below:

TEMPERATURE F (C)	RELATIVE HUMIDITY %	GAS CONSTANT $\frac{ft\text{-}lb_f}{lb_m\ R}$ $(\frac{J}{kg\ K})$
74 (23.3)	55	53.66 (288.5)
76 (24.4)	56	53.69 (288.6)
78 (25.6)	57	53.72 (288.7)

Based on the values given above, the range of R can be stated as $53.69 \frac{ft\text{-}lb_f}{lb_m\ R}$ ±0.05% $(288.6 \frac{J}{kg\ K}$ ±0.04%).

Pressure Ratio, $r=p_2/p_1$

The inlet pressure, p_1, was measured with a mercury column manometer, with scale divisions of 0.1 in. (2 mm). Differential pressure was measured with a U-tube manometer filled with gage oil. Scale divisions were also 0.1 in. (2 mm). Since all tests were conducted at room temperature, no corrections were made to the manometer readings for expansion.

In the calculator program, r is computed using the relation $r=1-\Delta p/p_1$. The value p_1 is converted to absolute pressure to compute r.

The error contribution from the manometer readings is ±0.1 in. (2 mm) of water for Δp, and ±0.1 in. (2 mm) of mercury for p_1. The compound effect of these two readings on the value of $(1-r)$ is ±6.1%.

Expansion Coefficient, Y

Y is a function of r, β, and the ratio of specific heats, γ. The value of γ used is 1.4. The error for Y was calculated by substituting values of r and β based on their ranges of error. The maximum variation for Y was found to be ±0.5%.

Compound Error

The contribution of each component is summarized below:

Variable, v	Error, e_v
β	0.02β
D	0.01D
C'	0.05C'
T_1	$0.05T_1$
R	0.00R
(1-r)	0.06 (1-r)
Y	0.00Y

The error caused by variations in the variables above can be determined by the Root-Sum Square method (8,9):

$$E=\left[\frac{\left(\frac{\partial q}{\partial \beta}e_\beta\right)^2+\left(\frac{\partial q}{\partial D}e_D\right)^2+\left(\frac{\partial q}{\partial C'}e_{C'}\right)^2+\left(\frac{\partial q}{\partial T_1}e_{T_1}\right)^2+\left(\frac{\partial q}{\partial (1-r)}e_{(1-r)}\right)^2}{q^2}\right]^{\frac{1}{2}}$$

The results are shown in tabular form for simplicity:

v	$(\frac{\partial q}{\partial v})(\frac{1}{q})$	$(\frac{\partial q}{\partial v})(\frac{1}{q})e_v$	$\{(\frac{\partial q}{\partial v})(\frac{1}{q})e_v\}^2$
β	$\frac{2}{\beta}$	$\frac{2}{\beta}(.02\beta)$	0.0016
D	$\frac{2}{D}$	$\frac{2}{D}(.01D)$	0.0004
C'	$\frac{1}{C'}$	$\frac{1}{C'}(.05C')$	0.0025
T_1	$\frac{1}{2T_1}$	$\frac{1}{2T_1}(.05T_1)$	0.000625
(1-r)	$\frac{1}{2(1-r)}$	$\frac{1}{2(1-r)}(.06(1-r))$	0.0009

Total Error$=\{\Sigma((\frac{\partial q}{\partial v})(\frac{1}{q})e_v)^2\}^{\frac{1}{2}}=0.078$

Percent Error= 7.8%

The manufacturer's stated accuracy for a stock (non-calibrated) Venturi is 2% when measuring steam or compressed air flow. The results of this analysis indicate that the flow values are most sensitive to changes in the flow coefficient C'. Temperature variations do not affect the results significantly. This is because the square root of the absolute temperature is the number used in the calculations.

Other Sources of Error

There are other, non-quantifiable sources of error that must be considered when the Venturis are used. One of these is the adequacy of the installation. The Venturi must be installed with a minimum of five diameters of straight pipe ahead of it and two diameters of straight pipe behind it. This requirement is to insure a fully developed velocity profile through the meter.

Another possibility for error specific to the test set-up used in this project is the possibility of leaks through the bypass valve around the Venturi.

When dealing with vacuum measurements, leaks are always hard to detect. Great care must be used when the manometers are installed to insure that there are no leaks that will affect the manometer reading.

VI. CONCLUSIONS

The results obtained by use of the charts are within the range of accuracy acceptable for industrial use. A considerable time savings is obtained by eliminating the need to calculate flows for each set of readings.

Temperature variations do not affect the flow values significantly. In future tests T_1 need not be measured as long as room temperatures are within the range of 70-80 F (21.1-26.7 C). This simplifies the test procedure. The only requirements will be to read the two manometers, and read the flow directly from the charts.

The charts developed will continue to be used for measuring and monitoring changes in the vacuum requirements of the equipment.

VII. LITERATURE CITED

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APPENDIX

CALCULATED FLOW DATA

FLOW DATA

VENTURI SIZE: ½ in. (13 mm)

D= 0.622 in. (16 mm) p_1= 8 in. (203 mm) Hg. Vac.

β= 0.323 T_1= 73 F (22.8 C)

C'= .9167

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	1.3 (0.6)	.997	102 (31.1)	7,557
4 (102)	1.9 (0.9)	.993	145 (44.2)	10,648
6 (152)	2.3 (1.1)	.989	177 (54.0)	12,993
8 (203)	2.7 (1.3)	.986	205 (62.5)	14,947
10 (254)	3.0 (1.4)	.982	229 (69.8)	16,648
12 (305)	3.2 (1.5)	.978	251 (76.5)	18,168
14 (356)	3.5 (1.6)	.975	272 (82.9)	19,549
16 (406)	3.7 (1.8)	.971	291 (88.7)	20,818
18 (457)	3.9 (1.9)	.967	309 (94.2)	21,996
20 (508)	4.1 (1.9)	.963	326 (99.4)	23,095
22 (559)	4.3 (2.0)	.960	343 (104.5)	24,127
24 (610)	4.5 (2.1)	.956	358 (109.1)	25,100
26 (660)	4.6 (2.2)	.952	373 (113.7)	26,021

FLOW DATA

VENTURI SIZE: ½ in. (13 mm)

D= 0.622 in. (16 mm)　　p_1= 12 in. (305 mm) Hg. Vac.

β= 0.323　　T_1= 73 F (22.8 C)

C'= .9167

Δp, in.	(mm) H_2O	FLOW, $\frac{ft^3}{min}$	$(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$	$(\frac{m}{s})$	Re
2	(51)	1.5	(0.7)	.996	113	(34.4)	6,806
4	(102)	2.1	(1.0)	.992	159	(48.5)	9,581
6	(152)	2.5	(1.2)	.987	196	(59.7)	11,681
8	(203)	2.9	(1.4)	.982	226	(68.9)	13,427
10	(254)	3.2	(1.5)	.978	253	(77.1)	14,942
12	(305)	3.5	(1.7)	.973	277	(84.3)	16,291
14	(356)	3.8	(1.8)	.969	300	(91.4)	17,514
16	(406)	4.1	(1.9)	.964	322	(98.1)	18,634
18	(457)	4.3	(2.0)	.960	342	(104.2)	19,669
20	(508)	4.5	(2.1)	.955	361	(110.0)	20,632
22	(559)	4.7	(2.2)	.950	379	(115.5)	21,534
24	(610)	4.9	(2.3)	.945	396	(120.7)	22,380
26	(660)	5.0	(2.4)	.941	413	(125.9)	23,178

FLOW DATA

VENTURI SIZE: ½ in. (13 mm)

D= 0.622 in. (16 mm) p_1= 16 in. (406 mm) Hg. Vac.

β= 0.323 T_1= 73 F (22.8 C)

C'= .9167

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	1.7 (0.8)	.995	128 (39.0)	5,991
4 (102)	2.4 (1.1)	.989	181 (55.2)	8,423
6 (152)	2.9 (1.4)	.983	222 (67.7)	10,255
8 (203)	3.3 (1.6)	.977	257 (78.3)	11,771
10 (254)	3.7 (1.7)	.971	288 (87.8)	13,080
12 (305)	4.0 (1.9)	.965	316 (96.3)	14,241
14 (356)	4.3 (2.0)	.959	342 (104.2)	15,288
16 (406)	4.5 (2.1)	.953	366 (111.6)	16,241
18 (457)	4.8 (2.3)	.947	389 (118.6)	17,117
20 (508)	5.0 (2.4)	.941	411 (125.3)	17,928
22 (559)	5.2 (2.5)	.935	432 (131.7)	18,681
24 (610)	5.4 (2.6)	.929	452 (137.8)	19,383
26 (660)	5.6 (2.6)	.923	471 (143.6)	20,041

FLOW DATA

VENTURI SIZE: ½ in. (13mm)

D= 0.622 in. (16 mm)

p_1= 20 in. (508 mm) Hg. Vac.

β= 0.323

T_1= 73 F (22.8 C)

C'= .9167

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ ($\frac{l}{s}$)	Y	V_2, $\frac{ft}{sec}$ ($\frac{m}{s}$)	Re
2 (51)	2.0 (0.9)	.992	151 (46.0)	5,045
4 (102)	2.8 (1.3)	.984	215 (65.5)	7,076
6 (152)	3.4 (1.6)	.976	263 (80.2)	8,598
8 (203)	3.9 (1.8)	.968	305 (93.0)	9,843
10 (254)	4.3 (2.0)	.959	342 (104.2)	10,906
12 (305)	4.7 (2.2)	.951	376 (114.6)	11,842
14 (356)	5.0 (2.4)	.942	407 (124.1)	12,677
16 (406)	5.3 (2.5)	.934	436 (132.9)	13,429
18 (457)	5.5 (2.6)	.925	464 (141.4)	14,112
20 (508)	5.8 (2.7)	.917	491 (149.7)	14,735
22 (559)	6.0 (2.8)	.908	516 (157.3)	15,306
24 (610)	6.2 (2.5)	.899	541 (164.9)	15,830
26 (660)	6.4 (3.0)	.890	565 (172.2)	16,313

FLOW DATA

VENTURI SIZE: 1 in. (25 mm)

D= 1.049 in. (27 mm) p_1= 8 in. (203 mm) Hg. Vac.

β= 0.567 T_1= 73 F (22.8 C)

C'= 1.046

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	13.4 (6.3)	.996	116 (35.4)	25,517
4 (102)	18.9 (8.9)	.992	165 (50.3)	35,935
6 (152)	23.0 (10.9)	.988	202 (61.6)	43,826
8 (203)	26.5 (12.5)	.984	233 (71.0)	50,393
10 (254)	29.5 (13.9)	.980	261 (79.6)	56,101
12 (305)	32.2 (15.2)	.976	286 (87.2)	61,193
14 (356)	34.6 (16.3)	.971	309 (94.2)	65,812
16 (406)	36.8 (17.4)	.967	331 (100.9)	70,051
18 (457)	38.9 (18.4)	.963	351 (107.0)	73,977
20 (508)	40.8 (19.3)	.959	370 (112.8)	77,637
22 (559)	42.6 (20.1)	.954	389 (118.6)	81,067
24 (610)	44.3 (20.9)	.950	406 (123.7)	84,296
26 (660)	45.9 (21.7)	.946	423 (129.0)	87,346

FLOW DATA

VENTURI SIZE: 1 in. (25 mm)

D= 1.049 in. (27 mm)　　p_1= 12 in. (305 mm) Hg. Vac.

β= 0.567　　T_1= 73 F (22.8 C)

C'= 1.046

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	14.8 (7.0)	.995	128 (39.0)	22,977
4 (102)	20.8 (9.8)	.990	182 (55.5)	32,328
6 (152)	25.3 (12.0)	.985	223 (68.0)	38,787
8 (203)	29.1 (13.7)	.980	257 (78.3)	45,246
10 (254)	32.4 (15.3)	.975	288 (87.8)	50,322
12 (305)	35.3 (16.6)	.970	316 (96.3)	54,835
14 (356)	37.9 (17.9)	.965	341 (103.9)	58,914
16 (406)	40.3 (19.0)	.959	365 (111.3)	62,645
18 (457)	42.5 (20.1)	.954	388 (118.3)	66,087
20 (508)	44.6 (21.0)	.949	409 (124.7)	69,284
22 (559)	46.5 (21.9)	.944	429 (130.8)	72,268
24 (610)	48.3 (22.8)	.939	449 (136.9)	75,065
26 (660)	50.0 (23.6)	.934	468 (142.6)	77,695

FLOW DATA

VENTURI SIZE: 1 in. (25 mm)

D= 1.049 in. (27 mm)

β= 0.567

C'= 1.046

p_1= 16 in. (406 mm) Hg. Vac.

T_1= 73 F (22.8 C)

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	16.7 (7.9)	.994	146 (44.5)	20,221
4 (102)	23.5 (11.1)	.987	206 (62.8)	28,402
6 (152)	28.6 (13.5)	.981	253 (77.1)	34,560
8 (203)	32.8 (15.5)	.975	292 (89.0)	39,638
10 (254)	36.4 (17.2)	.968	327 (99.7)	44,016
12 (305)	39.6 (18.7)	.961	359 (109.4)	47,886
14 (356)	42.5 (20.1)	.954	388 (118.3)	51,365
16 (406)	45.1 (21.3)	.948	415 (126.5)	54,528
18 (457)	47.5 (22.4)	.941	441 (134.4)	57,427
20 (508)	49.8 (23.5)	.934	465 (141.7)	60,101
22 (559)	51.8 (24.5)	.927	489 (149.0)	62,580
24 (610)	53.7 (25.4)	.921	511 (155.8)	64,887
26 (660)	55.5 (26.2)	.914	533 (162.5)	67,039

FLOW DATA

VENTURI SIZE: 1 in. (25 mm)

D= 1.049 in. (27 mm)

p_1= 20 in. (508 mm) Hg. Vac.

β= 0.567

T_1= 73 F (22.8 C)

C'= 1.046

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	19.8 (9.3)	.991	173 (52.7)	17,025
4 (102)	27.7 (13.1)	.982	245 (74.7)	23,852
6 (152)	33.6 (15.9)	.973	300 (91.4)	28,934
8 (203)	38.4 (18.1)	.964	347 (105.8)	33,095
10 (254)	42.6 (20.1)	.954	388 (118.3)	36,643
12 (305)	46.2 (21.8)	.945	426 (129.8)	39,746
14 (356)	49.4 (23.3)	.935	461 (140.5)	42,503
16 (406)	52.2 (24.7)	.926	494 (150.6)	44,979
18 (457)	54.8 (24.9)	.916	525 (160.0)	47,218
20 (508)	57.2 (27.0)	.907	554 (168.9)	49,253
22 (559)	59.4 (28.0)	.897	582 (177.4)	51,111
24 (610)	61.3 (29.0)	.888	609 (185.6)	52,810
26 (660)	63.1 (29.8)	.878	635 (193.5)	54,366

FLOW DATA

VENTURI SIZE: 1¼ in. (32 mm)

D= 1.38 in. (35 mm)

ß= 0.588

C'= 1.002

p_1= 8 in. (203 mm) Hg. Vac.

T_1= 73 F (22.8 C)

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	23.9 (11.3)	.996	112 (34.1)	33,344
4 (102)	33.7 (15.9)	.992	158 (48.2)	46,954
6 (152)	41.1 (19.4)	.988	193 (58.8)	57,259
8 (203)	47.2 (22.3)	.983	223 (68.0)	65,831
10 (254)	52.6 (24.8)	.979	250 (76.2)	73,282
12 (305)	57.3 (27.1)	.975	274 (83.5)	79,925
14 (356)	61.6 (29.1)	.971	296 (90.2)	85,949
16 (406)	65.6 (31.0)	.966	317 (96.6)	91,477
18 (457)	69.3 (32.7)	.962	336 (102.4)	96,595
20 (508)	72.7 (34.3)	.958	354 (107.9)	101,364
22 (559)	75.9 (35.8)	.953	372 (113.4)	105,833
24 (610)	78.9 (37.3)	.949	389 (118.6)	110,038
26 (660)	81.8 (38.6)	.945	405 (123.4)	114,009

FLOW DATA

VENTURI SIZE: 1¼ in. (32 mm)

D= 1.38 in. (35 mm)

p_1= 12 in. (305 mm) Hg. Vac.

β= 0.588

T_1= 73 F (22.8 C)

C'= 1.002

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	26.3 (12.4)	.995	123 (37.5)	30,024
4 (102)	37.1 (17.5)	.990	174 (53.0)	42,238
6 (152)	45.2 (21.3)	.985	213 (64.9)	51,458
8 (203)	51.8 (24.5)	.980	246 (75.0)	59,103
10 (254)	57.7 (27.2)	.974	276 (84.1)	65,726
12 (305)	62.8 (29.7)	.969	302 (92.1)	71,612
14 (356)	67.5 (31.9)	.964	327 (99.7)	76,930
16 (406)	71.8 (33.9)	.959	349 (106.4)	81,793
18 (457)	75.7 (35.7)	.953	371 (113.1)	86,277
20 (508)	79.3 (37.4)	.948	391 (119.2)	90,440
22 (559)	82.7 (39.1)	.943	411 (125.3)	94,325
24 (610)	85.9 (40.6)	.937	429 (130.8)	97,965
26 (660)	88.9 (42.0)	.932	447 (136.2)	101,387

FLOW DATA

VENTURI SIZE: 1¼ in. (32 mm)

D= 1.38 in. (35 mm) p_1= 16 in. (406 mm) Hg. Vac.

β= 0.588 T_1= 73 F (22.8 C)

C'= 1.002

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	29.8 (14.1)	.994	140 (42.7)	26,422
4 (102)	41.9 (19.8)	.987	197 (60.0)	37,114
6 (152)	51.0 (24.1)	.980	242 (73.8)	45,145
8 (203)	58.5 (27.6)	.974	280 (85.3)	51,771
10 (254)	64.9 (30.6)	.967	313 (95.4)	57,480
12 (305)	70.6 (33.3)	.960	343 (104.5)	62,525
14 (356)	75.7 (35.7)	.953	371 (113.1)	67,057
16 (406)	80.4 (37.9)	.946	397 (121.0)	71,176
18 (457)	84.6 (40.0)	.940	422 (128.6)	74,949
20 (508)	88.6 (41.8)	.933	445 (135.6)	78,428
22 (559)	92.1 (43.5)	.926	467 (142.3)	81,652
24 (610)	95.6 (45.1)	.919	489 (149.0)	84,649
26 (660)	98.7 (46.6)	.912	509 (155.1)	87,444

FLOW DATA

VENTURI SIZE: 1¼ in. (32 mm)

D= 1.38 in. (35 mm) p_1= 20 in. (508 mm) Hg. Vac.

β= 0.588 T_1= 73 F (22.8 C)

C'= 1.002

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	35.3 (16.6)	.991	165 (50.3)	22,253
4 (102)	49.4 (23.3)	.982	234 (71.3)	31,170
6 (152)	59.9 (28.3)	.972	287 (87.5)	37,808
8 (203)	68.5 (32.3)	.962	332 (101.2)	43,231
10 (254)	75.8 (35.8)	.953	372 (113.4)	47,856
12 (305)	82.2 (38.8)	.944	408 (124.4)	51,898
14 (356)	87.9 (41.5)	.934	441 (134.4)	55,487
16 (406)	93.0 (43.9)	.924	472 (143.9)	58,706
18 (457)	97.6 (46.1)	.915	502 (153.0)	61,618
20 (508)	101.8 (48.1)	.905	530 (161.5)	64,261
22 (559)	105.6 (49.9)	.896	557 (169.8)	66,671
24 (610)	109.1 (51.5)	.886	582 (177.4)	68,875
26 (660)	112.0 (52.9)	.876	607 (185.0)	70,890

FLOW DATA

VENTURI SIZE: 1½ in. (38 mm)

D= 1.61 in. (41 mm) p_1= 8 in. (203 mm) Hg. Vac.

β= 0.698 T_1= 73 F (22.8 C)

C'= 1.068

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ ($\frac{l}{s}$)	Y	V_2 $\frac{ft}{sec}$ ($\frac{m}{s}$)	Re
2 (51)	48.8 (23.1)	.995	119 (36.3)	49,179
4 (102)	68.7 (32.4)	.990	168 (51.2)	69,195
6 (152)	83.7 (39.5)	.985	206 (62.8)	84,312
8 (203)	96.2 (45.4)	.980	237 (72.2)	96,855
10 (254)	107.0 (50.5)	.975	265 (80.8)	107,728
12 (305)	116.6 (55.0)	.970	291 (88.7)	117,399
14 (356)	125.3 (59.1)	.965	314 (95.7)	126,147
16 (406)	133.2 (62.9)	.960	335 (102.1)	134,153
18 (457)	140.6 (66.4)	.955	355 (108.2)	141,546
20 (508)	147.4 (69.6)	.950	375 (114.3)	148,418
22 (559)	153.8 (72.6)	.945	393 (119.8)	154,841
24 (610)	159.8 (75.4)	.940	410 (125.0)	160,868
26 (660)	165.4 (78.1)	.935	427 (130.1)	166,546

FLOW DATA

VENTURI SIZE: 1½ in. (38 mm)

D= 1.61 in. (41 mm) p_1= 12 in. (203 mm) Hg. Vac.

β= 0.698 T_1= 73 F (22.8 C)

C'= 1.068

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	53.8 (25.4)	.994	131 (39.9)	44,274
4 (102)	75.6 (35.7)	.988	185 (56.4)	62,222
6 (152)	92.0 (43.4)	.982	227 (69.2)	75,728
8 (203)	105.6 (49.8)	.976	261 (79.6)	86,893
10 (254)	117.3 (55.4)	.969	292 (89.0)	96,534
12 (305)	127.7 (60.3)	.963	320 (97.5)	105,076
14 (356)	137.0 (64.7)	.957	346 (105.5)	112,770
16 (406)	145.5 (68.7)	.951	370 (112.7)	119,782
18 (457)	153.3 (72.4)	.945	392 (119.5)	126,228
20 (508)	160.6 (75.8)	.939	413 (125.9)	132,194
22 (559)	167.3 (79.0)	.933	433 (132.0)	137,742
24 (610)	173.6 (82.0)	.926	452 (137.8)	142,925
26 (660)	179.5 (84.7)	.920	471 (143.6)	147,781

FLOW DATA

VENTURI SIZE: 1½ in. (38 mm)

D= 1.61 in. (41 mm) p_1= 16 in. (406 mm) Hg. Vac.

β= 0.698 T_1= 73 F (22.8 C)

C'= 1.068

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	60.9 (28.8)	.992	149 (45.4)	38,951
4 (102)	84.5 (40.3)	.984	210 (64.0)	54,642
6 (152)	103.8 (49.0)	.977	257 (78.3)	66,381
8 (203)	118.9 (56.1)	.969	297 (90.5)	76,026
10 (254)	131.8 (62.2)	.961	332 (101.2)	84,304
12 (305)	143.2 (67.6)	.953	363 (110.6)	91,589
14 (356)	153.4 (72.4)	.945	392 (119.5)	98,108
16 (406)	162.7 (76.8)	.937	419 (127.7)	104,006
18 (457)	171.1 (80.8)	.929	445 (135.6)	109,388
20 (508)	178.8 (84.4)	.921	469 (142.9)	114,330
22 (559)	185.9 (87.8)	.913	491 (149.7)	118,889
24 (610)	192.5 (90.9)	.906	513 (156.4)	123,110
26 (660)	198.7 (93.8)	.898	534 (162.8)	127,029

FLOW DATA

VENTURI SIZE: 1½ in. (38 mm)

D= 1.61 in. (41 mm)

β= 0.698

C'= 1.068

p_1= 20 in. (508 mm) Hg. Vac

T_1= 73 F (22.8 C)

Δp, in. (mm) H_2O	FLOW, $\frac{ft^3}{min}$ $(\frac{l}{s})$	Y	V_2, $\frac{ft}{sec}$ $(\frac{m}{s})$	Re
2 (51)	71.9 (34.0)	.989	176 (53.6)	32,775
4 (102)	100.6 (47.5)	.978	249 (75.9)	45,827
6 (152)	121.8 (57.5)	.967	304 (92.7)	55,486
8 (203)	139.0 (65.6)	.956	351 (107.0)	63,333
10 (254)	153.6 (72.5)	.945	393 (119.8)	69,987
12 (305)	166.3 (78.5)	.934	430 (131.1)	75,769
14 (356)	177.5 (83.8)	.923	464 (141.4)	80,873
16 (406)	187.5 (88.5)	.911	496 (151.2)	85,425
18 (457)	196.4 (92.7)	.901	526 (160.3)	89,514
20 (508)	204.5 (96.5)	.890	555 (169.2)	93,206
22 (559)	211.9 (100.0)	.879	582 (177.4)	96,550
24 (610)	218.5 (103.2)	.868	608 (185.3)	99,586
26 (660)	224.6 (106.0)	.858	633 (192.9)	102,345

MEASUREMENT OF AIR FLOW AT VACUUM CONDITIONS USING SMALL VENTURIS

by

Hector Alonso

(ABSTRACT)

Small Venturis were used to measure air flow rates through cigarette-making machines to a vacuum header.

A programmable calculator was used to develop charts for each Venturi, showing flow versus differential pressure at inlet vacuums from 8 in. (203 mm) to 20 in. (508 mm) of mercury. Use of the charts eliminates the need to calculate the flow each time a test is run.

An error analysis indicated that large variations in temperature do not affect the result. The accuracy of the charts is not affected as long as the tests are run at room temperature.

The Venturis, ranging in size from ½ in. (13 mm) to 1½ in. (38 mm) will continue to be used to measure and monitor vacuum requirements of the machines.