Main Index

FUTURE METERING SYSTEMS

SONIC NOZZLES

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1. INTRODUCTION

The phenomenon of critical flow, although established analytically and experimentally before 1900, did not become popular in flow measurement until the 1950's. At that time critical flowmeters were used as a test device in performance evaluation of gas turbines and within the aerospace industry in its rocket propulsion projects. From these applications came an optimized critical flow meter, the critical flow venturi, also called sonic nozzle. After many years of effort in different laboratories in Europe and USA, the International Standardization Organisation has decided to publish a draft international standard (DIS) for measurement of gas flow by means of critical flow venturi nozzles.

2. TYPICAL FEATURES OF A CRITICAL FLOW VENTURI NOZZLE

A critical flow venturi nozzle (CFVN) or sonic nozzle (SN) is shown in figures 1 and 2. It consists of an inlet convergent, a toroidal or cylindrical throat and a divergent outlet. A CFVN is a constriction type flow meter in which the phenomenon of critical flow occurs when the gas velocity in the throat of the meter is accelerated to the local value of the velocity of sound.

2.1. Advantages

System simplicity

The CFVN requires less instrumentation and is less sensitive to installation and pulsation errors than subcritical devices. As long as critical flow conditions are maintained, downstream perturbations are not propagated upstream and do not introduce any error in the flow rate measurement. Only pressure and temperature need to be recorded in order to predict the flow rate through the CFVN.

Recovery

Due to the divergent outlet section downstream of the throat the CFVN is able to recover up to 90% to 95% of the stagnation pressure.

Repeatability

The CFVN has no movable part which may create performance drift. Experiences have demonstrated repeatability well within ±0,1%.

Predictability

The flow rate through a CFVN can be theoretically predicted with high enough accuracy for all practical purposes.

2.2. Limitations

Rangeability

The rangeability of the CFVN is limited to the possible variations of inlet pressure. It is convenient when large flow rates are required to instal a battery of CFVN as shown in figure 3.

Pressure loss

Critical flow conditions in the nozzle generate pressure loss of at least 5% to 10% of upstream pressure. For system design purpose this pressure loss should be put to 10%.

Real gas properties

For real gas calculations there is still a lack of knowledge, but for design purpose the model developed by R.C. Johnson prevails (1,2).

Construction

Due to the particular inlet, throat and outlet sections the construction requires very skillful machinist to build and inspect according to the tolerances. The larger the throat diameter, the easier the construction.

3. THEORETICAL CONSIDERATIONS

3.1. Ideal conditions

The theoretical calculations of flow through a CFVN is based on three main hypothesis:

- the flow is one-dimensional
- the flow is isentropic
- the gas is perfect

If these conditions are satisfied, the value of the mass flow rate through the CFVN is predicted to be:

$$q_{mi} = A^* \, C_i^* \, p_o \left(\sqrt{\frac{R}{M} \, T_o}\right)^{-1} \quad (1)$$

where

C_i^* is the critical flow function for one dimensional isentropic flow of a perfect gas, definded as:

$$C_i^* = \left[\gamma \left(\frac{2}{\gamma-1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}\right]^{\frac{1}{2}} \quad (2)$$

The other parameters are defined in the nomenclature.

3.2. Real conditions

In order to compensate for the deviation from non-one dimensional and non isentropic flow one introduces the notion of discharge coefficient, C. The discharge coefficient of a CFVN is less than unity since the flow is not one-dimensional and a boundary layer exists due to viscous effects. C may be determined by direct calibration or from an empirically determined function of the Reynolds number.

By direct calibration the nozzle discharge coefficient is obtained from the equation:

$$C = \frac{q_{act}}{q_{mi}} \quad (3)$$

where

q_{act} is the actual mass flowrate calculated from a primary calibration. From series of primary calibrations the following equation has been developed:

$$C = a - b \, Re_d^{-n} \quad (4)$$

where

Re_d is the CFVN throat Reynolds number defined as:

$$Re_d = \frac{4 q_m}{\pi d \mu_o}$$

The coefficients a and b are given in table 1. They are the same as those indicated in the forthcoming DIS for CFVN (3).

The flowrate, q_m, in real conditions becomes:

$$q_m = A_* C C_* \, p_o \left(\sqrt{\frac{R}{M} T_o}\right)^{-1} \qquad (5)$$

where

C^* is the critical flow function for one dimensional gas flow.

$$q_m = A_* C C_R \sqrt{(p_o \, \rho_o)} \qquad (6)$$

where

C_R is the real gas critical flow coefficient defined as

$$C_R = C_* \sqrt{Z} \qquad (7)$$

R.C. Johnson (2) has developed an empirical correlation for the critical flow metering of natural gas mixtures valid up to 70 bar. According to Johnson:

$$C_R = a_c f + b_c \qquad (8)$$

the compressibility, Z, being calculated by means of the Benedict, Webb, Rubin equation of state.

The coefficients a_c and b_c are given in tables 2 and 3 as function of pressure and temperature.

The gas composition factor, f, is defined as:

$$f = -\frac{1}{2} X_{N_2} + X_{CO_2} + X_{C_2H_6} + 2 X_{C_3H_8} + 3 X_{C_4H_{10}} \qquad (9)$$

where

X is the mole fraction of the gas whose chemical symbol appears in the subscript.

According to Johnson the composition factor, f, should be in the range 0 to 0.2. It should be noted that the composition range of the gas mixture, where this correlation is applicable, is quite limited. Table 4 gives the permissible range for all components in mole fractions. Although it has been recognized that this technique is not as accurate as one would desire, it is the only one which is currently available for practical use.

4. STANDARD CFVN AND INSTALLATION REQUIREMENTS

As indicated in figures 1 and 2, CFVN consists of a convergent inlet followed but the throat and divergent outlet. The divergent is shaped to provide a maximum pressure recovery.

A large number of inlet shapes and throat geometries have been proposed and studied. Discussions by ASME and ISO committees have reduced these shapes down to two which are currently considered as standard devices (3).

One is proposed by Hillbrath (4); it is identical to the design of Smith and Matz (5). It consists of a toroid of R/d=2.0, and a contraction ratio of 2,5. This device has no cylindrical throat and the diffuser is a cone of 4 degree half angle tangent to the continuation of the inlet toroid. Brain and Reid (6), Arnberg et al. (7) and Stratford (8) have also largely contributed to the toroidal CFVN development and design.

The second one is based on investigations performed by Jaumotte (9), Castillon (10), Masure et al. (11), Grenier (12) and Peignelin (13). It consists of a quarter of a torus tangent both to the inlet plane and to the cylindrical throat. The radius of curvature of the torus is equal to the throat diameter. The cylindrical throat has a length equal to the throat diameter. The diffuser is the same as for the toroidal throat venturi.

The inlet conduit up to 3 pipe diameter (3D) upstream of the venturi nozzle shall not deviate from circularity by more than 1% of its diameter and shall have an average roughness height which shall not exceed $75.10^{-4}\cdot D$ (m/m) of conduit diameter.

To avoid corrections for the dynamic pressure upstream of the nozzle, a CFVN shall never be used with a diameter ratio (throat/pipe) larger than 0.25 when placed in a circular conduit. In any other case it is recommended that the throat area shall never exceed 6% of the upstream area.

Pressure taps for upstream static pressure measurements shall be located 0.9 -1.1 D from the inlet plane of the nozzle. The diameter of pressure tap should preferably be 1.3 $\pm$0.3 mm. Downstream pressure shall be measured with a pressure tap 0.5 D downstream of exit plane. Temperature shall be measured 2D upstream and the diameter of the sensing element should not exceed 0.04 D.

5. UNCERTAINTIES

5.1. General

As mentioned previously, operation at critical flow conditions is characterized by a continuous acceleration of the flow from the venturi inlet to some location downstream of the throat.

Figure 4 shows an ideal Mach number distribution along venturi length at typical subcritical and critical flow conditions. Ideal weight flow rate per unit area at the venturi throat is shown in figure 5 as a function of throat Mach number and throat pressure ratio. Variation of venturi throat static pressure as a function of maximum venturi Mach number is indicated in figure 6. Operation at critical conditions, as compared with operation at subcritical conditions, results in a marked reduction of the error in flow rate resulting from errors in venturi pressures.

The rate of change of air flow with respect to Mach number is large at low Mach number (Ma from 0.2 - 0.4). The rate of change is zero at Ma=1. At critical flow conditions the throat static pressure is constant.

5.2. Draft international standard

In the DIS document (3) it is indicated that the relative uncertainty of the discharge coefficients calculated according to equation (4) is ±0.5%. This uncertainty is for a confidence level of 95%.

European laboratories as NEL and Gaz de France which operate tests facilities for primary calibration of CFVN (gravimetry and volumetry) claim an accuracy better than ±0.25 to ±0.3% on their discharge coefficients.

5.3. Uncertainty calculations

Details for practical uncertainty calculations are indicated in the standard ISO-5168: Estimation of uncertainty of a flow-rate measurement.

The practical working formula for mass flow uncertainty claculations is:

$$E_{q_m}^2 = 4\ E_d^2 + E_c^2 + E_{p_o}^2 + \frac{1}{4}\ E_{T_o}^2 + \frac{1}{4}\ E_M^2 + E_{C*}^2$$

Assuming the following relative uncertainties:

E_d	=	0.05%	throat diameter
E_C	:	see table 5	discharge coefficient
E_{P_o}	:	see table 5	stagnation pressure
E_{T_o}	=	0.15%	stagnation temperature
E_M	:	see table 5	molecular weight
E_{C*}	:	see table 5 and figure 7	critical flow factor

Based on these above indicated uncertainties, the relative error on the flow rate has been calculated. Table 5 shows that e_q varies between $\pm 0.45\%$ and $\pm 0.76\%$

6. APPLICATIONS

6.1. General

The CFVN has two main application fields. One concerns secondary standards for gas flow meter calibration and control, the second is for turbine testing.

Turbine testing requires the accurate measurement of air flow. CFVN´s are normally used because they are approximately 3 times more accurate than subsonic metering devices (15).

The CFVN has been used as secondary standard by Gaz de France who uses this type of device to control the flowmeters installed on their grid. In UK NEL has actively promoted its use within gas metering.

In the US, the Natural Gas Pipeline Co. of America has also used CFVN to verify their line meters (16).

Besides, tests have shown that the method of using a set of sonic nozzles (figure 3), arranged in parallel in a package of short length, can prove to be a particurlarly effective means of obtaining performance traceability for flowmeters which measure flow rates well in excess of those which can be covered on existing primary standard test facilities.

6.2. Practical criteria

When a CFVN is intended for use, for instance with a natural gas whose composition factor, f, is within the previously mentioned validity range (0 to 0.2), the following procedure is recommended:

- determine roughly the nozzle capacity, i.e. A*. Figure 8 shows the mass flowrate variation as function of stagnation pressure for different throat diameters.
- manufacture or buy the right nozzle (either with toroidal or cylindrical throat). Refer to DIS recommendations.
- have the CFVN primary calibrated in order to determine the discharge coefficient. Alternatively determine the discharge coefficient through a secondary calibration or by means of equation (4).
- apply Johnson method to calculate the real gas critical flow coefficient, C_R and use an appropriate state equation to calculate Z.
- calculate the mass flow rate from equation (5) or (6).

Particular attention must be paid to the gas composition. The above mentioned formula is only valid for gases whose composition corresponds to what is indicated in table 4. For other gases and for pressures higher than 70 bar there is no methods which are directly applicable. However, the fundamental procedure used by Johnson is a general one and can also be used for other gas compositions. It should be noted that when the gas contains important quantities of heavy components (for instance more than 0.4% of C_4) precautions should be taken to prevent possible condensation effects.

7. CONCLUSIONS

Recommendations have been given for two types of standardized CFVN. Essential features of these designs are given as indications. A final document on that topic will be issued by the International Organization for Standardization (3).

The CFVN is normally not suited for on line flow rate measurements in field installations, but it is very useful as secondary standard for gas flow meter calibration and for verification of line meters (16). The CFVN is used for testing of turbines (15).

The accuracy and the repeatability are two main advantages of the CFVN. The mass flow rate through a CFVN is easily predicted from theoretical calculations. Uncertainties of the order of ±0.7% on the flow rate may be obtained when an ±0.5% uncertainty on the discharge coefficient is considered. Improvement on the flow-rate accuracy may be obtained by direct calibration of the CFVN. In this case accuracy better than ±0.5% is achieved.

Methods are available to calculate the mass flow rate through a CFVN for natural gas mixtures which have up to 0.4% of C_4 components.

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1. NOMENCLATURE

The nomenclature used in this report is shown below:

A^*	Area of critical flow venturi nozzle throat	L^2	m^2
C	Coefficient of discharge for the venturi nozzle	Dimension-less	
C_d	Coefficient of discharge for the orifice	Dimension-less	
C^*	Critical flow function	Dimension-less	
C_i^*	Critical flow function for one dimensional flow of a perfect gas	Dimension-less	
d	Diameter of orifice or throat of primary device	L	m
D	Upstream internal pipe diameter	L	m
e_X	Absolute uncertainty of the quantity X	[X]	
E	Velocity of approach factor $E=(1-\beta^4)^{-\frac{1}{2}}$	Dim.less	
f	Gas composition factor	Dim.less	
k	Pressure loss coefficient	Dim.less	
$\dot{m}$	Total mass rate of flow in the loop	M/t	kg/s
Ma	Mach-number	Dim.less	
M	Molecular weight	M	kg
p_o	Stagnation pressure of the gas at nozzles inlet	$ML^{-1}T^{-2}$	Pa
p	Static pressure of the gas	$ML^{-1}T^{-2}$	Pa
Δp	Differential pressure	$ML^{-1}T^{-1}$	Pa
Q	Total volume rate of flow in the loop	L^3/t	m^3/s
q_m	Mass rate of flow through a CFVN	M/t	kg/s
q_v	Volume rate of flow through a CFVN	L^3/t	m^3/s
Re	Reynolds number	Dim.less	
R	Universal gas constant	$L^2t^{-2}T^{-1}$	$Nm/^oK$
T	Temperature of the gas	T	^oK
T_o	Stagnation temperature of the gas	T	^oK
U	Mean axial velocity of the fluid in the pipe	L/t	m/s
Z	Compressibility factor	Dim.less	

β	Diameter ratio, $\beta=\frac{d}{D}$	Dim.less	
γ	Ratio of specific heat capacities	Dim.less	
κ	Isentropic exponent	Dim.less	
μ	Dynamic viscosity of the gas	$ML^{-1}\,t^{-2}$	kg/ms^2
ρ	Density of the gas	ML^{-3}	kg/m^3
φ	Product coefficient $\varphi=A*CC*\sqrt{\frac{R}{M}}^{-1}$	$Lt(MT)^{\frac{1}{2}}$	$ms(^{o}K/kg)^{\frac{1}{2}}$
θ	Sensitivity coefficient	-	
ε	Expansibility factor	Dim.less	

TABLE 1

Toroidal throat		Cylindrical throat	
$10^5 < Re_d < 10^7$	a = 0.993 54 b = 1.525 n = 0.5	$10^4 < Re_d < 4 \times 10^5$	a = 1 b = 7.24 n = 0.5
		$4 \times 10^5 < Re_d < 2.8 \times 10^6$	a = 0.9886 b = n = 0
		$2.8 \times 10^6 < Re_d < 2 \times 10^7$	a = 1 b = 0.2215 n = 0.2

TABLE 2

VALUES OF COEFFICIENT α_C

TEMP DEG C	INLET STAGNATION PRESSURE - MEGAPASCALS						
	0	1	2	3	4	5	6
0	¯.0293	¯.0331	¯.0371	¯.0407	¯.0437	¯.0452	¯.0442
5	¯.0298	¯.0336	¯.0373	¯.0408	¯.0436	¯.0452	¯.0447
10	¯.0304	¯.0340	¯.0375	¯.0409	¯.0436	¯.0452	¯.0450
15	¯.0309	¯.0343	¯.0377	¯.0410	¯.0436	¯.0451	¯.0452
20	¯.0314	¯.0347	¯.0380	¯.0412	¯.0436	¯.0451	¯.0454
25	¯.0319	¯.0351	¯.0383	¯.0413	¯.0436	¯.0452	¯.0456
30	¯.0324	¯.0355	¯.0385	¯.0414	¯.0437	¯.0452	¯.0457
35	¯.0328	¯.0358	¯.0387	¯.0414	¯.0437	¯.0452	¯.0458
40	¯.0332	¯.0361	¯.0390	¯.0416	¯.0437	¯.0453	¯.0459

TABLE 3

VALUES OF COEFFICIENT b_c

TEMP DEG C	INLET STAGNATION PRESSURE - MEGAPASCALS						
	0	1	2	3	4	5	6
0	.6709	.6708	.6709	.6714	.6722	.6737	.6756
5	.5707	.6706	.6708	.6713	.6722	.6736	.6755
10	.6704	.6704	.6706	.6712	.6721	.6734	.6753
15	.6701	.6702	.6704	.6710	.6720	.6733	.6751
20	.6699	.6699	.6702	.6703	.6718	.6731	.6749
25	.6695	.6697	.6700	.6706	.6716	.6729	.6746
30	.6692	.6694	.6698	.6704	.6714	.6727	.6744
35	.6689	.6691	.6695	.6702	.6712	.6724	.6741
40	.6686	.6688	.6693	.6700	.5709	.6722	.6738

TABLE 4

Methane	0.840 - 1.000
Ethane	0 - 0.11
Propane	0 - 0.020
2-Methyl Propane	0 - 0.004
Butane	0 - 0.004
Nitrogen	0 - 0.023
Carbon Dioxide	0 - 0.017

E_c	E_{p_o}	E_M	E_{c*}	E_{q_m}
0.3	0.1	0.25	0.25	0.44
			0.40	0.54
		0.5	0.25	0.49
			0.40	0.58
	0.2	0.25	0.25	0.47
			0.40	0.57
		0.5	0.25	0.52
			0.40	0.61
	0.3	0.25	0.25	0.52
			0.40	0.61
		0.5	0.25	0.57
			0.40	0.65
0.5	0.1	0.25	0.25	0.59
			0.40	0.67
		0.5	0.25	0.63
			0.40	0.71
	0.2	0.25	0.25	0.62
			0.40	0.69
		0.5	0.25	0.66
			0.40	0.73
	0.3	0.25	0.25	0.66
			0.40	0.73
		0.5	0.25	0.69
			0.40	0.76

TABLE 5 RELATIVE UNCERTAINTIES

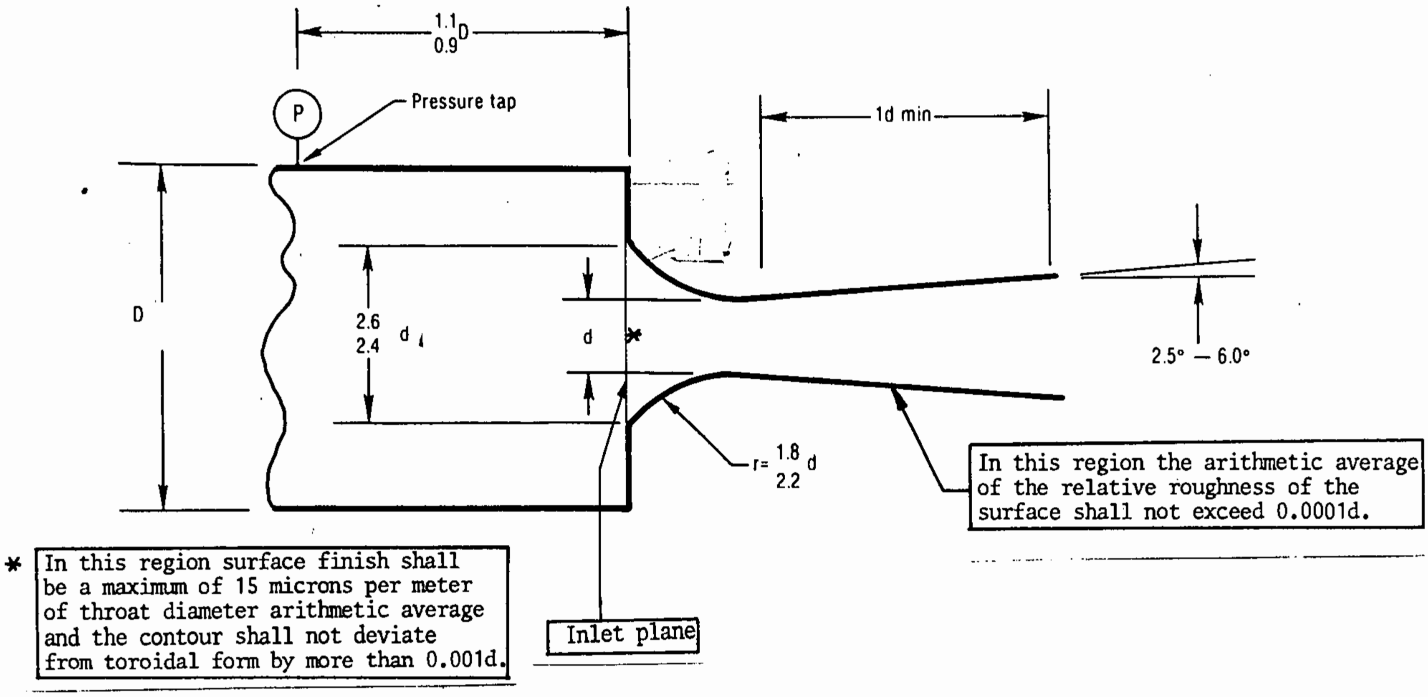

FIGURE 1 TOROIDAL THROAT VENTURI NOZZLE

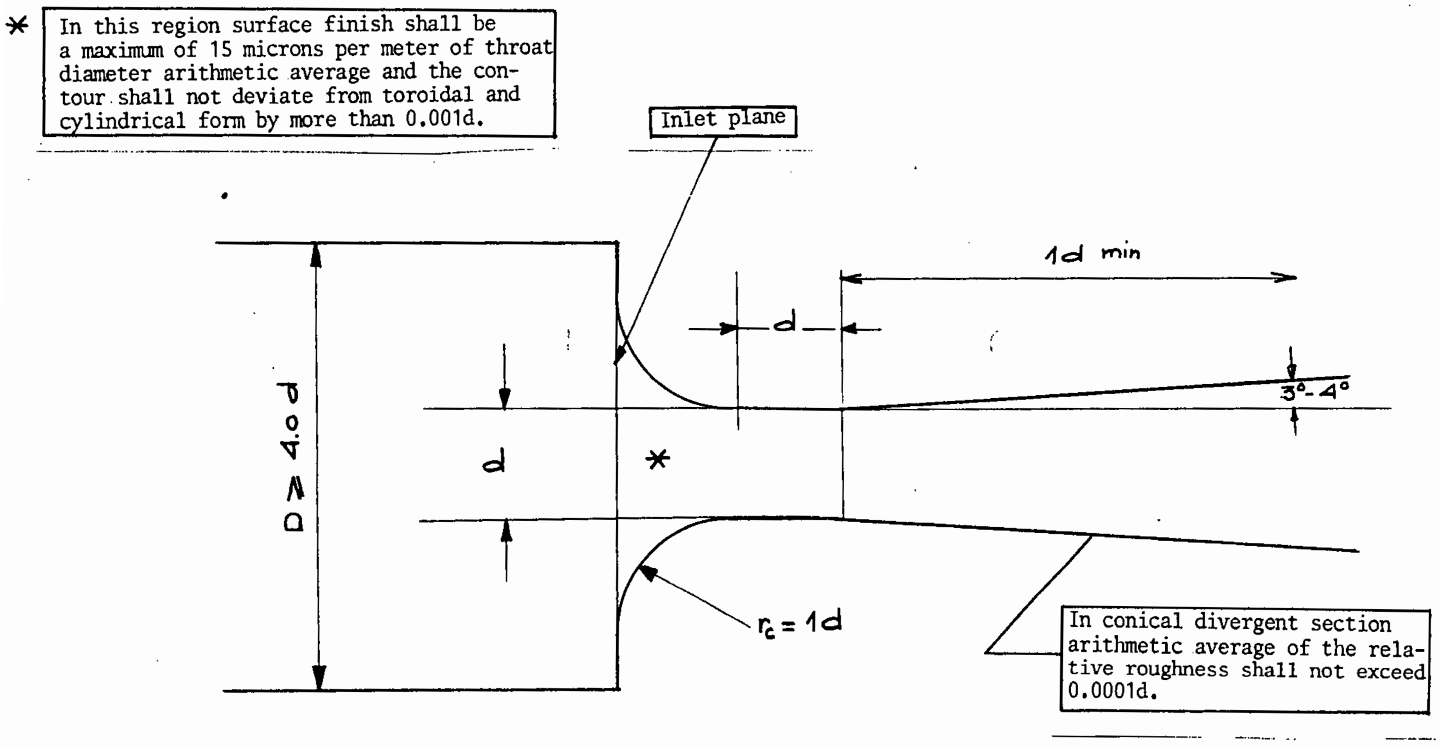

FIGURE 2 CYLINDRICAL THROAT VENTURI NOZZLE

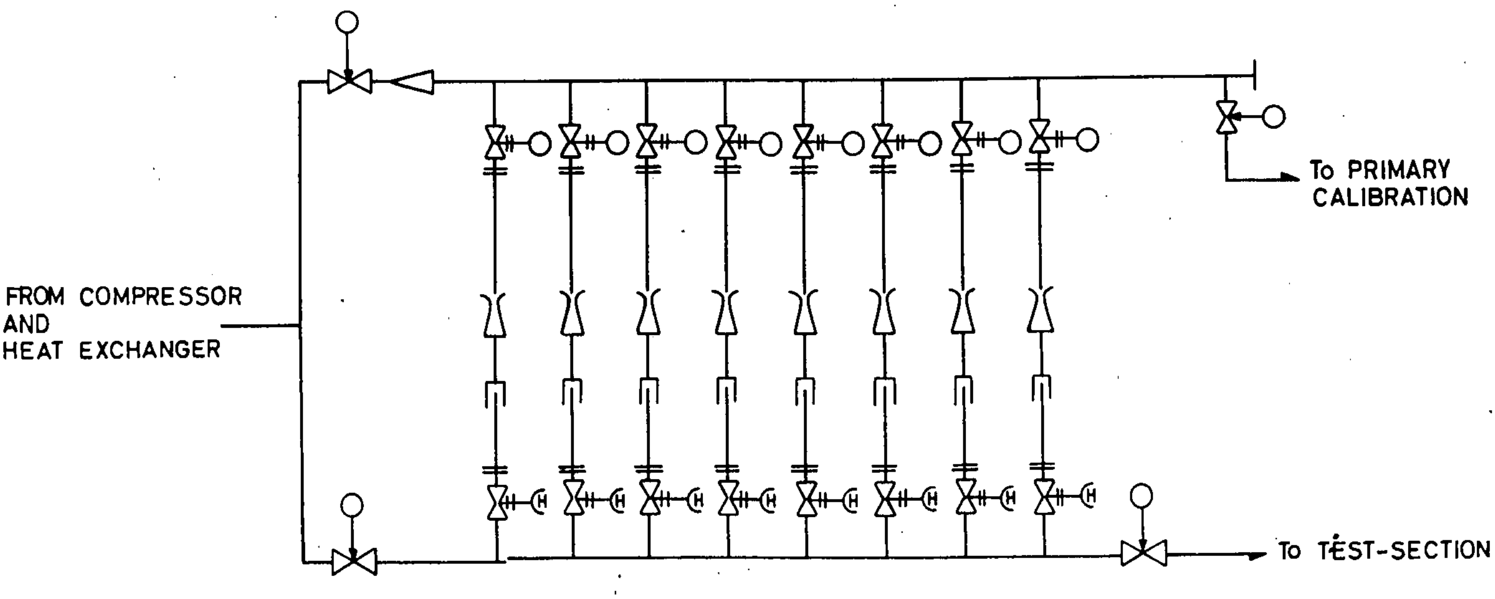

FIGURE 3 BATTERY OF VENTURI NOZZLES

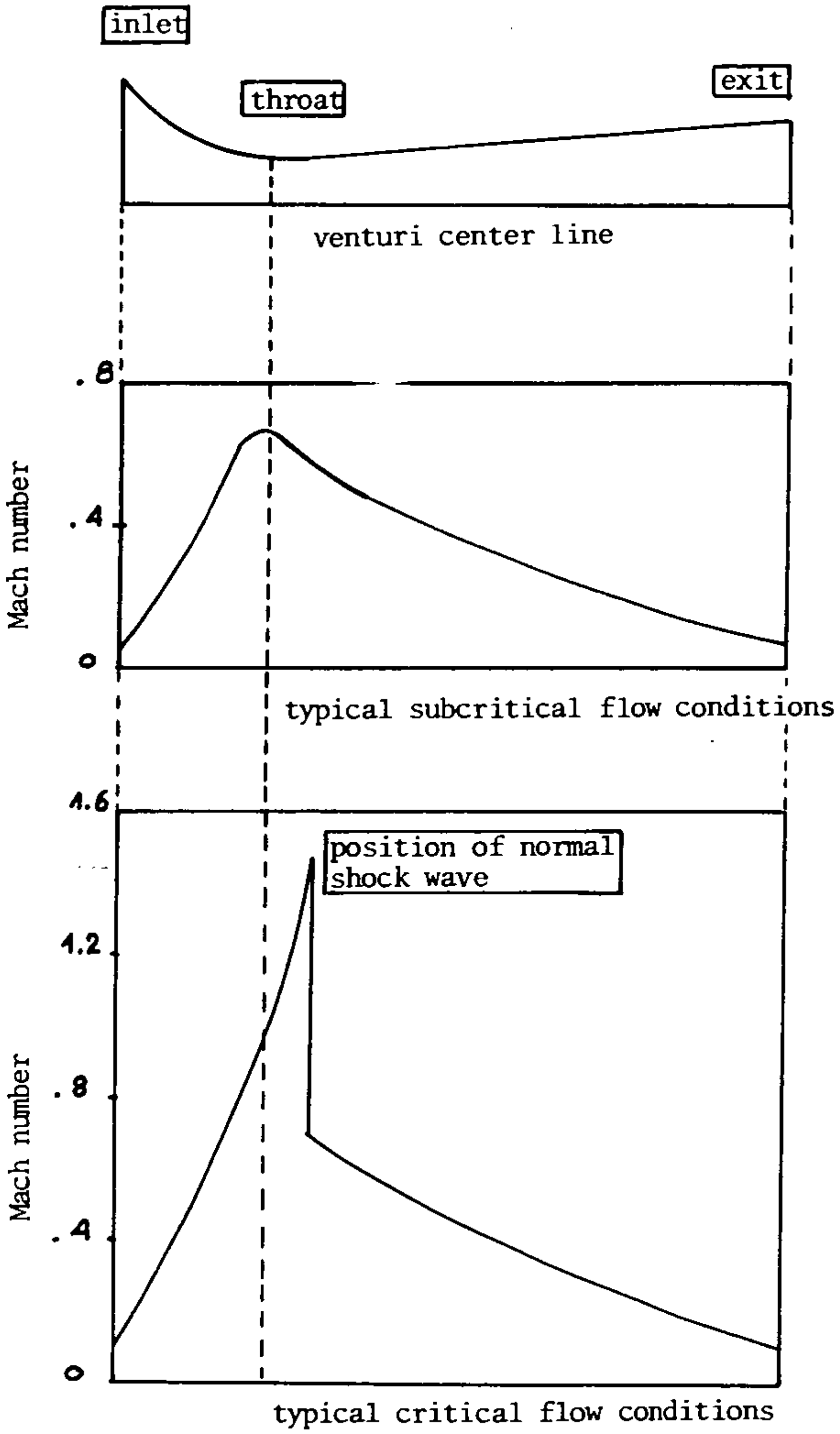

FIGURE 4 IDEAL MACH NUMBER DISTRIBUTION ALONG VENTURI LENGTH AT TYPICAL SUB/CRITICAL FLOW CONDITIONS (ref.5)

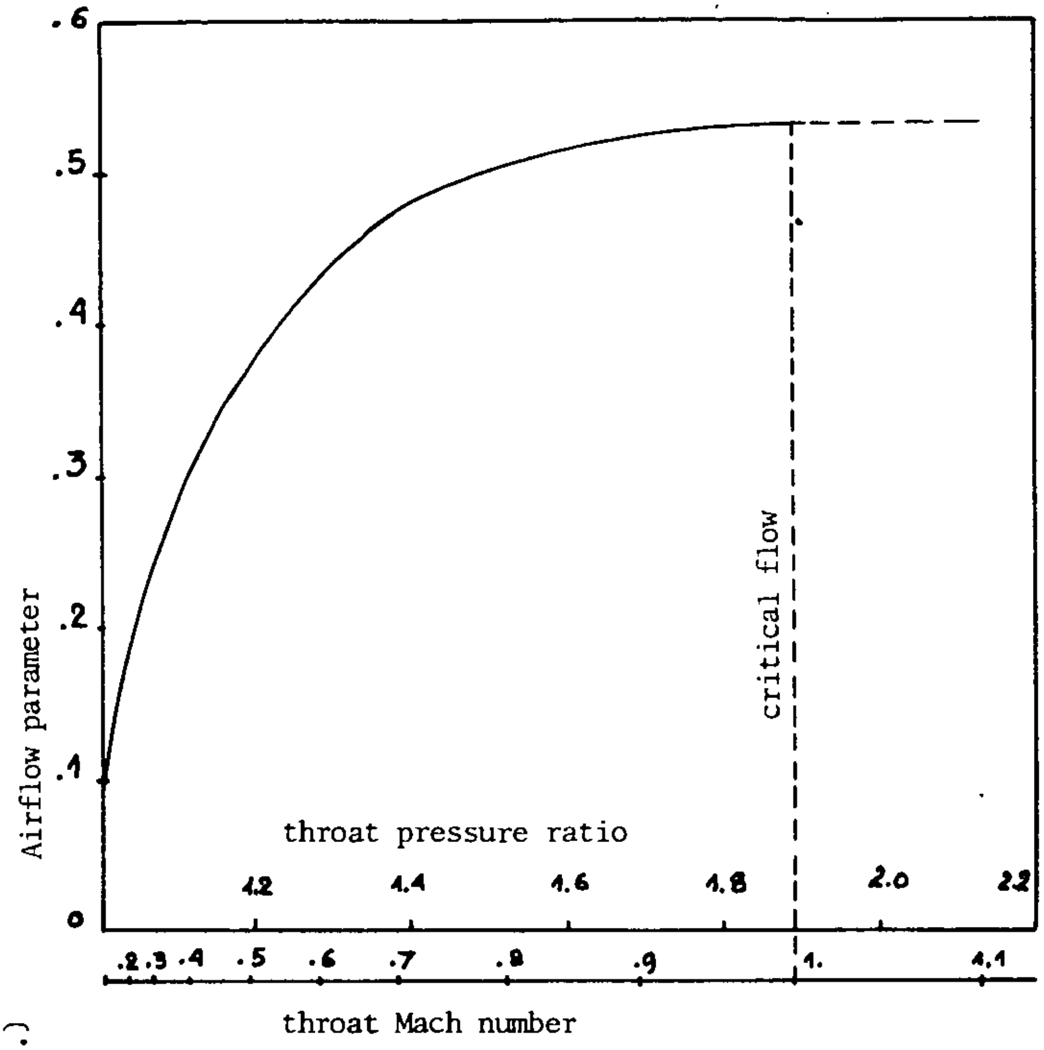

FIGURE 5
(ref. 5)

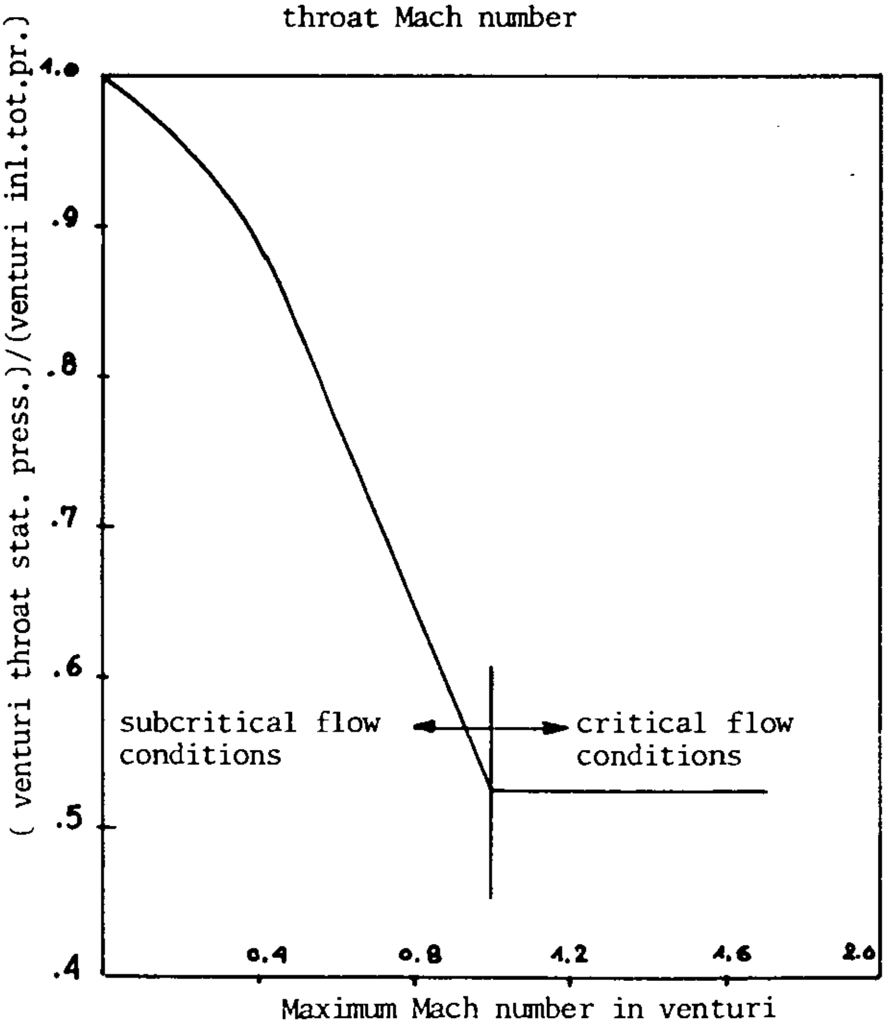

FIGURE 6
(ref. 5)

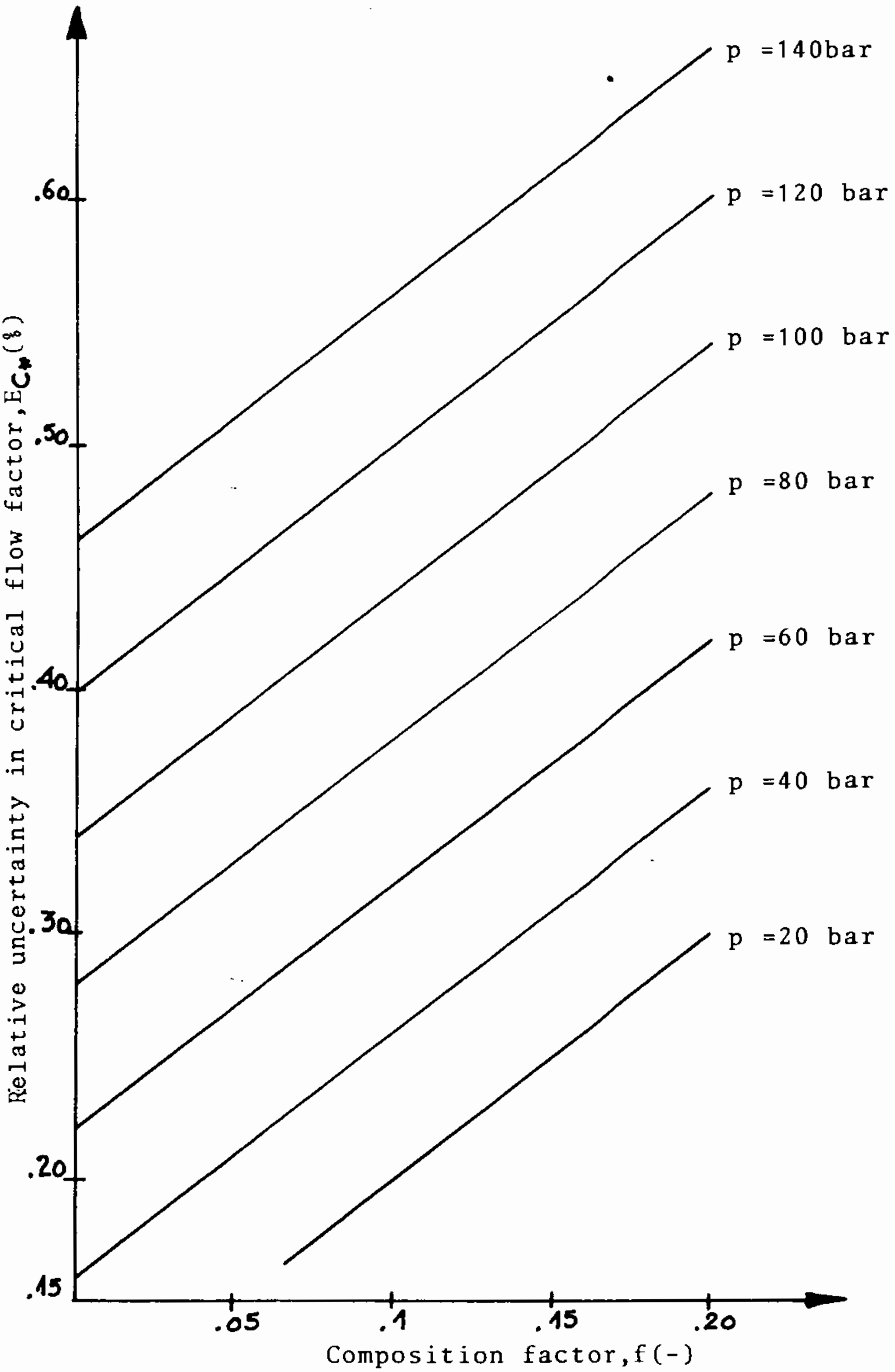

FIGURE 7 RELATIVE UNCERTAINTY IN CRITICAL FLOW FACTOR VS. THE COMPOSITION FACTOR AT DIFFERENT PRESSURES.

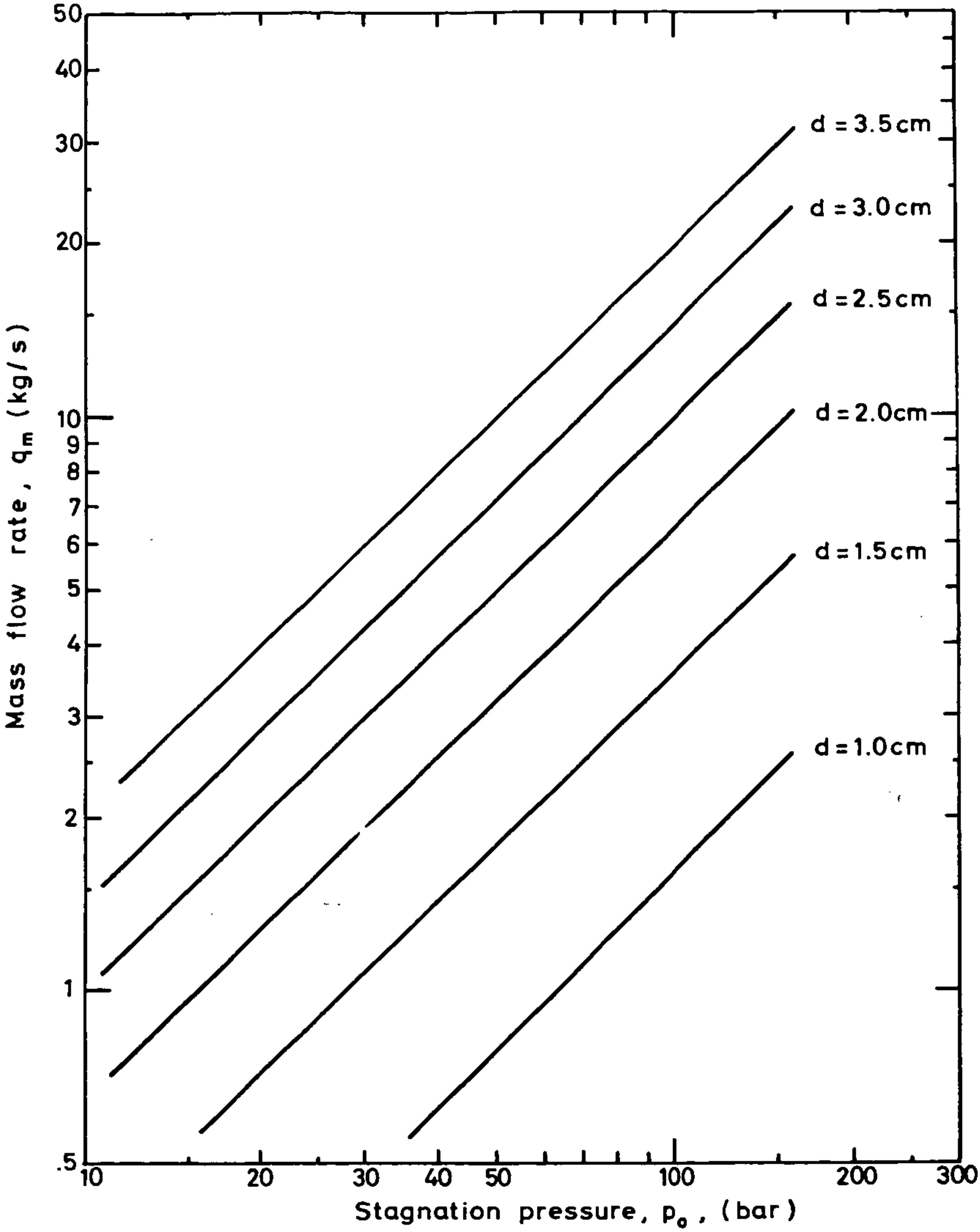

FIGURE 8. MASS FLOW-RATE AS FUNCTION OF STAGNATION PRESSURE FOR DIFFERENT THROAT DIAMETERS. (T_0=30°C). THE CURVES ARE ONLY FOR ROUGH ESTIMATES.