"EXPERIMENTAL EVALUATION OF FRICTION IN HIGH SPEED COMPRESSIBLE HOMENERGIC FLOW AND DEVELOPMENT OF FRICTION CHOKED GAS FLOW METERING DEVICE

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ABSTRACT

The rapid changes in fluid properties in high speed homenergic flow associate with them changes of momentum flux of appreciable magnitude that would affect wall shear stress. An experimental rig is designed to evaluate the frictional effects on high speed compressible flow in constant area ducts. Accurate measurements of flow parameters are determined. The Fanning friction coefficient is obtained for the range of Mach numbers 0.2 to 1.0 and Reynolds numbers 2×10^5 to 5.5×10^5 and compared with previous workers for incompressible flow. An empirical relation to describe the friction coefficient for this flow is developed. Implication of the analysis resulted in the development of friction choked gas flow device suitable for flow metering and for preparation of premixed metered explosive or poisonous gas mixtures. The device is tested with dry air and other gases and showed very good agreement between analytical characteristics and experimental measurements. The device proves to have high accuracy, safety, simplicity and adequacy for laboratory and industrial uses.

Keywords: Compressible flow, Homenergic flow, Friction choking, Experimental, Gas metering.

Nomenclature

a	Speed of sound, m/s
B	Barometer reading, cm Hg
f	Friction coefficient
$\dot{m}$	Mass flow rate, Kg/s
P	Pressure, cm Hg, Kg_f/cm^2
$\bar{R}$	Universal gas Constant., Kg_f.m/Kg mol.°K
T	Temperature, °C,°K
W	Molecular weight.
ρ	Density, Kg/m^3
τ_f	Viscous shear stress.
A	Cross section area, m^2
D	diameter, m
F	Friction force, Kg_f
M	Mach number of flow
Q	Hydraulic diameter of Hydraulic radius, m
Re	Reynold number
V	Velocity of flow, m/s
γ	Specific heat ratio
μ	Viscosity, Kg/m.s

Suffixes

e : means exit   f : means friction
o : Means stagnation

INTRODUCTION

Internal compressible flow has an important role in diverse engineering fields including stationary power plants, aircraft propulsion engines, gas transport plants, high vacuum technology etc. The present work, however, has been initiated in seeking a proper way to accurately and safely meter fuel gas and fuel/air mixtures for the combustion experiments. Measurements of propane gas flow rate for pulsating combustors that generate strong disturbances transmitted upstream of the meter, affect accuracy to great extent [1], [2]. Supercritical outflow would confine unsteadiness only downstream of the meter. Another situation that presents major problem is the preparation of homogeneous premixed gas fuel/air mixture with specific ratio. The problem relates to explosion hazards and non assurance of the adequacy of the prepared mixture when using the normal way using storage mixing vessel in which gas constituents are metered according to their partial pressures. In either case, when using friction choked meter, supercritical outflow of the meter would arrest the flame if flash back would result from combustion source.

The rapid change in fluid properties for high speed compressible flow in pipe associate changes in momentum flux of appreciable magnitude that would affect wall shear stress. However, previous works such as [3], [4], [5] and [6] recommend use of a friction factor estimated on low speed incompressible flow. This conclusion is critically examined for high speed compressible flow for substantiation or disapproval before the design and calibration of the presented friction choked gas mattering device.

FRICTION AND FRICTION CHOKED FLOW ANALYSIS REVIEW

Compressible flow conservation equations with inclusion of viscous effects is introduced for one-dimension constant area circular duct control volume with wetting area of distance dx. The duct is insulated for homenergic flow. The flow is steady of perfect gas with constant specific heats.

Local sonic speed and local Mach numbers are

$$a = \left(\frac{\partial P}{\partial \rho}\right)_s = \sqrt{\gamma R T} \qquad (1)$$

$$M = V/a \qquad (2)$$

The continuity equation is :

$$\frac{d\rho}{\rho} + \frac{dV}{V} = 0 \qquad (3)$$

The energy equation is

$$\frac{dT}{T} = -\frac{(\gamma - 1)M\,dM}{\left(1 + \frac{\gamma-1}{2}M^2\right)} \qquad (4)$$

Which upon integration for homenergic flow results

$$T_o = T\left(1 + \frac{\gamma-1}{2}M^2\right) = \text{Constant} \qquad (5)$$

Since there must be an isentropic process between static and stagnation state, the stagnation pressure is

$$P_o = P\left(1 + \frac{\gamma-1}{2}M^2\right)^{\gamma/\gamma-1} \qquad (6)$$

The momentum equation is

$$A\rho V dV = -AdP - dF_f \qquad (7)$$

The Mach number variation with flow distance for the infinitesimal C.V. is obtained after introduction of friction coefficient in equation (7) and algebraic manipulation using (2), (5) and the state equation.

$$\frac{\gamma f dx}{2Q} = \frac{1 - M^2}{M^3\left(1 + \frac{\gamma-1}{2}M^2\right)}dM \qquad (8)$$

in which f is defined as:

$$f = \tau_f / \frac{1}{2}\rho V^2 \qquad (9)$$

in which Q is the hydraulic diameter for Darcy friction coefficient and is the hydraulic radius for Fanning friction coefficient.

Integration of equation (9) for flow distance which changes the initial Mach number M to sonic speed M = 1.

$$\frac{\gamma f}{2Q}x = \frac{1}{2}\left(\frac{1-M^2}{M^2}\right) + \frac{1}{4}(\gamma+1)\ln\frac{\left(\frac{\gamma+1}{2}\right)M^2}{1+\frac{\gamma-1}{2}M^2} \qquad (10)$$

The friction factor used in this study is based on Fanning and Q is, therefore, the hydraulic radius.

The continuity equation is written in forms of Mach number defining a useful mass flow parameter as:

$$\frac{\dot{m}'\sqrt{T_o}}{P} = M\sqrt{\frac{\gamma W}{\bar{R}}}\sqrt{1+\frac{\gamma-1}{2}M^2} = \omega_{P,T_o,\gamma,W} \qquad (11)$$

For friction choked flow, the mass flow rate per unit area of pipe is given from equation (11) as:

$$\dot{m}' = P_e\frac{\sqrt{\gamma(\gamma+1)W}}{2\bar{R}T_o} \qquad (12)$$

After the proper determination of the friction coefficient variation with Mach number and Reynolds number in the hot rolled seamless steel tube. The same tube is used to fabricate the friction choked flow meter device with the pipe exits into a drum that connects downstream to a calibrated American standard orifice meter for flow measurement comparison [7,8]. For the friction choked meter,it is required to match exit pipe condition to the inlet Mach number. It is then only needed to measure the upstream total pressure and total temperature.

For isentropic flow at pipe inlet, need is there to relate the friction choked flow to the upstream total pressure and total temperature.
therefore:

$$\dot{m}' = \gamma\left[\frac{2}{\gamma+1}\right]^{\frac{\gamma+1}{2(\gamma-1)}}\frac{P_o}{(A/A^*)\sqrt{T_o}} \qquad (13)$$

in which A/A^* is the ratio of tube area to an imaginary throat area for isentropic nozzle.

The ratio of (A/A^*) as function of Mach number [3] is

$$\frac{A}{A^*} = \frac{1}{M}\left[\left(\frac{2}{\gamma+1}\right)\left(1+\frac{\gamma-1}{2}M^2\right]^{\frac{\gamma+1}{2(\gamma-1)}} \qquad (14)$$

The friction analysis for homenergic flow in the next sections in the tests range of Mach number and Reynolds numbers gives the following empirical relation for friction coefficient in the form.

$$f = C/R_e^n \qquad (15)$$

where C and n are constants to be determined and for the choked friction flow equation (10) is written in the form.

$$\frac{4fx}{D} = \frac{1-M^2}{\gamma M^2} + \frac{\gamma+1}{2\gamma}\ln\frac{(\gamma+1)M^2}{2(1+\frac{r-1}{2}M^2)} = \phi(M,\gamma) \qquad (16)$$

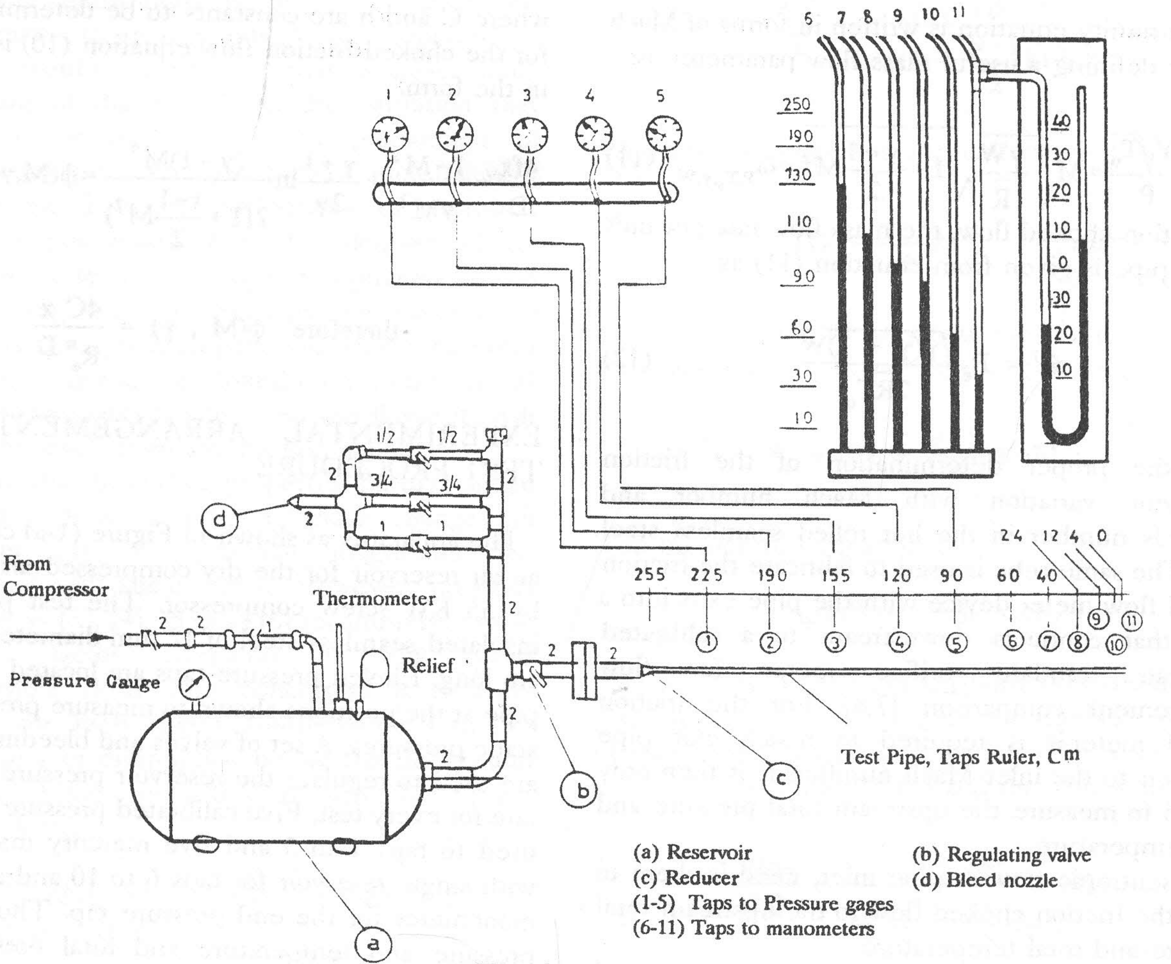
$$\text{therefore} \quad \phi(M\ ,\ \gamma) = \frac{4C}{R_e^n}\frac{x}{D} \qquad (17)$$

EXPERIMENTAL ARRANGEMENT AND TEST PROCEDURE

The apparatus as shown in Figure (1-a) consists of an air reservoir for the dry compressed air supplied by 55 KW screw compressor. The test pipe is an insulated seamless steel of 12 mm diameter and 225 cm long. Eleven pressure taps are located along the pipe at the positions shown to measure precisely the static pressures. A set of valves and bleeding nozzles are used to regulate the reservoir pressure and flow rate for every test. Five calibrated pressure gages are used to taps 1 to 5 and five mercury manometers with single reservoir for taps 6 to 10 and a mercury manometer for the end pressure tap. The reservoir pressure and temperature and total pressure and temperature upstream of bleed nozzles are measured with calibrated pressure gages and thermometers. The barometer reading is recorded for each experiment.

In every test run, the flow is adjusted to be steady and sonic discharge is obtained when the pressure at end tap is greater than the barometer reading. In each test run, the pressure at the eleven taps, the barometer pressure and temperature in laboratory and the reservoir total pressure and temperature are recorded.

Figure (1-b) shows the set up for mass flow rate calibration of the friction choked device. The choked pipe holder consists of an upstream long radius bellmouth where the upstream total pressure and temperatures are measured and flow discharges into a drum. The drum discharges into a 50 mm pipe that ends with a calibrated American standard orifice meter.



(a) Reservoir
(b) Regulating valve
(c) Reducer
(d) Bleed nozzle
(1-5) Taps to Pressure gages
(6-11) Taps to manometers

Fig. (1-a)

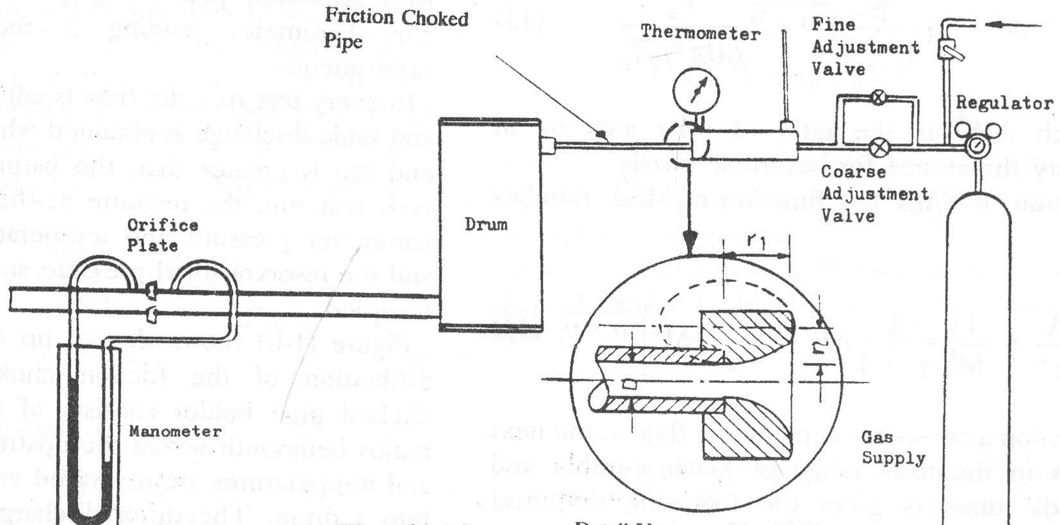


Fig. (1-b)

Fig (1) DIAGRAMATIC SKETCH OF EXPERIMENTAL RIG
(1-a) Friction Analysis
(1-b) Friction Choked Pipe Calibration.

Table (1)

Test Run No.1 To= 29 C

Taps	Gauge Pressure (cm Hg)	Abs. Pressure (cm Hg)
1	172.85	249.02
2	139.7	215.87
3	125.04	201.21
4	117.68	193.85
5	99.3	175.47
6	81.3	157.47
7	60.4	136.57
8	45	121.17
9	35	111.17
10	21.7	97.87
11	4.6	80.77

Test Run No.2 To= 29 C

Taps	Gauge Pressure (cm Hg)	Abs. Pressure (cm Hg)
1	202.27	278.44
2	165.5	241.67
3	147.11	223.28
4	139.75	215.92
5	117.68	193.85
6	98.9	175.07
7	75.6	151.77
8	58.4	134.57
9	47.4	123.57
10	33	109.17
11	13.4	89.57

Test Run No. 3 To= 29.5 C

Taps	Gauge Pressure(cm Hg)	Abs. Pressure(cm Hg)
1	242.7	318.87
2	202.27	278.44
3	180.21	256.38
4	172.85	249.02
5	147.11	223.28
6	125.5	201.67
7	98.9	175.07
8	79.4	155.57
9	66.8	142.97
10	50.3	126.47
11	27.4	103.57

Test Run No. 4 To= 29.5 C

Taps	Gauge Pressure (cm Hg)	Abs. Pressure (cm Hg)
1	301.57	377.74
2	253.7	329.87
3	231.7	307.87
4	216.99	293.16
5	191.24	267.41
6	164.8	240.97
7	132.8	208.97
8	119.9	196.07
9	95.1	171.27
10	75.3	151.47
11	48	124.17

RESULTS AND DISCUSSION

A series of tests are carried out to determine the different flow parameters variation along the pipe.

Figure (2) shows the variation of static pressures along the test pipe for only five tests. Results are recorded for four tests as sample for concise reporting are sown in Table (1).

The mass flow parameter (WPTO) as given by equation (11) is plotted against mach number in Figure (3). The mass flow parameter at different taps is obtained by multiplying (WPTO) by (P_{11}/P) were P is the static pressure at different taps. The Mach number is, therefore, determined at each pressure tap from equation (11). Fig (4), then shows the Mach number variation along the pipe length. The temperature ratio (To/T) and pressure (Po/P) are plotted against Mach number, as determined from equations (5) and (6), in Figure (5).

Since the total temperature To is measured for each test run, the static temperature variation along the pipe is determined and plotted in Figure (6). It is noticed the drop in static temperature due to expansion that resulted from friction. however, the static temperature variation is essentially the same instead of the large mass flow variation for different tests due to the incremental small change in total temperature. Figure (7) presents the large drop in total pressure along the pipe due to the degradation of available high speed flow energy because of friction. The above steps are summerised in Table (2) for some sample tests.

The friction parameter $(\gamma fx/2Q)$, as determined from equation (10), as function of Mach number is presented graphically in Figure (2). For each pressure tap, the friction parameter is obtained to correspond to the determined Mach number. The parameter change $(\gamma f\, \Delta x/2Q)$ is then determined for each two consequetive taps. The average friction coefficient can be obtained. The preceding steps are summarised in Table (3)

The Reynold's number at each tap is calculated from the viscosity at the corresponding static temperature and the mass flow rate for each test run. This is summerised in Table (4).

The friction coefficient variation with Reynold's number for the high speed hornenergic flow obtained from all tests is shown in Figure (8).

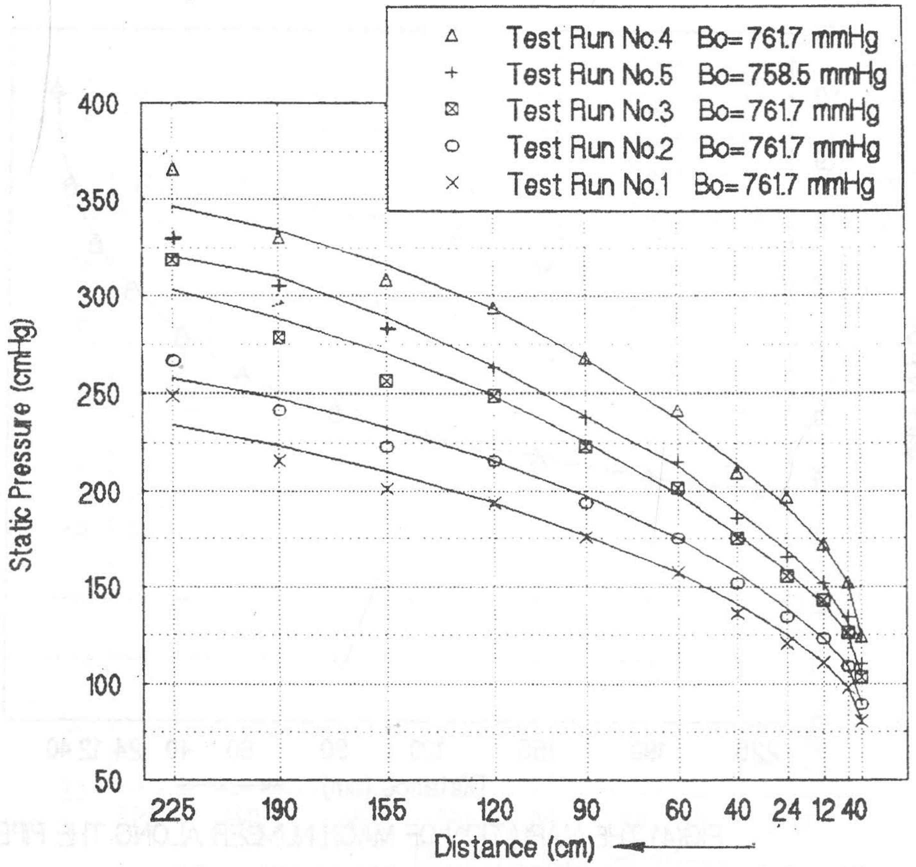
An empirical relation describing the experimental results in the range $200 \times 10^3 < Re < 550 \times 10^3$, is obtained in the form.

$$f = 0.063 / Re^{\{0.217\}} \tag{18}$$

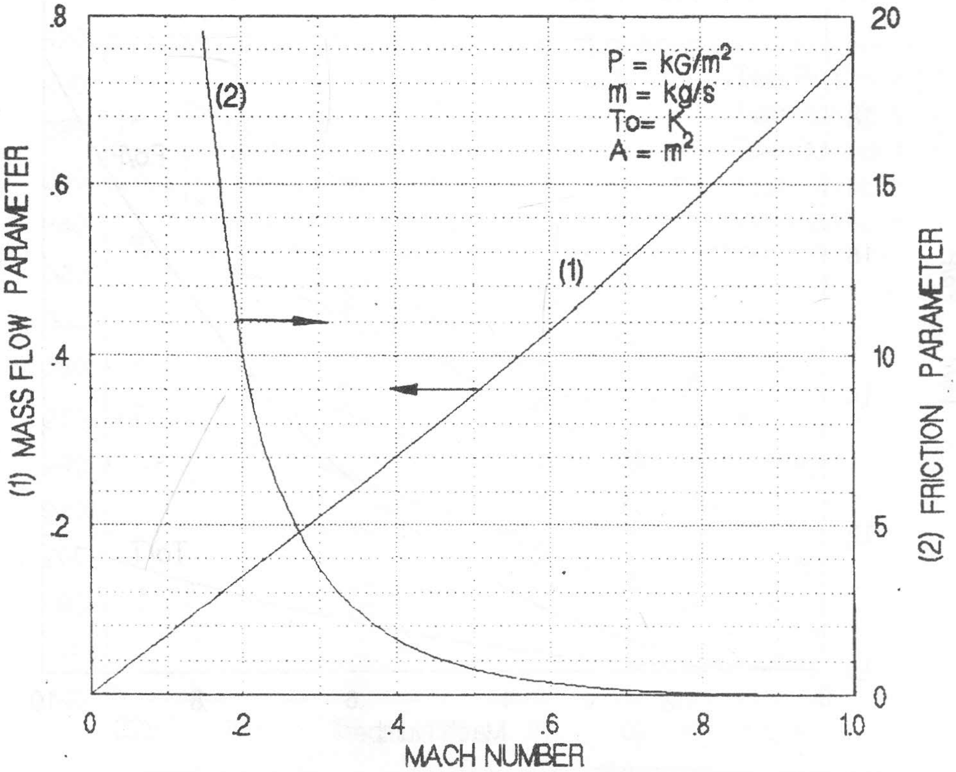
Were c = 0.063 and n = 0.217 in equation (17). The results of the present investigation are compared with previous works such as Karman-Nikuradse for smooth pipe [3], Koo for smooth pipes in Re number range from 3×10^6 to 3×10^6 [7], Generaux for most engineering purposes and Re range from 4×10^3 to 20×10^6 [9] and data from a number of observers given by McAdams [9] for clean pipes. The results show discrepancy, however, the results agree well with the Moody chart for friction factors in the turbulent region of rough pipes [10]. It is concluded that the friction coefficient as reported by equation (9) is considered to include momentum flux effects as well as shear stress effects. However, one effect counteracts the other in such away in the subsonic to sonic flow that makes the Moody chart still the best and good reference for friction factor determination.

For the friction choked meter device, it may be realized from equation (13) that for a certain inlet pipe mach number and a certain values stagnation temperature and gas specific heat ratio, the mass flow rate is straight line against $P_o/\sqrt{T_o}$. To determine the mass flow rate, it is necessary, therefore, to match the choked exit pipe condition to the inlet Mach number. ϕ is then determined from equation (17) before $\dot{m}$ is predicted for a certain (A/A^*). The viscosity of the gas and hence Reynolds number for the calculation is based on inlet pipe condition which is practically assigned at room temperature.

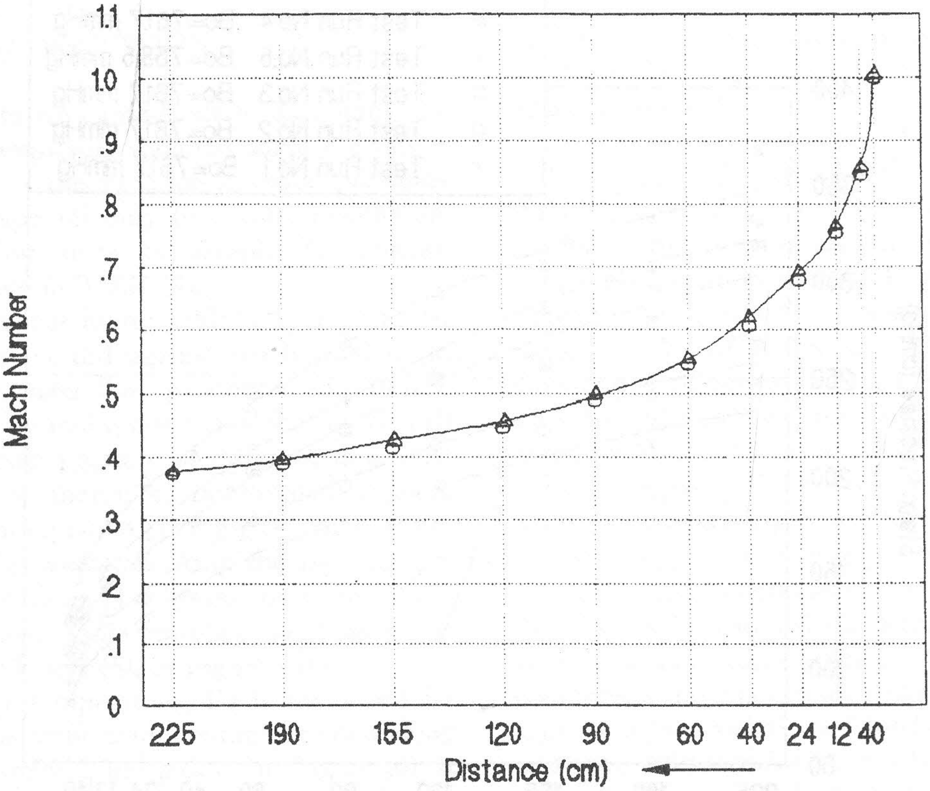
The metering characteristics of the friction choked device based on theoretical prediction for dry air and some other gases, are shown in Figure (9) to Figure (13). The effect of the changes in diameter and length of the choked pipe are also shown in the figures. The strong effect of pipe diameter and to lesser extent on length as described from the equations relating the match of the exit choked pipe and inlet Mach number, can be realised. The accuracy of flow measurements would, then, depend primarily on the accuracy of total pressure measurement ahead of the meter. The following are the properties of the gases used in the calculations.



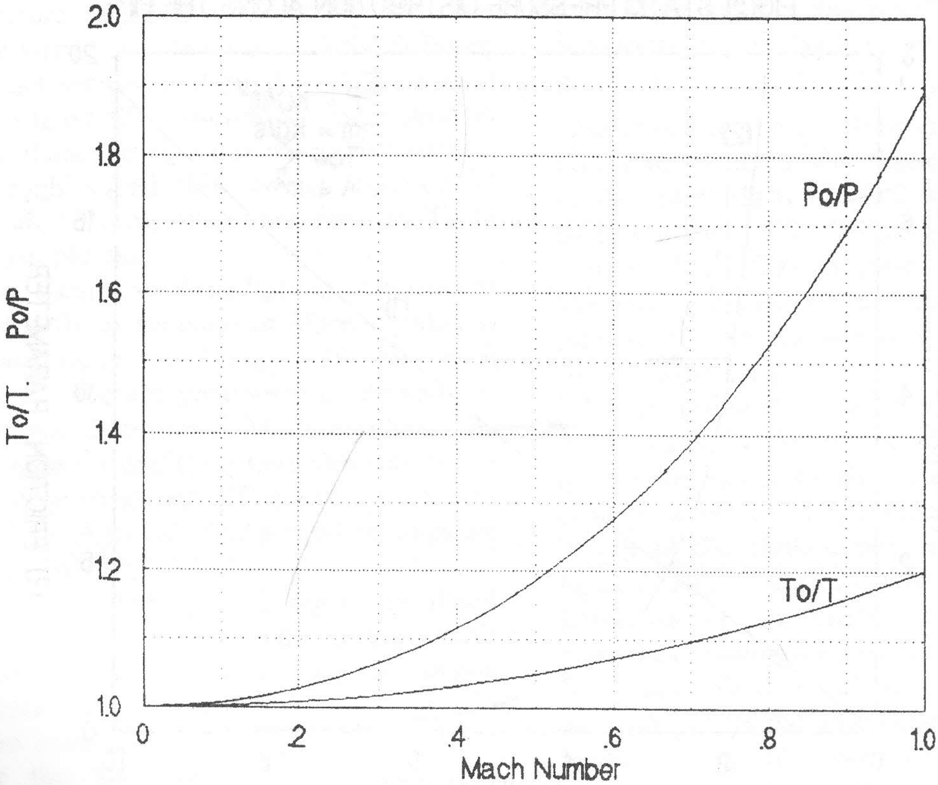
FIG(2) STATIC PRESSURE DISTRIBUTION ALONG THE PIPE



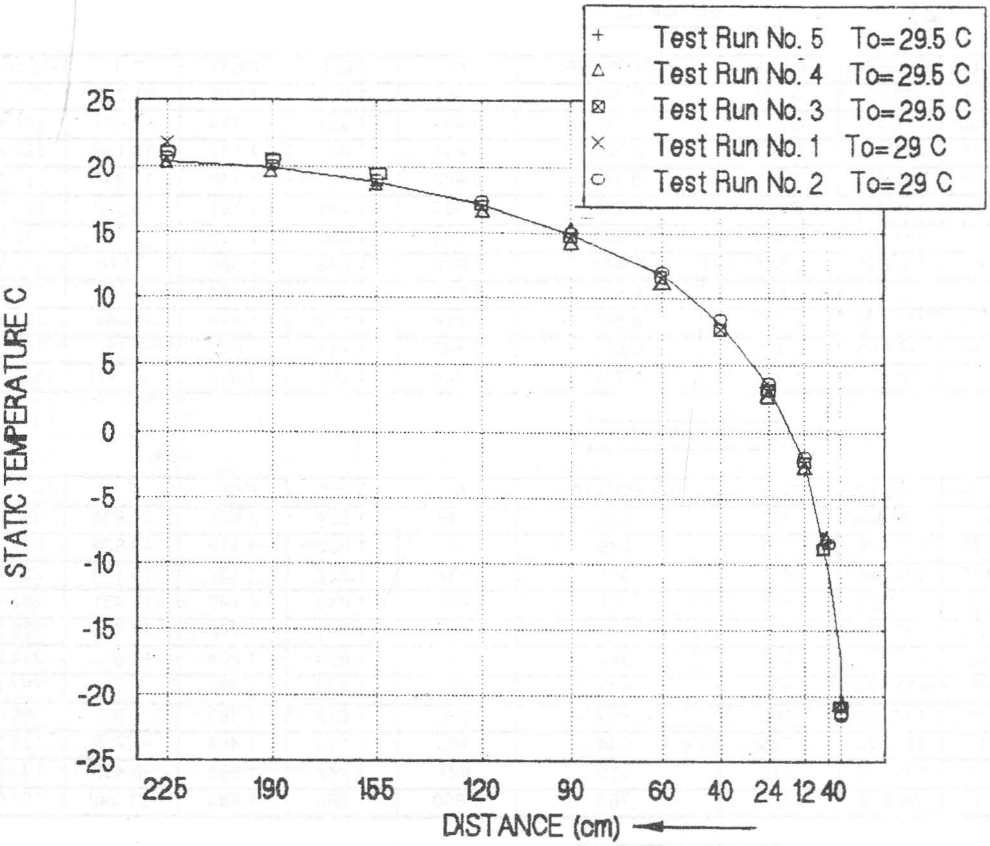
FIG(3) MASS FLOW PARAMETER AND FRICTION PARAMETER VARIATION WITH MACH NUMBER



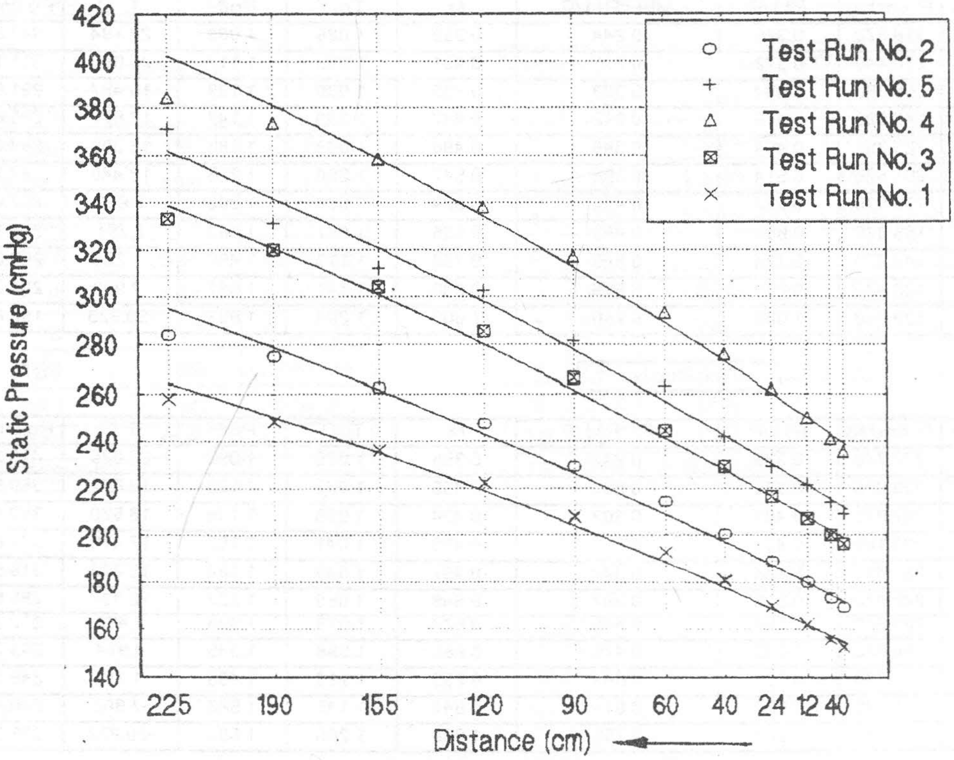
FIG(4) THE VARIATION OF MACH NUMBER ALONG THE PIPE



FIG(5) TEMPERATURE RATIO & PRESSURE RATIO VARIATION WITH MACH NUMBER



FIG(6) STATIC TEMPERATURE VARIATION ALONG THE PIPE



FIG(7) STAGNATION PRESSURE DISTRIBUTION ALONG THE PIPE

Table (2)

Test Run No. 1

Taps	X cm	P cm Hg	P11/P	MFP*P11/P	M	To/T	Po/P	T C	Po cm Hg
1	225	249.020	0.324	0.243	0.351	1.025	1.089	21.726	271.204
2	190	215.870	0.374	0.281	0.404	1.033	1.119	19.471	241.504
3	155	201.210	0.401	0.301	0.432	1.037	1.137	18.134	228.743
4	120	193.850	0.417	0.313	0.448	1.040	1.148	17.357	222.448
5	90	175.470	0.460	0.345	0.493	1.049	1.180	15.020	207.131
6	60	157.470	0.513	0.385	0.546	1.060	1.225	12.006	192.856
7	40	136.570	0.591	0.444	0.624	1.078	1.300	7.170	177.583
8	24	121.170	0.667	0.500	0.697	1.097	1.384	2.239	167.661
9	12	111.170	0.727	0.545	0.754	1.114	1.458	-1.852	162.102
10	4	97.870	0.825	0.619	0.846	1.143	1.597	-8.792	156.266
11	0	80.770	1.000	0.750	1.000	1.200	1.893	-21.340	152.906

Test Run No. 2

Taps	X cm	P cm Hg	P11/P	MFP*P11/P	M	To/T	Po/P	T C	Po cm Hg
1	225	278.440	.322	.241	.348	1.024	1.088	21.839	302.837
2	190	241.670	.371	.278	.400	1.032	1.117	19.639	269.825
3	155	223.280	.401	.301	.432	1.037	1.137	18.148	253.792
4	120	215.920	.415	.311	.446	1.040	1.146	17.451	247.491
5	90	193.850	.462	.347	.494	1.049	1.182	14.923	229.098
6	60	175.070	.512	.384	.545	1.059	1.224	12.083	214.209
7	40	151.770	.590	.443	.623	1.078	1.299	7.250	197.152
8	24	134.570	.666	.499	.696	1.097	1.383	2.305	186.047
9	12	123.570	.725	.544	.753	1.113	1.456	-1.735	179.911
10	4	109.170	.820	.615	.841	1.142	1.589	-8.450	173.520
11	0	89.570	1.000	.750	1.000	1.200	1.893	-21.340	169.565

Test Run No.3

Taps	X cm	P cm Hg	P11/P	MFP*P11/P	M	To/T	Po/P	T C	Po cm Hg
1	225	318.870	0.325	0.244	0.352	1.025	1.089	22.194	347.356
2	190	278.440	0.372	0.279	0.401	1.032	1.117	20.060	311.115
3	155	256.380	0.404	0.303	0.435	1.038	1.139	18.487	291.913
4	120	249.020	0.416	0.312	0.447	1.040	1.147	17.877	285.623
5	90	223.280	0.464	0.348	0.496	1.049	1.183	15.300	264.200
6	60	201.670	0.514	0.385	0.547	1.060	1.225	12.440	247.103
7	40	175.070	0.592	0.444	0.624	1.078	1.300	7.623	227.677
8	24	155.570	0.666	0.499	0.696	1.097	1.383	2.751	215.106
9	12	142.970	0.724	0.543	0.752	1.113	1.455	-1.256	208.076
10	4	126.470	0.819	0.614	0.840	1.141	1.587	-7.902	200.727
11	0	103.570	1.000	0.750	1.000	1.200	1.893	-20.923	196.069

Test Run No. 4

Taps	X cm	P cm Hg	P11/P	MFP*P11/P	M	To/T	Po/P	T C	Po cm Hg
1	225	377.740	0.329	0.247	0.356	1.025	1.092	22.026	412.308
2	190	329.870	0.376	0.282	0.406	1.033	1.120	19.847	369.520
3	155	307.870	0.403	0.303	0.434	1.038	1.138	18.520	350.401
4	120	293.160	0.424	0.318	0.455	1.041	1.152	17.479	337.866
5	90	267.410	0.464	0.348	0.497	1.049	1.184	15.273	316.521
6	60	240.970	0.515	0.387	0.548	1.060	1.227	12.337	295.629
7	40	208.970	0.594	0.446	0.627	1.079	1.303	7.456	272.330
8	24	196.070	0.633	0.475	0.665	1.088	1.345	4.914	263.795
9	12	171.270	0.725	0.544	0.753	1.113	1.456	-1.296	249.391
10	4	151.470	0.820	0.615	0.841	1.141	1.588	-7.962	240.595
11	0	124.170	1.000	0.750	1.000	1.200	1.893	-20.923	235.067

MFP = Mass flow parameter at M = 1

Table (3)

Test Run No. 1

Taps	x cm	$(\gamma f/2m)x$	$(\gamma f/2m)\Delta x$	f
1	0	2.447		
2	35	1.617	1.185	6.93E-03
3	70	1.262	.485	2.79E-03
4	105	1.132	.481	3.09E-03
5	135	.781	.601	4.21E-03
6	165	.531	.496	4.37E-03
7	185	.285	.380	4.48E-03
8	201	.151	.198	3.02E-03
9	213	.087	.122	2.62E-03
10	221	.029	.087	3.04E-03
11	225	2.7575E-08		

Test Run No. 2

Taps	x cm	$(\gamma f/2m)x$	$(\gamma f/2m)\Delta x$	f
1	0	2.382		
2	35	1.599	1.147	7.26E-03
3	70	1.234	.477	2.97E-03
4	105	1.122	.464	3.17E-03
5	135	.770	.599	4.29E-03
6	165	.523	.488	4.25E-03
7	185	.282	.372	4.53E-03
8	201	.151	.195	3.04E-03
9	213	.087	.121	2.61E-03
10	221	.030	.087	3.09E-03
11	225	2.758E-08		

Test Run No. 3

Taps	x cm	$(\gamma f/2m)x$	$(\gamma f/2m)\Delta x$	f
1	0	2.302		
2	35	1.542	1.061	7.03E-03
3	70	1.241	.486	2.92E-03
4	105	1.056	.473	3.06E-03
5	135	.767	.540	4.28E-03
6	165	.516	.491	4.18E-03
7	185	.276	.317	4.43E-03
8	201	.199	.189	2.98E-03
9	213	.087	.170	2.59E-03
10	221	.029	.087	3.11E-03
11	225	2.7575E-08		

Test Run No. 4

Taps	x cm	$(\gamma f/2m)x$	$(\gamma f/2m)\Delta x$	f
1	0	2.391		
2	35	1.571	1.131	6.50E-03
3	70	1.260	.455	2.97E-03
4	105	1.115	.468	3.12E-03
5	135	.792	.590	3.86E-03
6	165	.526	.509	4.21E-03
7	185	.282	.376	3.77E-03
8	201	.149	.197	2.90E-03
9	213	.085	.122	3.65E-03
10	221	.027	.085	3.09E-03
11	225	2.758E-08		

Table (4)

Test Run No. 1

Taps	T C	μ (kg/m.sec)	m (kg/s)	$4m/\pi D$	Re 1E-3
1	21.84	1.81E-05	5.36E-02	5.688	313.501
2	19.64	1.80E-05	5.36E-02	5.688	315.382
3	18.15	1.80E-05	5.36E-02	5.688	316.508
4	17.45	1.79E-05	5.36E-02	5.688	317.167
5	14.92	1.78E-05	5.36E-02	5.688	319.163
6	12.08	1.77E-05	5.36E-02	5.688	321.775
7	7.25	1.74E-05	5.36E-02	5.688	326.057
8	2.31	1.72E-05	5.36E-02	5.688	330.542
9	-1.73	1.70E-05	5.36E-02	5.688	334.430
10	-8.45	1.67E-05	5.36E-02	5.688	341.396
11	-21.34	1.60E-05	5.36E-02	5.688	354.755

Test Run No. 2

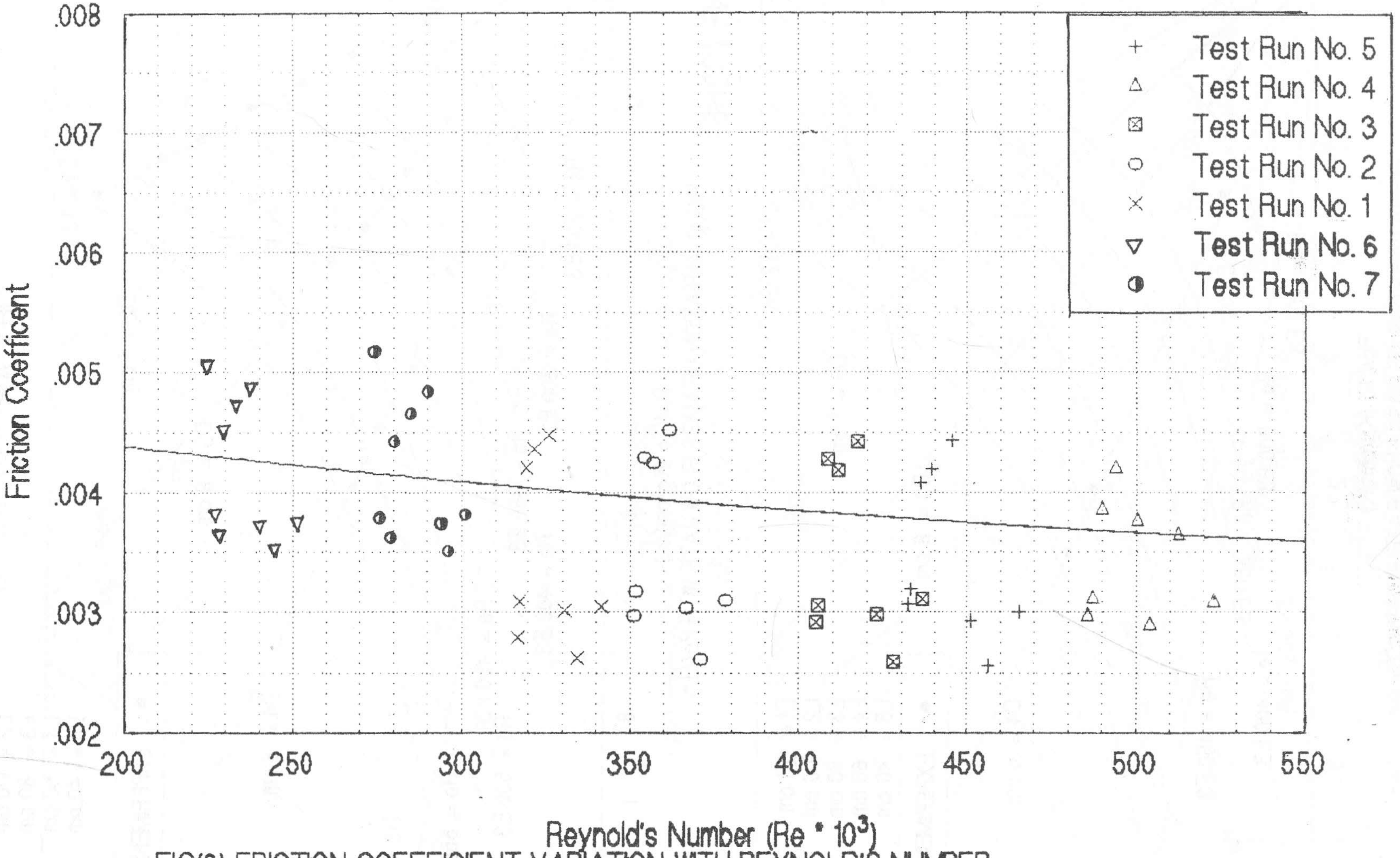
Taps	T C	μ (kg/m.sec)	m (kg/s)	$4m/\pi D$	Re 1E-3
1	22.19	1.82E-05	5.94E-02	6.307	347.553
2	20.06	1.81E-05	5.94E-02	6.307	349.587
3	18.49	1.80E-05	5.94E-02	6.307	350.980
4	17.88	1.80E-05	5.94E-02	6.307	351.634
5	15.30	1.78E-05	5.94E-02	6.307	354.029
6	12.44	1.77E-05	5.94E-02	6.307	356.759
7	7.62	1.75E-05	5.94E-02	6.307	361.502
8	2.75	1.72E-05	5.94E-02	6.307	366.487
9	-1.26	1.70E-05	5.94E-02	6.307	370.740
10	-7.90	1.67E-05	5.94E-02	6.307	378.203
11	-20.92	1.61E-05	5.94E-02	6.307	393.407

Test Run No. 3

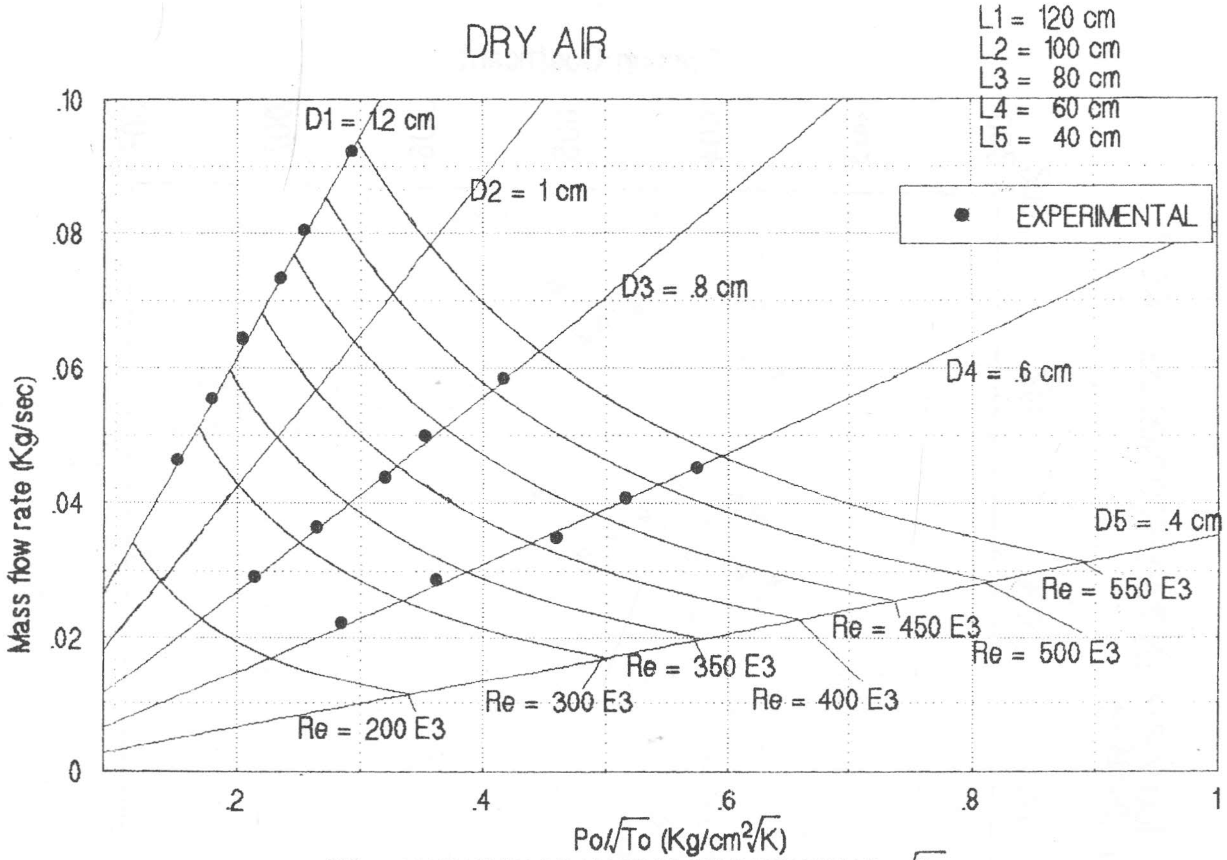
Taps	T C	μ (kg/m.sec)	m (kg/s)	$4m/\pi D$	Re 1E-3
1	22.03	1.82E-05	6.86E-02	7.287	401.167
2	19.85	1.81E-05	6.86E-02	7.287	403.442
3	18.52	1.80E-05	6.86E-02	7.287	405.136
4	17.48	1.79E-05	6.86E-02	7.287	405.797
5	15.27	1.78E-05	6.86E-02	7.287	408.611
6	12.34	1.77E-05	6.86E-02	7.287	411.781
7	7.46	1.75E-05	6.86E-02	7.287	417.232
8	4.91	1.73E-05	6.86E-02	7.287	422.894
9	-1.30	1.70E-05	6.86E-02	7.287	427.730
10	-7.96	1.67E-05	6.86E-02	7.287	436.240
11	-20.92	1.61E-05	6.86E-02	7.287	453.931

Test Run No. 4

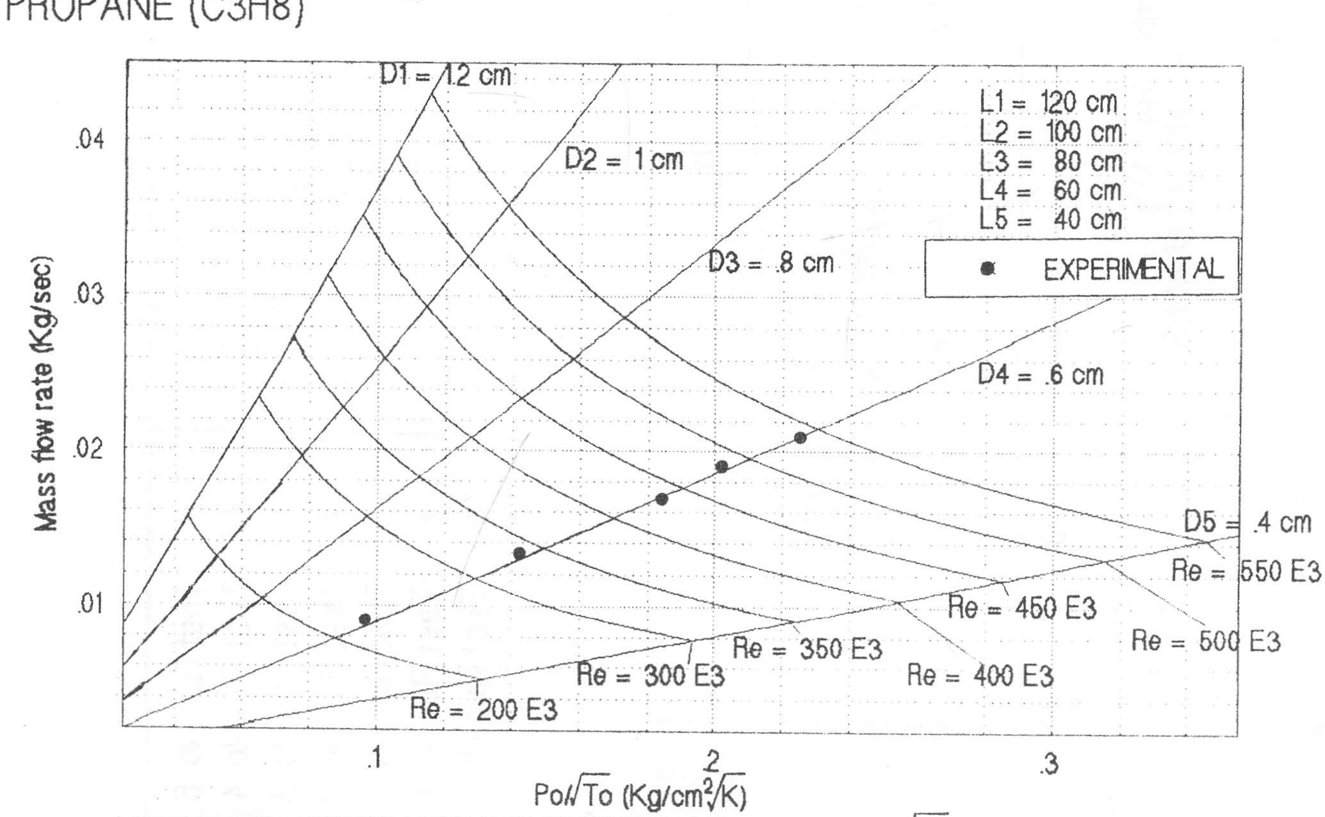
Taps	T C	μ (kg/m.sec)	m (kg/s)	$4m/\pi D$	Re 1E-3
1	21.73	1.81E-05	8.23E-02	8.737	481.173
2	19.47	1.80E-05	8.23E-02	8.737	483.961
3	18.13	1.80E-05	8.23E-02	8.737	485.674
4	17.36	1.79E-05	8.23E-02	8.737	487.028
5	15.02	1.78E-05	8.23E-02	8.737	489.919
6	12.01	1.77E-05	8.23E-02	8.737	493.821
7	7.17	1.74E-05	8.23E-02	8.737	500.449
8	2.24	1.72E-05	8.23E-02	8.737	503.972
9	-1.85	1.70E-05	8.23E-02	8.737	512.866
10	-8.79	1.67E-05	8.23E-02	8.737	523.101
11	-21.34	1.60E-05	8.23E-02	8.737	544.218



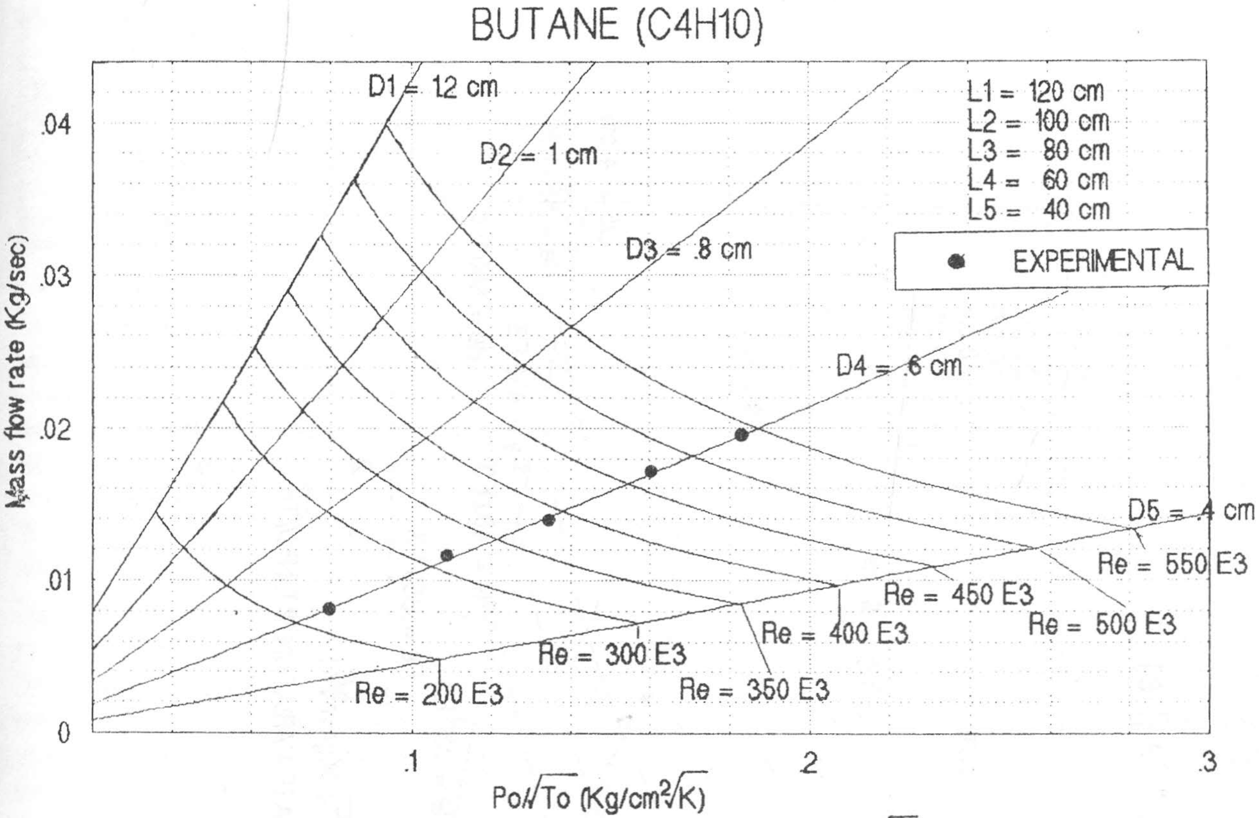
FIG(8) FRICTION COEFFICIENT VARIATION WITH REYNOLD'S NUMBER



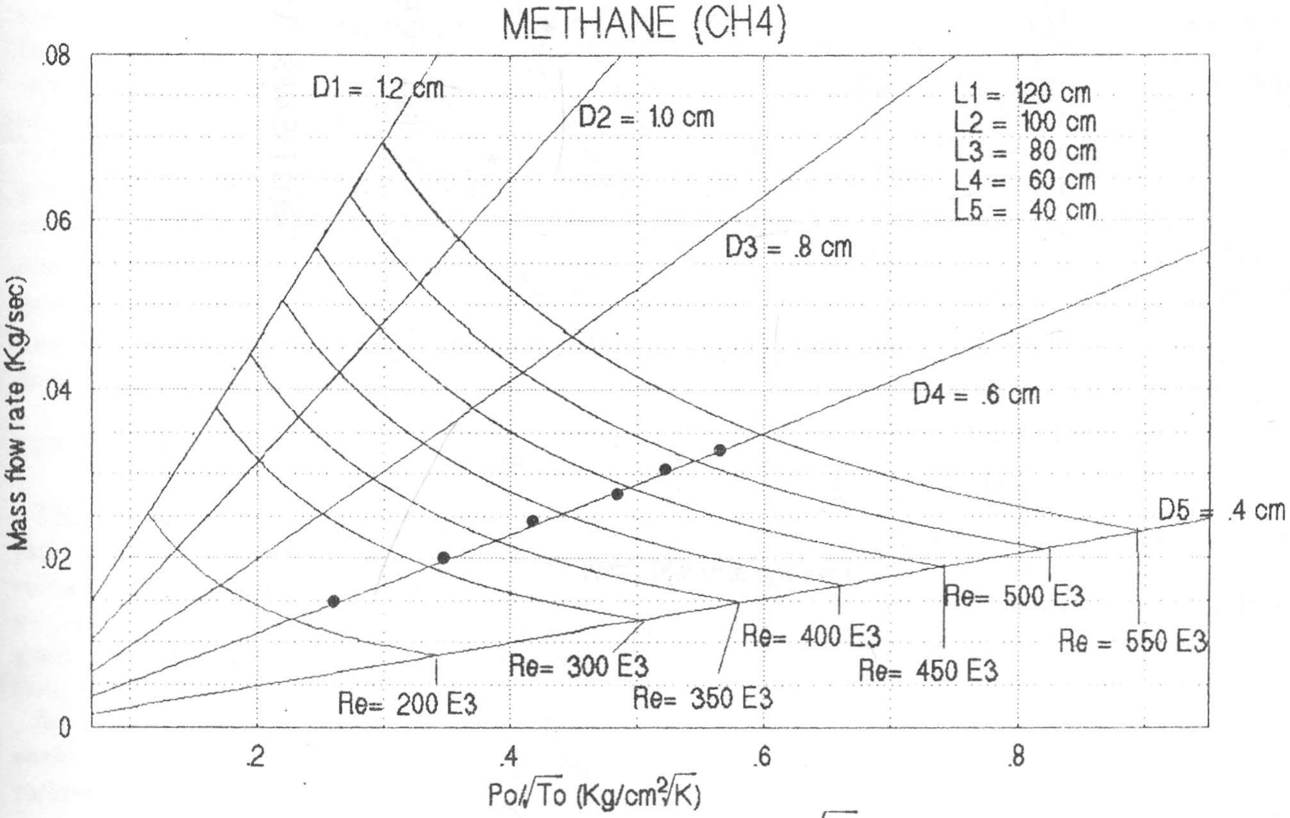
FIG(9) VARIATION OF MASS FLOW RATE WITH Po/√To



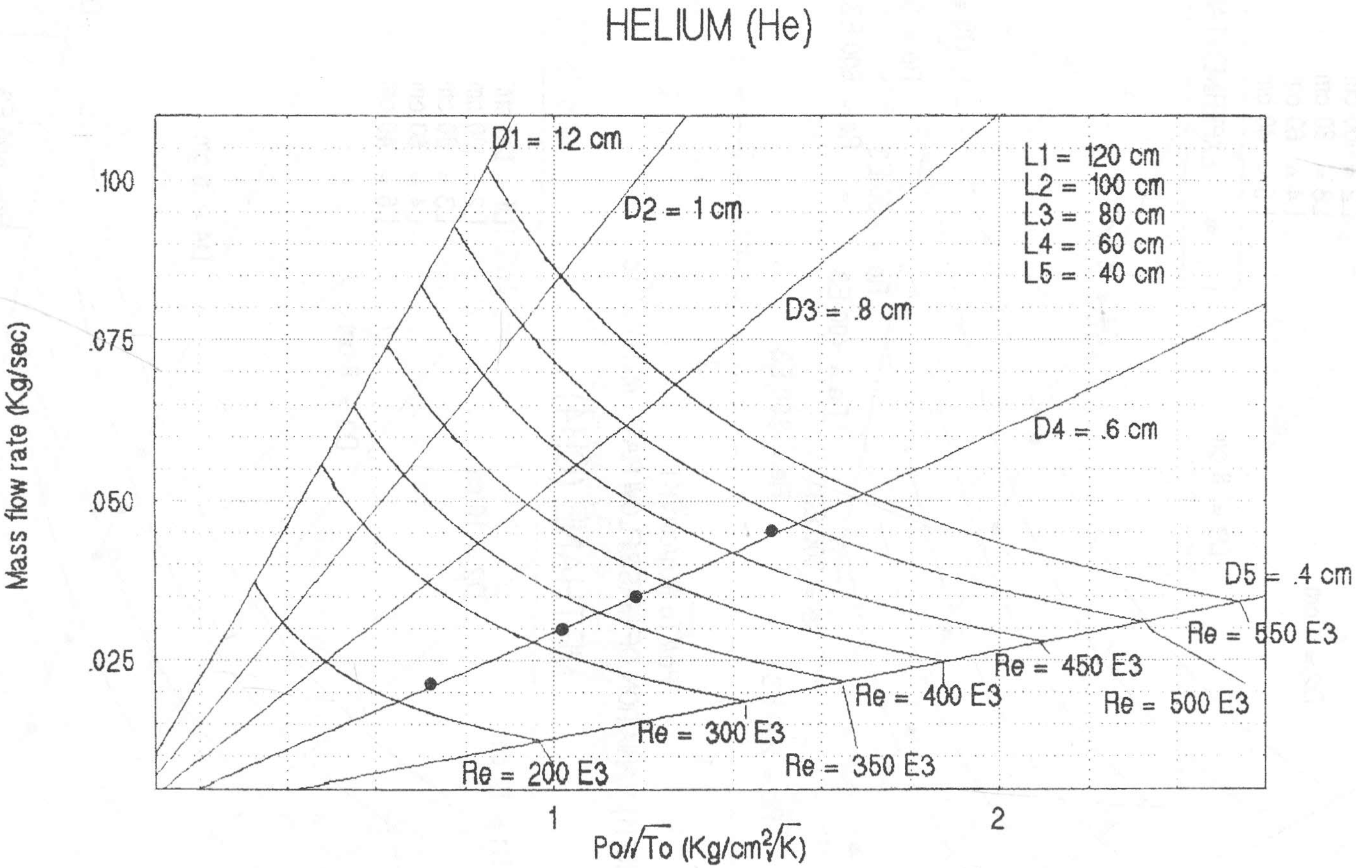
FIG(10) VARIATION OF MASS FLOW RATE WITH Po/√To



FIG(11) VARIATION OF MASS FLOW RATE WITH Po/√To



FIG(12) VARIATION OF MASS FLOW RATE WITH Po/√To



FIG(13 THE MASS FLOW RATE VARIATION WITH Po/√To

Gas	W Mol. Wt.	γ Sp. Ht ratio	R $kg_f m/Kg^{o}K$	Gas Viscosity kg/m.s
Dry air	28.97	1.4	29.27	1.8×10^{-5}
Propane	44.09	1.12	19.23	8.3×10^{-6}
Butane	58.04	1.1	14.61	7.71×10^{-6}
Helium	4.003	1.66	211.846	1.985×10^{-5}
Methane	16.04	1.3	52.869	1.045×10^{-5}

Uncertainties in measuring static pressure for the five upstream taps and the six downstream taps, total temperature, pipe diameter and locating hole positions of pressure taps, are estimated. Errors in determining flow variables and friction coefficients indicate uncertainties within 0.7 % and 1.6 %, respectively for upstream locations and 2.0 % and 2.8 % respectively for downstream locations.

The experimentally determined values of $(\dot{m} - P_o/\sqrt{T_o})$ using the calibration set up in Figure (1-b), are also shown in Figure (9) to Figure (13). The maximum error between the measured and predicted values are within ± 1.5 %. The very good agreement proves the reliability of the theoretical prediction procedure and the adequency of the device for a wide range of flow measurement.

The preparation of premixed gas mixture with specific ratio from gas bottels or gas lines proved to be reliable and easy. This is done through adjustment of the upstream control valves, upstream of two friction choked pipes (or more) and exhausting to a common plenum of the premixed gas. The valves are controlled to predetermined total pressures and total temperature of either gas obtained from the respective $(\dot{m} - P_o/\sqrt{T_o})$. The device proves to have high accuracy, safety, simplicity and adequacy for Laboratory and industrial uses.

CONCLUSIONS

The friction coefficient in high speed compressible flow includes momentum flux effects as well as shear stress effects. However, one effect counteracts the other in such way that the Moody chart still good reference determination tool in the turbulent flow, subsonic to sonic range.

An empirical expression is developed for the of sonic flow in hot rolled steel rough pipe for turbulent flow in the form.

$$f = 0.063/Re^{0.217} \quad 200 \times 10^3 < Re < 550 \times 10^3$$

The fact that friction factor being almost constant for the large Reynolds number is characteristic feature for complete turbulence in high speed homenergic compressible flow in pipe.

The experiment proves to be a valuable demonstration rig showing flow parameters variation for high speed compressible flow.

A friction choked gas flow metering device is developed which is suitable for flow metering and for preparation of premixed explosive or poisonous gas mixtures having specific or variable ratio. The device proves to have high accuracy, safety, simplicity and adequacy for laboratory and industrial uses.

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