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TWO-PHASE (LIQUID-VAPOR), MASS-LIMITING FLOW WITH HYDROGEN AND NITROGEN*

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J. A. Brennan, D. K. Edmonds, and R. V. Smith

ABSTRACT

Experimental data on critical (choked) mass flow in a constant area test section are presented. The data are compared to some simple analytical models which have been recommended for design purposes. The data show the same general behavior as that reported for other non-cryogenic fluids.

Key Words: Choking, hydrogen, nitrogen, shocks, two-phase flow.

1. Introduction

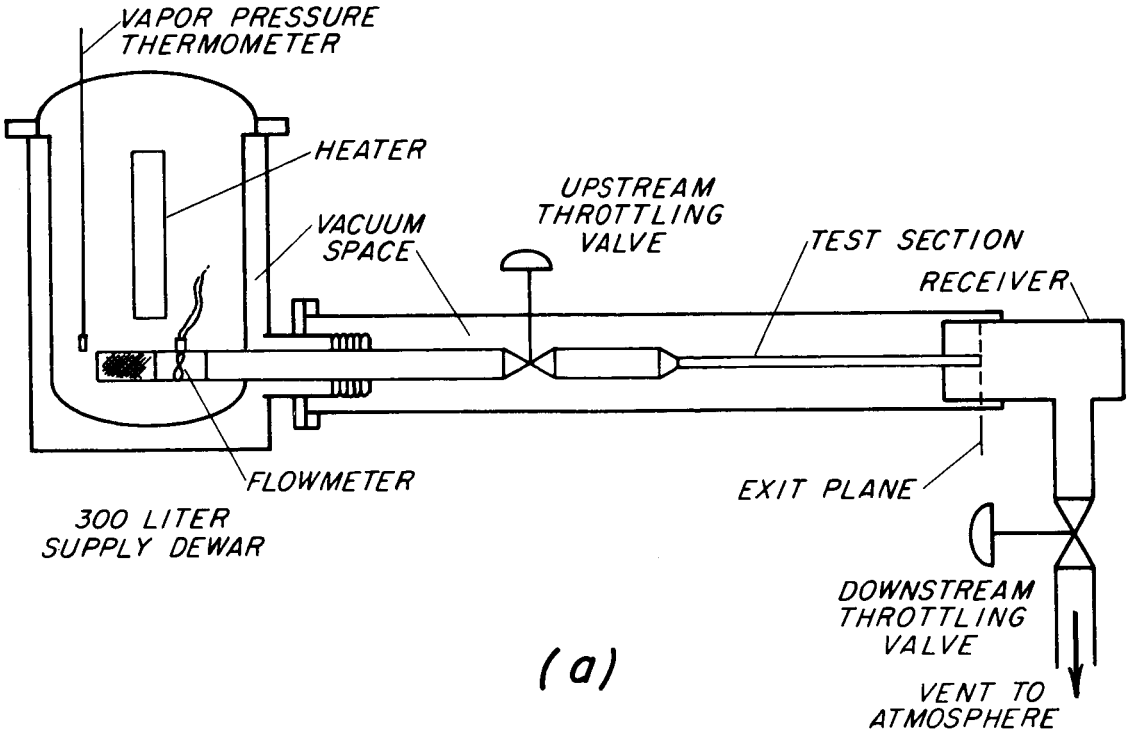
Two-phase choking may occur in many cryogenic systems, but information necessary for confident design of such systems is not readily available. For those not familiar with two-phase, mass-limiting flow, it should be pointed out that effective or mean critical velocities in two-phase flow are considerably lower than either the gas- or liquid-phase critical velocities. For example: 8.5% quality hydrogen at 2 atmospheres has a mean critical velocity of approximately 135 meters per second as reported here, while critical velocity in saturated vapor is 367 meters per second and critical velocity in saturated liquid is 1017 meters per second [Roder et al. 1965]

There have been some experimental results published on steam-water, air-water, and commercial refrigerant, two-phase systems and these results have been summarized by Smith [1963a] and Isbin [1964], but, to the knowledge of the authors, no results from cryogenic constant-area systems are available in the literature. The purpose of this report is to provide experimental data to serve as a guide for designers and to compare these data with analytical results considering simple models [Smith 1963a].

2. Apparatus and Procedure

The experimental apparatus is shown schematically in figure 2.1 (a). It consisted of an open flow or blow-down system exhausting to the atmosphere. Temperature of the liquid in the supply dewar was controlled with the electric heater and measured with the vapor pressure thermometer. Volume flow rate was measured with a turbine-type flowmeter located inside the supply dewar where there was always 100% liquid. Dewar pressure was maintained by controlling the gas pressure in the ullage volume and the test section pressure was controlled by the upstream and the downstream throttling valves.

The test section was a vacuum insulated, straight stainless steel tube 17.78 cm long with an inside diameter of 0.844 cm. Five pressure taps were axially spaced as shown in figure 2.1 (b). The tap at the exit plane was a 0.79 mm o.d. tube with the center line coincident with the



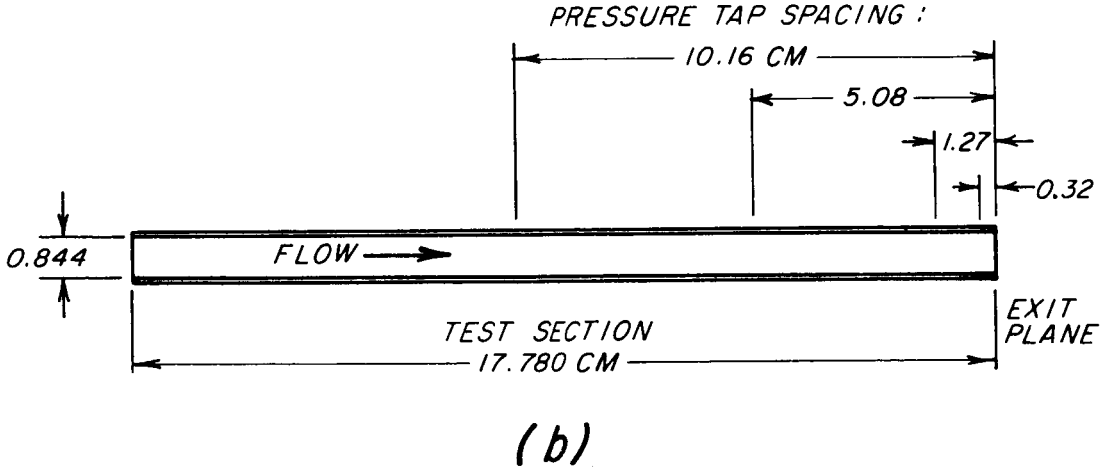


Figure 2.1 Schematic of test apparatus

exit plane. The other four taps were carefully deburred holes 0.53 mm in diameter. (The same test section was used in an earlier experimental program with Refrigerant 11 [Edmonds and Smith 1965].)

A test was started by setting the temperature and pressure of the liquid in the dewar to predetermined values after which the recording apparatus was calibrated. The two throttling valves were set and flow started. All pressures were sensed by pressure tranducers and continuously recorded, along with the flowmeter output, on a multichannel oscillograph recorder. In the calculation of the mass qualities it was assumed that the flow was steady with liquid and vapor velocities equal, one-dimensional, adiabatic, and in thermal equilibrium at the exit plane. Under these conditions the quality can be determined by

$$h_o = h_f + xh_{fg} + 10^{-7}\left(\frac{u^2}{2}\right) \tag{1}$$

where

h_o = stagnation enthalpy, joules/gm

h_f = saturated liquid enthalpy at exit plane, joules/gm

h_{fg} = enthalpy difference between saturated vapor and saturated liquid at exit plane, joules/gm

x = ratio of vapor weight to mixture weight

u = velocity, centimeters/second

Since the velocity is not known it must be calculated from

$$u = Gv = G(v_f + xv_{fg}) \tag{2}$$

where

G = Mass velocity, $\frac{gm}{sec.\ cm^2}$

v_f = specific volume of saturated liquid at exit plane, $\frac{cm^3}{gm}$

v_{fg} = specific volume difference between saturated vapor and saturated liquid at exit plane, $\frac{cm^3}{gm}$

Substituting (2) into (1) yields

$$h_o = h_f + xh_{fg} + \frac{G^2}{2}\left(v_f + xv_{fg}\right)^2 (10)^{-7} \qquad (3)$$

Expanding and rearranging (3) the quality was calculated from

$$x^2 \frac{\left(Gv_{fg}\right)^2}{2(10)^7} + x\left(h_{fg} + \frac{G^2}{10^7} v_f v_{fg}\right) + h_f - h_o + \frac{G^2}{2(10)^7} v_f^2 = 0 \qquad (4)$$

Since thermal equilibrium was assumed the properties at the exit plane were evaluated at the exit plane pressure. The stagnation enthalpy was determined from the temperature and pressure in the supply dewar and assumed constant.

The most acceptable definition for mass limited flow would be "no increase in mass flow as the receiver pressure is reduced." Since it was not possible to test for mass flow changes with reduction in downstream pressures during these blowdown tests (because of small capacity), another criterion, borrowed from single-phase critical flow behavior, was used. If critical flow exists at the exit of a straight tube, a pressure discontinuity (shock) would be expected to occur at or very near the exit

plane. Thus, following single-phase flow behavior, critical flow could be said to exist in any case where there is a pressure difference between the exit plane pressure and the receiver pressure. This was the criterion used to test for critical flow in the reported experimental study. Some investigations [see for example Edmonds and Smith 1965] have indicated that two-phase, mass-flow rates may be influenced by downstream pressure changes even though small pressure differences between the exit plane and the receiver pressure may exist; therefore, the experimental data shown in the figures are divided into two parts, one for data where the exit-plane minus the receiver pressure was less than 0. 68 atm and the other where the difference was greater than 0. 68 atm. The 0. 68 atm (10 psid) division was selected, somewhat arbitrarily, as the value below which the measured flow rates could have been below the critical value. For the case where the pressure differential was greater than 0. 68 atm, the reported rates were maximum rates within maximum experimental errors. This division did not appear to separate the data, however.

Inaccuracy in the mass flow measurements in the nitrogen tests was estimated at a maximum of ±4 percent and for hydrogen a maximum of ± 3 percent. The difference in these accuracy figures was the result of having the flowmeter used in the hydrogen tests calibrated with liquid hydrogen while the flowmeter used in the nitrogen tests was calibrated warm by the manufacturer and corrected for thermal expansion to low

temperature. The manufacturer's temperature corrected curve was used in all the nitrogen results. Pressure measurements were estimated to be accurate within 0.2 atm in tests at low qualities and 0.1 atm in tests at high qualities. Uncertainties in the quality calculation resulting from the measurement errors in flow and pressure at two points which are considered typical are 3.1 ± 1.5% and 26.5 ± 0.5%

3. Results and Discussion

Experimental results are given in tables 3.1 and 3.2 and shown graphically in figures 3.1, 3.2, and 3.3 where the mass velocity is plotted against exit plane pressure in several quality ranges for nitrogen and hydrogen.

The results in figures 3.1, 3.2, and 3.3 are compared to some simple analytical models. A complete description of the models considered is given by Smith [1963a] where he recommended using a combination of models to bracket the unexpected data. The homogeneous, thermal equilibrium model (T.E.) was intended to provide a lower limit for all ranges of qualities. The homogeneous, metastable model (MET) was intended to provide upper-limit values for qualities up to 1 percent in systems with no mixing and up to 10 percent where flow disturbances and mixing is likely to occur. The metastable model shown is one in which the flow is in thermal equilibrium up to the point of choking but at that point it is assumed that there is no mass transfer between the phases. For

Table 3.1 Nitrogen Results

Mass Flow per unit area, gm/sec·cm^2	Exit Plane Pressure, atm.	Receiver Pressure, atm.	Quality, percent
1423.2	1.60	1.29	2.5
1301.4	1.54	1.27	2.8*
1007.4	1.50	1.23	3.2*
1408.2	2.50	2.40	3.3
1415.6	1.92	1.37	3.4
1459.6	1.85	1.61	3.5
1331.4	3.04	2.98	3.6
1314.9	1.83	1.25	3.8
1409.6	2.26	1.41	3.8
1107.3	1.83	1.16	4.1
596.2	1.41	1.10	4.3*
1432.7	3.41	3.34	4.3
861.9	1.81	1.25	4.6*
1314.1	2.62	1.40	4.7
641.7	1.74	1.00	5.2
888.0	2.08	1.16	5.2
1403.7	3.01	1.44	5.2
1284.7	3.00	1.43	5.3
1307.0	4.33	4.21	5.4
819.0	2.51	1.51	5.8
1088.2	3.50	3.19	6.0
1537.9	4.98	4.44	6.2
1082.3	3.26	1.34	6.6
1532.9	4.75	1.76	6.6
1220.6	3.70	1.51	6.9
277.6	0.99	0.94	7.4
1245.9	4.60	1.54	7.4
1317.4	4.90	4.22	7.4
434.1	1.32	0.91	7.6
1311.7	4.64	1.61	8.0
645.0	2.45	1.09	8.1
456.4	1.54	1.04	8.2*
1227.3	5.03	4.15	8.9
1240.1	4.76	1.60	9.2
935.9	4.12	0.92	9.8
1209.2	5.17	4.22	9.8
272.1	0.98	0.93	9.9

* Denotes runs where exit plane pressure exceeded pressure just upstream of the exit plane.

Table 3.1. Nitrogen Results (continued)

Mass Flow per unit area, gm/sec·cm^2	Exit Plane Pressure, atm.	Receiver Pressure, atm.	Quality, percent
1171.4	5.41	4.32	10.4
509.7	1.84	1.05	10.5
820.6	3.65	1.24	10.5
1144.3	5.31	<1.91	10.6
1226.5	4.74	1.67	10.6
571.5	2.18	1.07	10.9
1181.1	5.45	4.29	11.0
296.8	1.07	0.97	11.1
379.2	1.34	0.99	11.3*
1041.6	5.49	3.99	11.4
1274.4	4.99	1.79	11.6
505.5	1.91	1.04	12.0
998.2	5.15	<1.75	12.2
510.3	2.04	1.08	13.2
431.1	1.62	1.06	13.3*
266.06	1.01	0.92	13.5*
339.0	1.32	1.02	15.0*
401.4	1.58	1.03	15.2*
257.4	1.00	0.90	15.4
752.2	3.67	1.18	15.8
219.0	0.94	0.91	16.0
246.8	1.00	0.92	17.0
452.5	1.91	1.03	17.0
302.2	1.18	0.97	17.2*
420.3	1.67	0.99	17.2
495.1	2.04	1.04	17.7
519.0	1.67	1.09	17.8*
369.8	1.52	1.00	18.6*
442.6	1.74	1.02	18.7
223.6	0.96	0.91	19.0
473.9	2.04	1.09	19.0

Table 3.1. Nitrogen Results (continued)

Mass Flow per unit area, gm/sec·cm^2	Exit Plane Pressure, atm.	Receiver Pressure, atm.	Quality, percent
296.7	1.27	0.96	20.1*
342.3	1.25	0.94	20.6*
390.5	1.56	1.02	20.6*
388.6	1.76	1.07	21.3
425.2	1.88	1.07	21.3
212.0	0.95	0.88	21.6
283.0	1.08	0.97	21.8
285.5	1.22	0.92	21.9
220.1	0.98	0.90	22.1
314.2	1.43	1.05	22.7
325.6	1.40	1.01	23.3*
227.0	0.97	0.90	24.1
233.4	1.08	0.94	24.7
252.2	1.12	0.95	24.9
193.6	0.96	0.90	25.8
218.6	1.00	0.92	25.8*
193.4	0.93	0.86	26.5

Table 3.2. Hydrogen Results

Mass Flow per unit area, gm/sec·cm^2	Exit Plane Pressure, atm.	Receiver Pressure, atm.	Quality, percent
415.3	1.60	1.53	3.1*
533.2	2.17	1.66	4.8
371.2	1.64	1.38	4.9
404.2	1.84	1.49	5.0
265.8	1.61	1.39	5.8
365.7	1.94	1.41	6.3
377.3	2.18	1.36	7.0
248.9	1.76	1.42	7.9*
332.9	2.22	1.35	8.3
299.2	2.00	1.94	8.5*
229.1	1.72	1.31	9.6*
239.6	1.73	1.14	9.7
254.1	2.00	1.18	10.9
221.7	1.66	1.15	11.2
217.7	1.69	1.13	12.8
199.7	1.49	1.07	13.1
170.5	1.26	1.02	13.4
226.4	1.81	1.12	13.6
359.1	3.45	1.47	14.1
355.6	3.72	3.65	14.2
322.8	2.84	1.33	15.0
404.6	4.05	1.56	16.2
378.2	4.06	1.51	16.6
359.7	4.09	3.27	17.2
218.0	1.92	1.14	17.4
398.6	4.67	1.58	17.6
391.6	4.74	4.37	18.2
320.7	2.68	1.44	18.6
330.2	2.90	1.44	19.8

* Denotes runs where exit plane pressure exceeded pressure just upstream of the exit plane.

Table 3.2. Hydrogen Results (continued)

Mass Flow per unit area, gm/sec·cm^2	Exit Plane Pressure, atm.	Receiver Pressure, atm.	Quality, percent
200.3	1.85	1.17	20.0
249.9	2.44	1.24	21.0
163.6	1.51	1.18	21.5
311.8	3.33	1.48	22.3
267.2	2.73	1.32	22.7
207.6	2.03	1.25	22.8*
129.3	1.23	1.17	23.0
376.6	4.21	1.50	23.2
177.0	1.67	1.07	23.4
190.6	1.76	1.08	23.6
354.5	3.99	1.59	23.6
151.1	1.37	1.03	23.9
160.3	1.52	1.16	24.8*
233.7	2.44	1.24	25.4
294.1	3.14	1.39	26.0
129.2	1.26	1.16	26.3*
301.5	3.24	1.39	26.9
154.4	1.50	1.10	27.1
202.2	2.07	1.25	27.2*
163.3	1.64	1.20	27.8
203.2	2.16	1.00	28.3*
117.5	1.15	1.05	28.5
195.2	1.63	1.12	28.9
191.1	1.98	1.17	29.5
121.4	1.22	1.12	29.8
132.2	1.27	0.98	29.8
118.4	1.18	1.07	30.2*
191.2	1.99	1.21	30.3
113.9	1.13	0.98	31.0*
123.1	1.21	1.10	31.3
135.0	1.36	1.05	31.6
131.2	1.32	1.14	31.7*
123.0	1.23	1.06	31.8
135.4	1.40	1.08	32.6
106.2	1.10	1.02	33.0
102.8	1.07	1.03	34.2

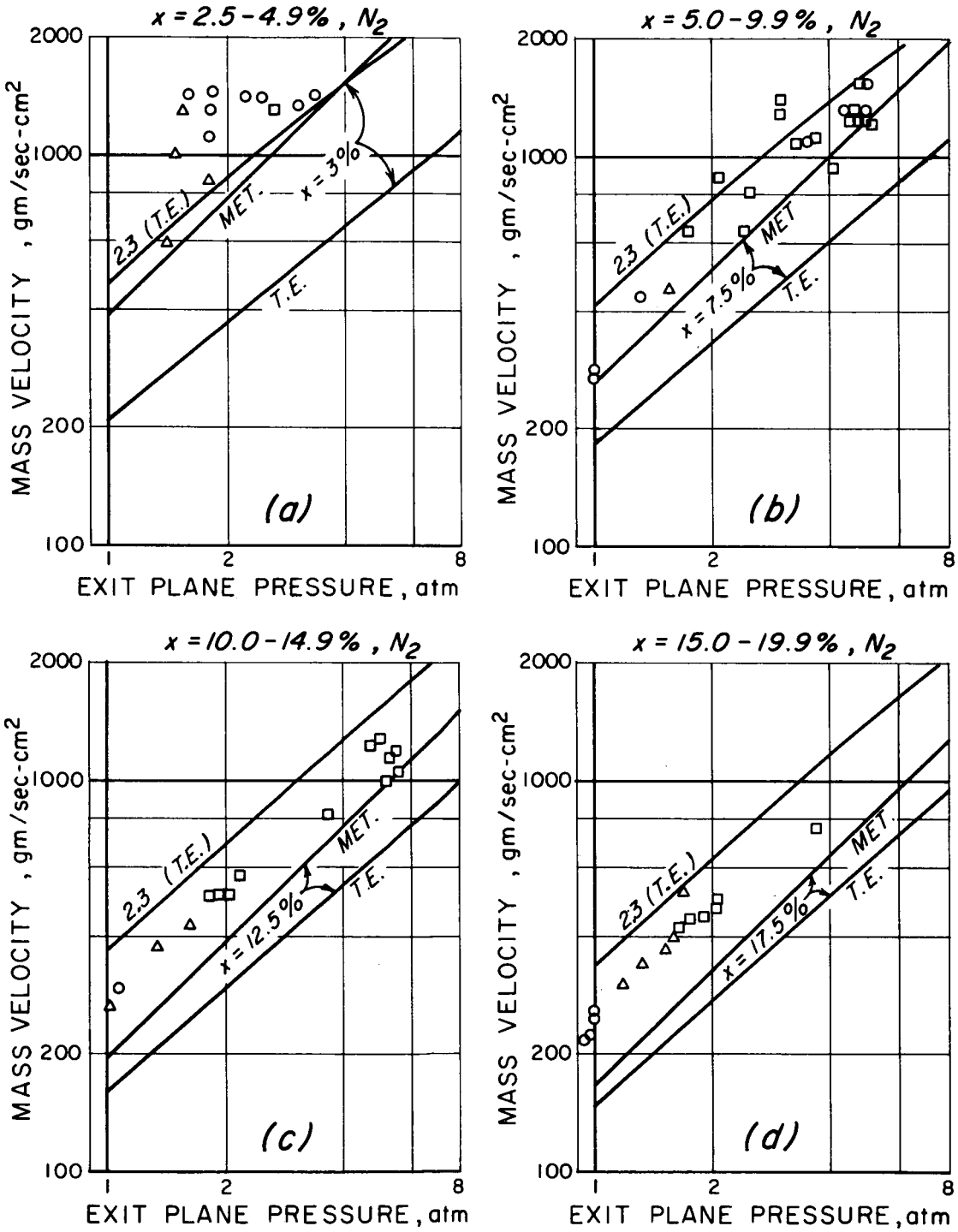


Figure 3.1 Comparison of experimental results with model predictions for nitrogen

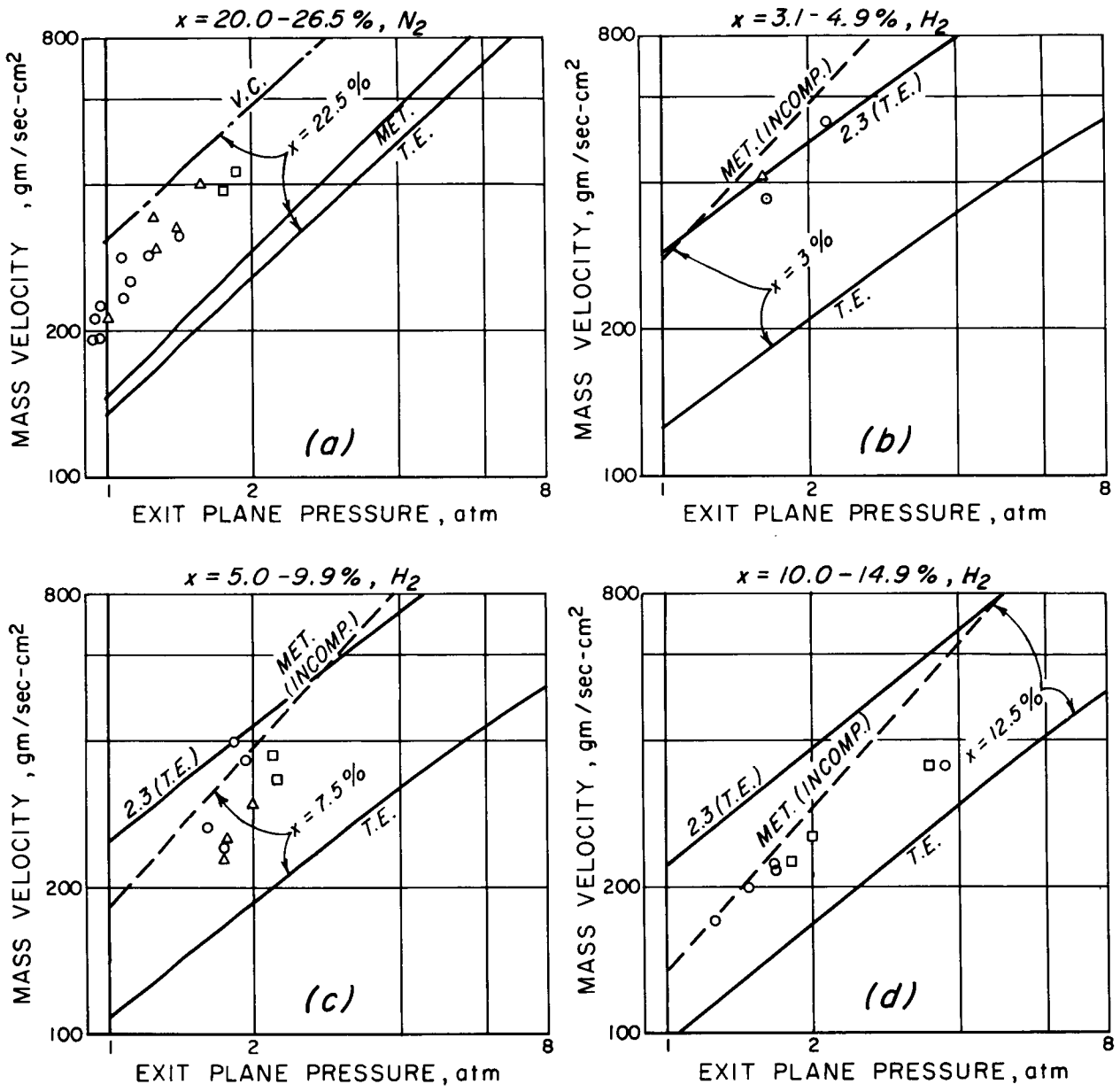


Figure 3.2 Comparison of experimental results with model predictions for nitrogen and hydrogen

SYMBOLS: o $(P_{E.P.} - P_{REC.}) \leq 0.68$ atm

□ $(P_{E.P.} - P_{REC.}) > 0.68$ atm

△ PRESSURE RECOVERY UPSTREAM OF E.P.

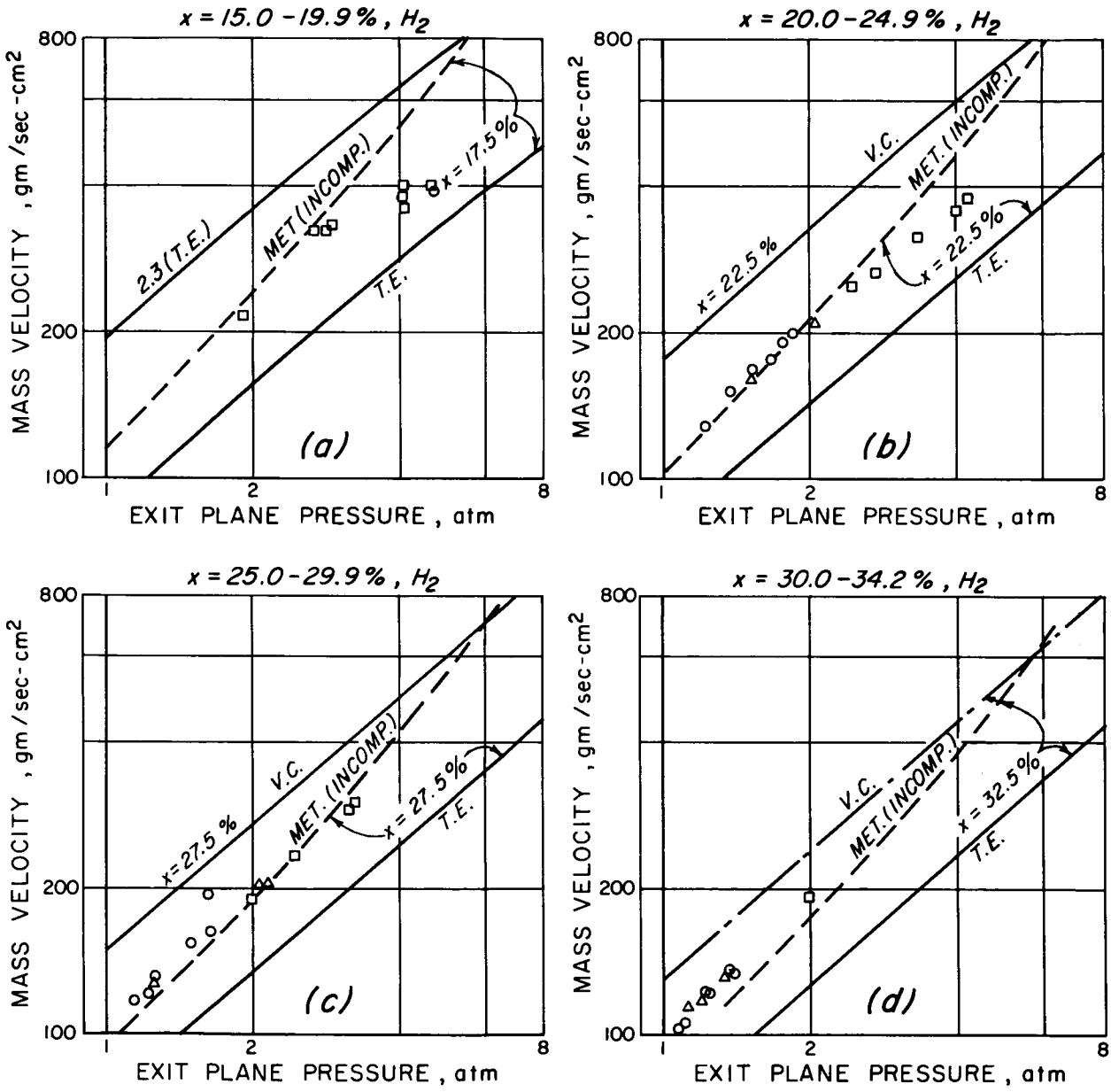


Figure 3.3 Comparison of experimental results with model predictions for hydrogen

qualities above 20 percent the vapor-choking model (V. C.) was recommended for predicting upper-limit values. In the quality range from 1 to 10 percent for non-mixing systems and from 10 to 20 percent for all systems, it was recommended that the upper limit be determined by multiplying the homogeneous, thermal equilibrium model by 2. 30. Since none of the models provided an adequate upper limit in this latter region Smith [1963a] recommended taking the upper limit of the experimental data he had summarized. Hence the multiplying factor of 2. 30 on the homogeneous thermal equilibrium model. These model recommendations did a fairly good job of bracketing the data, except at the lowest qualities.

In the evaluation of the metastable model for hydrogen, Smith took into account the compressibility of the liquid since hydrogen is more compressible than most liquids. This model only provided an upper bound on the data at low qualities and high exit plane pressures. If liquid compressibility is ignored, however, the metastable model provides an upper limit to most of the data for qualities as high as 20 percent. Therefore, only the incompressible model is shown on the graphs.

There are several possible explanations for the deviations between the experimental data and the models, but without additional information these explanations must necessarily be speculative. Therefore, only a brief discussion is included here and for more detailed discussions the

two-phase flow literature should be consulted. The data are tabulated for this purpose.

For the nitrogen data, most points fall somewhat above the metastable model prediction and considerably above the thermal equilibrium model prediction, similar to the case of Refrigerant 11 [Edmonds and Smith 1965], but with considerably better agreement than that shown for straight tube experiments using water [Smith 1963b]. This might be explained by attributing the deviation from the metastable model to a slip ratio (ratio of vapor velocity to liquid velocity) as suggested by Fauske [1965], or perhaps by assuming a thermal equilibrium behavior with a much larger slip ratio as proposed by several researchers, for example Moody [1965]. For hydrogen, much of the data fall between the predictions of the two models. This may indicate that hydrogen, with its relatively low molar enthalpy difference of vaporization, may tend more toward the homogeneous thermal equilibrium case. This reasoning would also explain the behavior of water which has a relatively large molar enthalpy difference and is known to deviate widely from the homogeneous, thermal equilibrium model [Isbin et al. 1957].

The scatter in the data at low qualities is not unexpected, since this is the region where the assumption of adiabatic flow would give the largest errors in quality and where the experimental uncertainties are most noticeable.

During some of the tests a lower pressure was measured at the pressure tap located 3.2 mm from the exit plane than was measured at the exit plane. Only runs with low pressure differential between the exit plane and the receiver (the highest differential for nitrogen was 0.58 atm and for hydrogen it was 1.16 atm) exhibited this pressure phenomenon and the critical mass flow rates for these runs, which are separately identified on the figures, do not deviate abnormally from the rest of the data. A typical test section pressure profile for one of these runs, along with a run with a normal pressure profile, is shown in figure 4.1. It is not fully understood what caused the pressure recoveries upstream of the exit plane but there are at least three explanations possible. One is simple a measurement error caused by the way in which the pressures were measured and made noticeable only under certain flow conditions. A second possibility is a change of phase occurring such that the pressure measurement was affected adversely; and the third possibility is that the shock had moved back into the tube a short distance, started, perhaps, by a change in roughness at the pressure tap located 3.2 mm from the exit plane. No single, completely defendable explanation can be stated at this time, however.

4. Conclusions

1. Data presented for mass-limiting, two-phase flow of hydrogen and nitrogen show the same general behavior as that reported for other fluids.

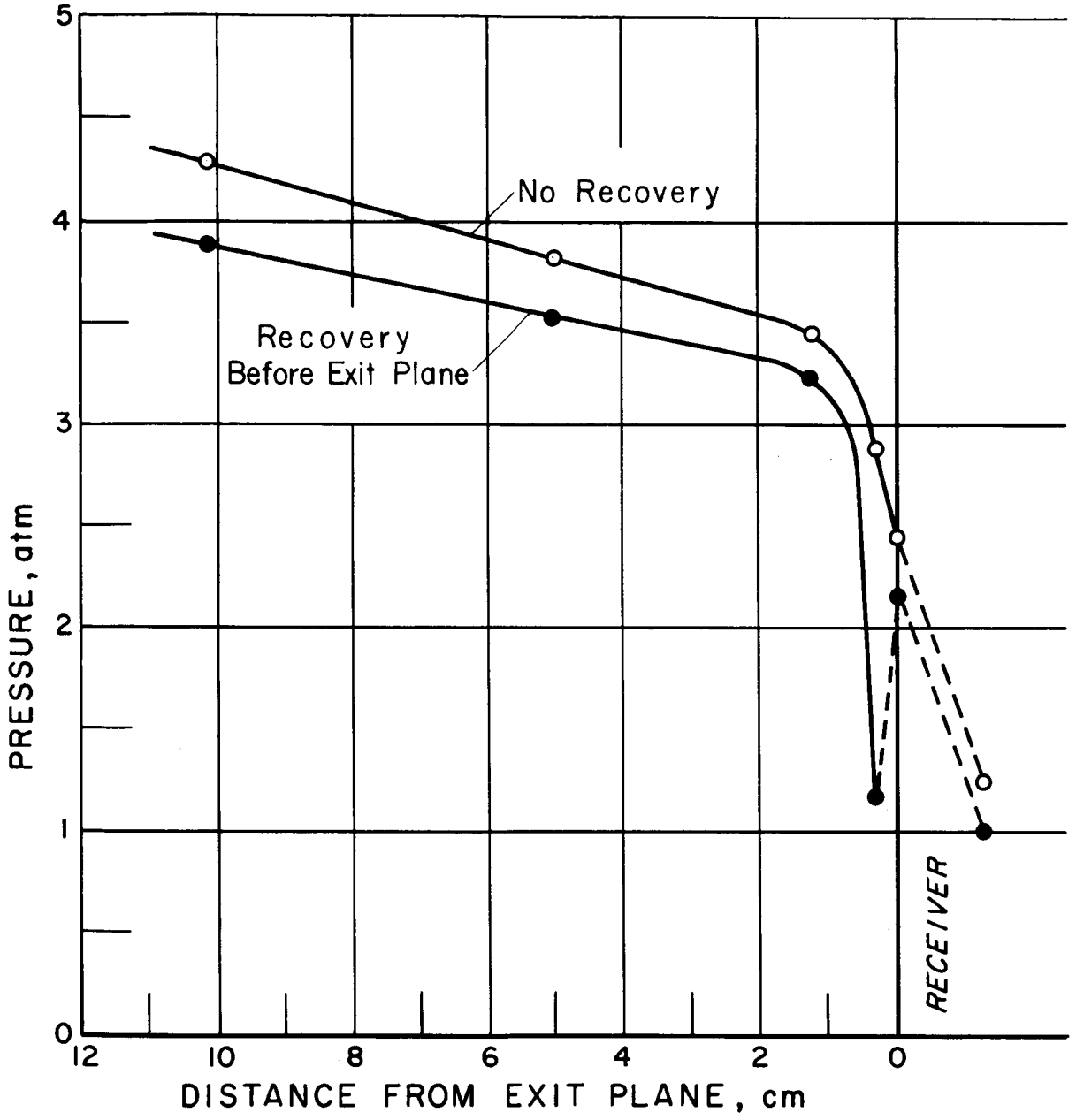


Figure 4.1 Test section pressure profile for tests with and without a pressure recovery upstream of the exit plane

2. Flow rate predictions based on simple analytical procedures and models generally describe the pressure, quality, and flow rate behavior, and may be selected to establish upper and lower limits for critical flow rates of hydrogen and nitrogen in a straight tube.

5. Nomenclature

h_0 = stagnation specific enthalpy (assumed constant and evaluated at dewar conditions), joules/gm

h_f = saturated liquid specific enthalpy at exit plane, joules/gm

h_{fg} = specific enthalpy difference between saturated vapor and saturated liquid at exit plane, joules/gm

u = velocity, cm/sec

G = mass flow per unit area, gm/sec-cm^2

v_f = saturated liquid specific volume at exit plane, cm^3/gm

v_{fg} = specific volume difference between saturated vapor and saturated liquid at exit plane, cm^3/gm

x = mass quality = mass of gas phase divided by total mass

$P_{E.P.}$ = exit plane static pressure, atm

P_{REC} = receiver static pressure, atm

T.E. = homogeneous, thermal equilibrium model

MET = homogeneous, metastable model

V.C. = vapor-choking model

Incom = incompressible

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