COMPARISON OF MASS LIMITING TWO-PHASE FLOW IN A STRAIGHT TUBE AND IN A NOZZLE*

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SUMMARY. This paper reports the experimental data obtained at mass-limiting and near-mass-limiting conditions for a straight tube and two nozzle test sections. The experimental system was a Refrigerant 11 flow loop. Fluid qualities entering the test sections were 0.042, 0.116, and 0.156.

It was noted that as the pressure differential between the exit-plane and the receiver was increased, the exit-plane pressure approached a constant value, for all test sections. The mass flow also approached a constant value for the straight tube, but for the nozzles the mass flow continued to increase with increasing differential pressure but at a lower rate of increase. The deviations from the straight tube behavior were greater for the nozzle with the largest angle of convergence.

Predicted mass-limiting flow rates from the Fauske and a meta-stable model were compared with the experimental data. The models adequately predicted the flow rate for data where the exit-plane pressure was almost constant (within ± 30%). author

Introduction

Most of the previous investigations in the field of mass-limiting, two-phase flow have been primarily concerned with flow in straight tubes and, to a lesser extent, in orifices. Several recent reviews summarize most of this work [1, 2, 3].

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Mass-limiting flow may be defined as a condition where the flow rate is not changed by further reduction in downstream pressures. This would be expected to occur at or very near a straight or converging section exit or at a minimum area point in a system. Flow in nozzles has been the subject of only a few studies, two using air-water [4, 5], and several for single component systems [6, 7, 8] with saturated liquid at the entrance. Additionally, the flow behavior of a system as the differential pressure between the exit-plane and the receiver is varied from a relatively small difference to the point where the exit-plane pressure is not affected by the receiver pressure, has not been well documented. The purpose of this paper is to present experimental data for straight tubes and nozzles in this region where mass-limiting flow conditions are approached.

Experimental Apparatus

The experimental system was a Refrigerant 11 (CCl_3F) flow loop shown with the test sections in fig. 1. Inlet conditions were controlled by upstream valves and the electric heaters. The inlet flow pattern could be visually observed through the glass tube just upstream of the test sections. Relative pressures were read on the mercury manometer board and pressures on a carefully calibrated, 12 in. dial laboratory gage (bourdon tube). The maximum error in pressure measurements was estimated to be ± 0.20 lb_f/in^2. The flow rate was measured at the weigh tank. After steady flow had been achieved the runs were approximately 3 min. in duration and the maximum error in the mass flow rate per unit area was estimated to be ± 1/2%.

Although there were wall taps in the straight tube and in the long nozzle, pressures reported for both nozzles were those measured by a center probe shown in fig. 2. Radial pressure measurements indicated that this was a more representative pressure of the fluid stream. For the nozzles this probe did not cause a measureable effect on the mass flow rate per unit area. On the straight tube the probe did affect this flow rate, however, so the exit-plane pressures were those measured by the wall tap and corrected to the center probe pressure reading by using the measured differences between these readings. Some typical pressure differences are shown in fig. 2. These differences were in general agreement with those found by Klingebiel [9].

The temperature measurement provided on the probe was used to approximate the degree of metastability. The only part of this paper where these measurements would be considered was in the comparisons of these data with predictive models where the measured metastability would affect the quality determination. It was found that for the long nozzle and the straight tube in the exit-plane quality range of the data reported (above 10% quality) the tendency toward metastability appeared to be smaller than at lower quality. So because of this and because probe temperature measurements were not recorded for all runs, metastability is not reported in this paper.

Test Procedure

Quantitative comparison of the experimental results appears possible only through the use of flow models, since conditions varied differently through all of the test sections. A form of standardization for the tests was devised by maintaining the pressure and stagnation enthalpy constant at the indicated upstream flow control tap on the test section. Tests were run beginning at a high or a low pressure differential between the exit-plane and the receiver and continuing throughout the range. Except for the low quality runs these data produced rather smooth curves with little scatter. To rerun the low quality tests for reproducibility, however, one tends to get a new set of curves. It was believed that this discrepancy was due, in part at least, to a variation of the general flow pattern at the entrance for the different runs. This was partially borne out by observations at the glass test section,' and this flow pattern dependence indicates that pressure and quality and flow rate conditions are really not sufficient to control a two-phase experiment at this low quality. Thus, as mentioned by a number of previous investigators, this flow pattern change may be a significant contributing factor to much of the scatter in two-phase data.

Experimental Results

The results in figs. 3, 5, and 7 indicate that each geometry has different characteristics at the near-mass-limiting conditions. The sets of figures are for the same experimental conditions except for the quality range. Although there was more scatter in the data for the lower quality runs the general behavior was the same. All curves show, to varying degrees, a change of slope at some differential pressure between the exit-plane and the receiver. For the straight tube, true mass-limiting conditions are developed at pressure differentials above this change-of-slope differential, but this is not the case for the long or short nozzle curves. There, the change-of-slope appears simply to indicate a reduced rate of mass-flow increase with the increasing differential pressure.

Figures 4, 6, and 7 show the exit-plane pressures as a function of the pressure differential. Here one may observe that the change-of-slope point on the mass flow curves (figs. 3 and 7) marks the approximate point where the exit-plane pressure approaches a constant value.

So, in the sense of changing exit-plane pressures, a choking condition appears to have occurred for the nozzles even though the mass flow rate continues to increase. Although not shown, it was also observed that the pressure profiles upstream of the exit-plane did not change with changes in the receiver pressure for pressure differentials higher than the apparent mass-flow, change-of-slope differential. Also, as might be expected, the short-nozzle axial pressure gradient near the exit-plane was considerably greater than that of the straight tube.

There are two items of further interest to report regarding the curves. First, there was a dip in the curve for the long nozzle shown in fig. 3 and 5 in the area between 8 and 12 psi differential. It was suspected that this was the result of a disturbance initiated by the pressure tap just upstream of the exit-plane. In a later test this tap was filled at the nozzle surface and the surface was smoothed. A reasonably smooth curve resulted; the dip had disappeared. A similar influence of a pressure tap near the exit-plane of a nozzle has previously been reported [6, 7], but the apparent dependence of this interference on pressure differential has not been previously observed.

The second item of interest in the results is related to the dependence on the flow pattern mentioned earlier. In fig. 5 dashed lines on the straight tube data connect points obtained from the same set of runs. For the set of data points that appear to reach a mass-limiting value, annular flow was observed upstream of the test section. For the set of data points which show the most pronounced upward slope, separated flow (vapor above liquid) was observed upstream of the test section. Other differences in flow patterns were observed which appeared to be related to different point sets in other tests, but the pattern differences were not sufficiently distinct to record.

A somewhat related series of tests were reported by Fauske and Min [10]. These data were obtained from a Refrigerant 11 loop using straight tubes with variable L/D. As the L/D was reduced exit-plane to receiver pressure differential required to change the flow rate slope was reduced slightly; however, at the change of slope, mass-limiting flow was reported for all test sections.

Comparison of Mass Flow Data with Proposed Analytical Expressions

Two predictive expressions were used in this study. The Fauske [11] expression was chosen because it has become rather well known and because it is generally representative of the results from expressions based on slip-ratio and thermodynamic equilibrium concepts. The homogeneous, metastable model as reported in [3] was chosen because it was known to generally describe the experimental data and because its assumptions of homogeneous flow and metastable behavior offered a considerable contrast to the Fauske-type of model.

Both expressions are derived from the concept that mass-limiting flow occurs when

$$G^2 = -(\partial p/\partial v)_s \qquad (1)$$

where G is the mass flow per unit area, p the pressure, v the specific volume, and s the entropy. Fauske introduces a slip ratio influence on the specific volume and assumes thermal equilibrium for the evaluation of (1). The metastable model assumes a homogeneous mixture (no slip between phases) and evaluates (1) as though there is no mass transfer between phases at the point of mass-limiting flow. This system has been developed for two-component systems which are summarized and slightly modified in [3].

For this and almost all other reported data, the quality at the exit-plane has been calculated rather than measured. This obviously requires some assumptions and introduces an uncertainty into the model comparison. The system is basically to solve the following equation

$$h_o = h_f + x\, h_{fg} + \frac{u^2}{2} \qquad (2)$$

for the quality, x, where h is the specific enthalpy, u the velocity, and subscripts f and g refer to the liquid and gas phases. For the results shown it was assumed that the fluid was in thermal equilibrium up to the exit-plane (not necessarily for the evaluation of eq. 1), and that the last term in (2) may be approximated by using the average (no-slip) velocity. These appear to be rather standard assumptions. The further assumption made is that the center pressure probe represents the exit-plane pressure as mentioned previously with the discussion of fig. 2.

The results are shown in figs. 8, 9, and 10. The points shown in figs. 3 through 7 which were used in this study are indicated in these figures. A few items may be noted regarding these results. First, that both models predict the flow rate beyond the stable-exit-plane-pressure, or change-of-mass-flow-rate slope, point reasonably well although the model assumptions are quite different. Secondly, the mass-flow ratios are highest for the straight tube where true mass-limiting flow appeared to occur, lower for the long nozzle, and still lower for the short nozzle where there were successively less tendencies toward mass-limiting flow. This tendency could be construed to permit speculation that mass-limiting flow might be reached with a nozzle and at a value in general agreement with the straight tube data; however, the limits of the experimental system prevented the determination of whether or not this would be the case. For the data recorded with the nozzles the mass flow rate does not appear to be approaching a constant.

Thirdly, there is a considerable uncertainty in the values in the comparative figures because of the quality calculation and exit-plane pressure determinations. If, for example, the flow through the test sections were metastable, then the exit-plane quality would be lower than that computed, the predicted mass-flow rate higher, and all curves would be lowered. For a guide to the significance of this calculation, if there were no increase in quality in flow through the test sections, the values from the predictive models would be increased by as much as 70%. Conversely, use of the wall pressure measurement rather than the center probe would shift the curves slightly upward.

Finally, in comparing these data with results from air flow in straight tubes and conical nozzles [12] one finds the two-phase case considerably different. For both straight tubes and similar nozzles with air flow, mass limiting flow occurs essentially when the receiver pressure reaches the critical exit plane pressure and this critical flow rate is in reasonably good agreement with the predicted valve. Comparable discharge coefficients were .93 for the straight tube, .95 for the short nozzle, and .97 for the long nozzle. As the back or receiver pressure is reduced below the critical pressure, the flow increase was only about 1% for the range of back pressures reported in this paper.

For the two-phase case, all test sections required a significant difference between the receiver and exit plane pressures before there were indications of mass-limiting flow, such as changes slope of the mass flow rate or exit pressure curves. At that point of change, the straight tube then exhibited characteristics similar to the single-phase case except for a low quality run with a separated-flow pattern entering the test section. For the long nozzle with higher quality runs (.116 entering and about .18 at exit) there was about a 5% increase to the point of slope change and a further increase of about 5% for the range of back pressures reported. Although there was more scatter in the low quality data, the general behavior appeared to be much the same.

For the short nozzle at the higher quality runs (.116 entering and .15 to .16 exit) there was a 10 to 20% increase before the slope change and about a 5% increase after the change of slope. For the lower quality runs (.042 entering and .11 to .13 exit) no noticeable change of slope was indicated for the back pressures tested before the flow rates exceeded the capacity of the system. Also, as mentioned previously, neither nozzle showed evidence of approaching true choking flow for the range of receiver pressures tested.

Conclusions

1. Nozzles do not appear to exhibit mass-limiting flow characteristics at the same differential pressures as straight tubes, and true-mass-limiting flow may not be possible for some nozzles. Mass-limiting flow appears to be less likely with short,wide-angle nozzles.

2. For nozzles, the exit-plane pressures do appear to reach constant values when the flow rate does not.

3. Flow rate appears to be a function of small changes in system geometry such as pressure taps near the exit-plane and flow conditions which influence the upstream flow pattern.

4. These points suggest that most of the predictive expressions for mass-limiting flow in the current literature may require modification for the case of nozzle flow. However, comparisons of the predictions from Fauske and metastable models with the experimental data indicate that the models generally predict the flow rates for all test sections, after the exit-plane pressure becomes constant, within ± 30%. The ratios of the experimental values to the predicted values are lowest for the short nozzle, somewhat higher for the long nozzle, and highest for the straight tube where mass-limiting flow did occur.

Nomenclature

h = enthalpy

G = mass flow rate per unit area

p = pressure

s = entropy

v = specific volume

u = axial fluid velocity

x = quality

Subscripts

f = liquid

g = gas

fg = difference between liquid and gas values

o = stagnation conditions

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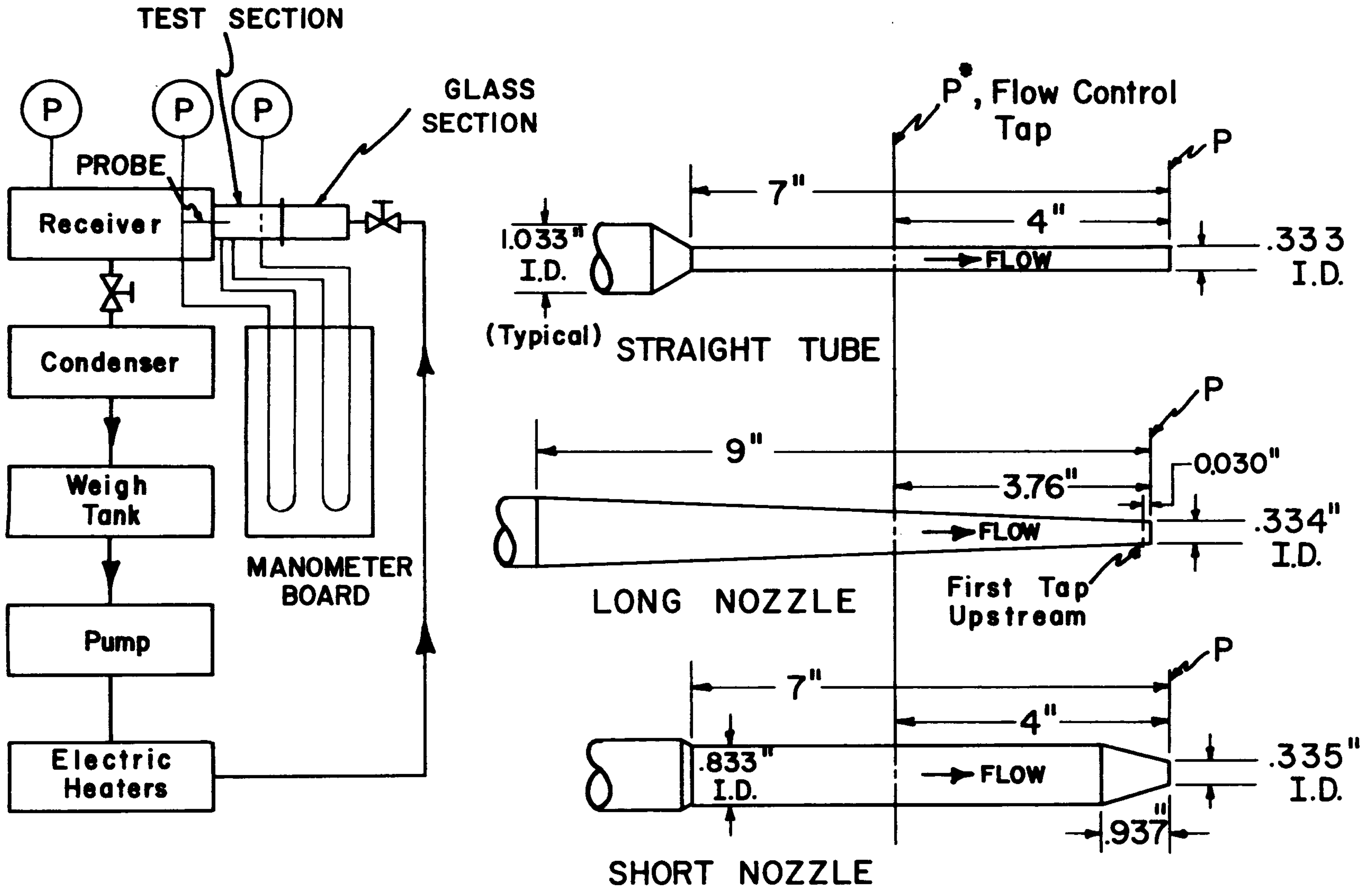

Figure 1. Refrigerant 11 Loop and Test Section.

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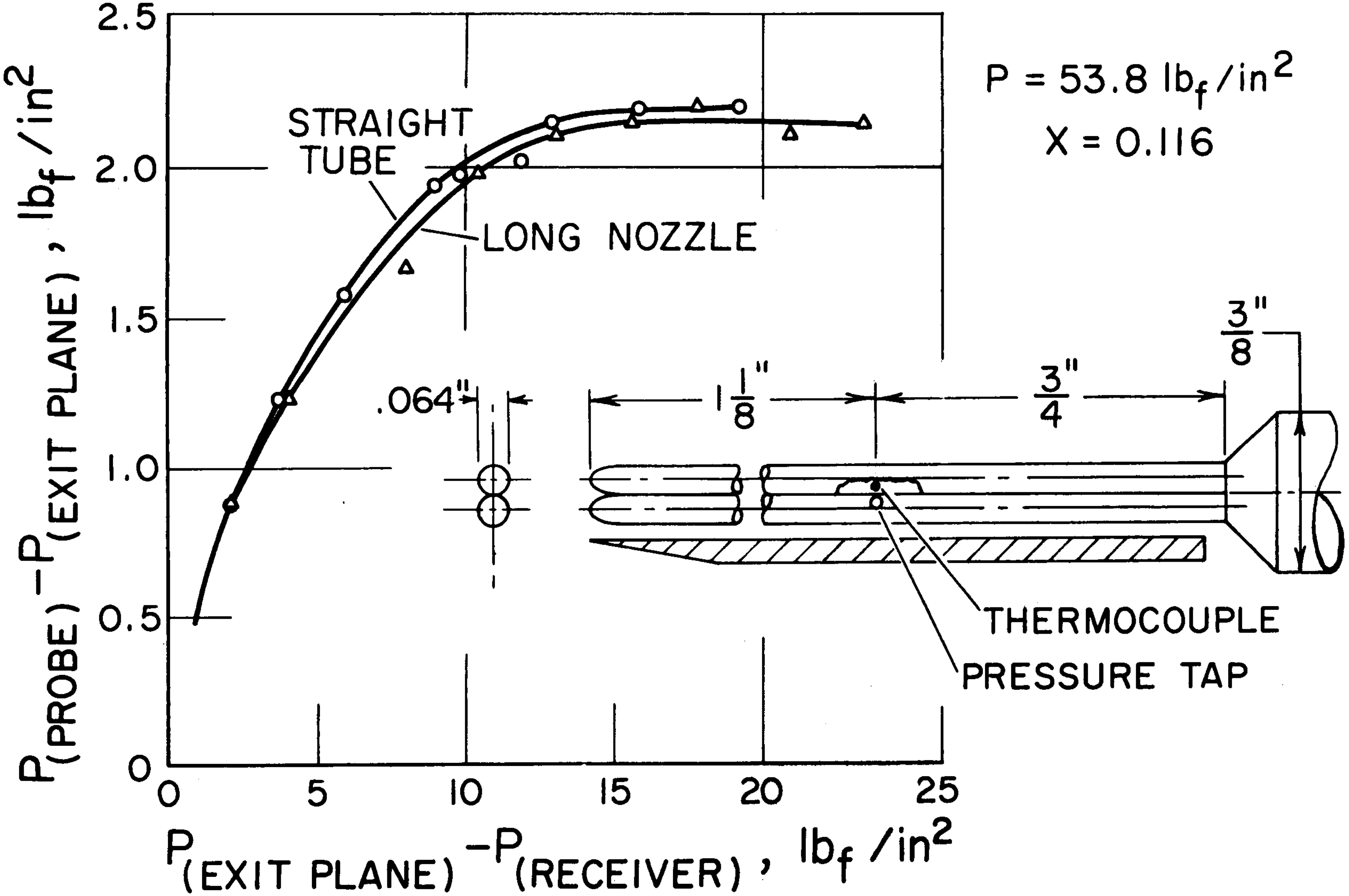

Figure 2. Details of Probe and Comparison of Center and Wall Tap Pressure Measurements.

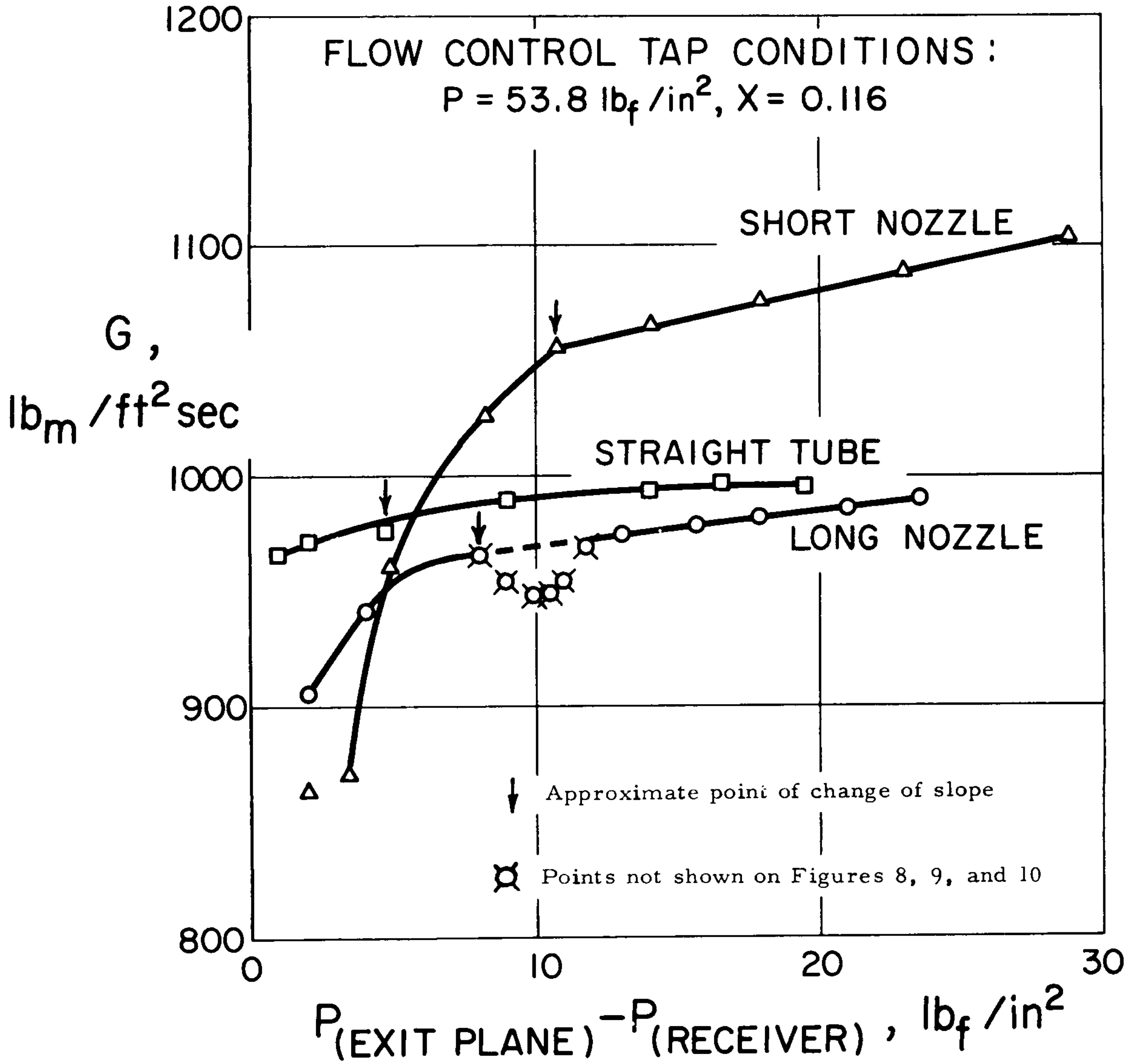

Figure 3. Mass Flow as a Function of Exit-Plane to Receiver Pressure Differential.

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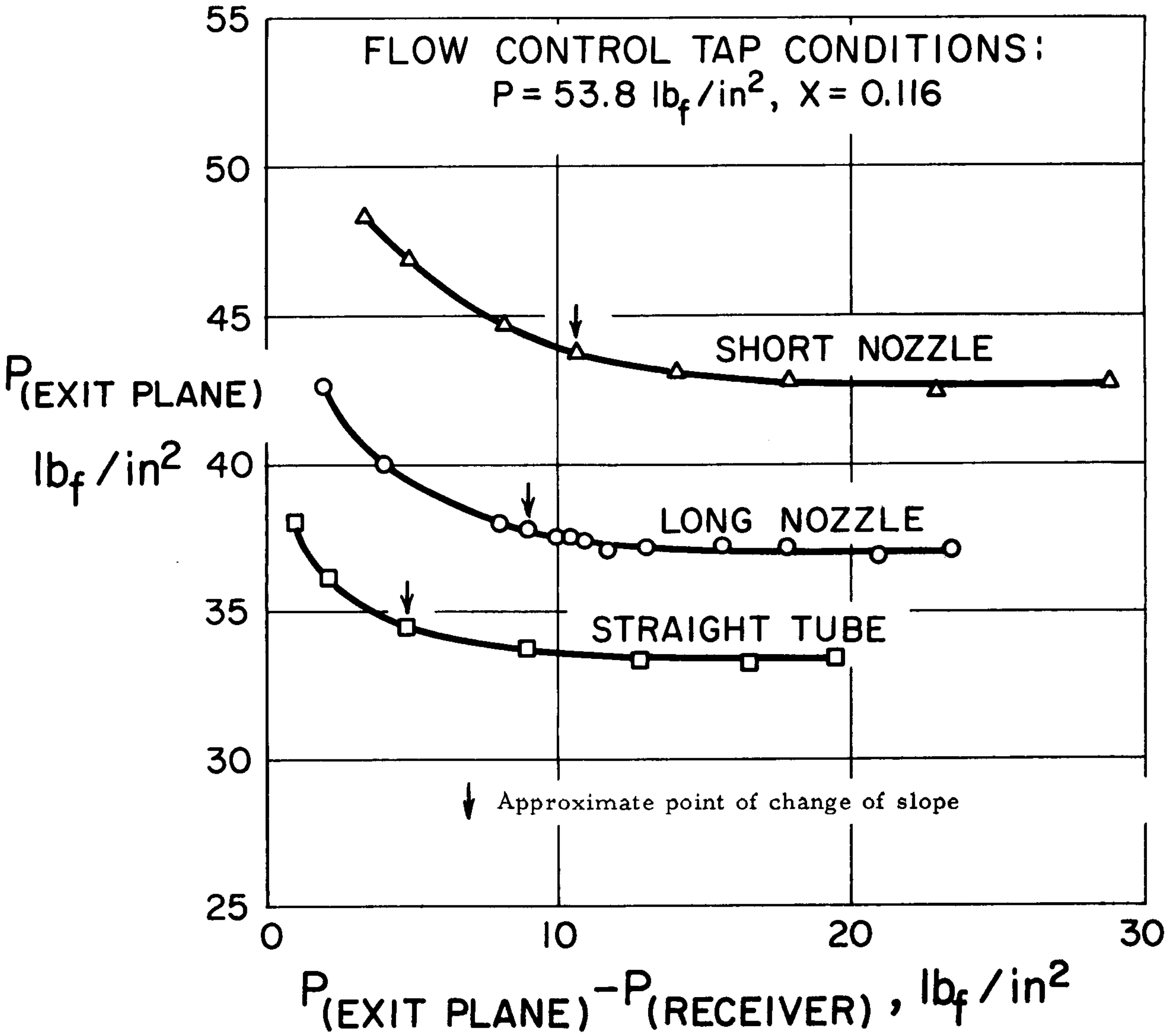

Figure 4. Exit-Plane Pressure as a Function of Exit-Plane to Receiver Pressure Differential.

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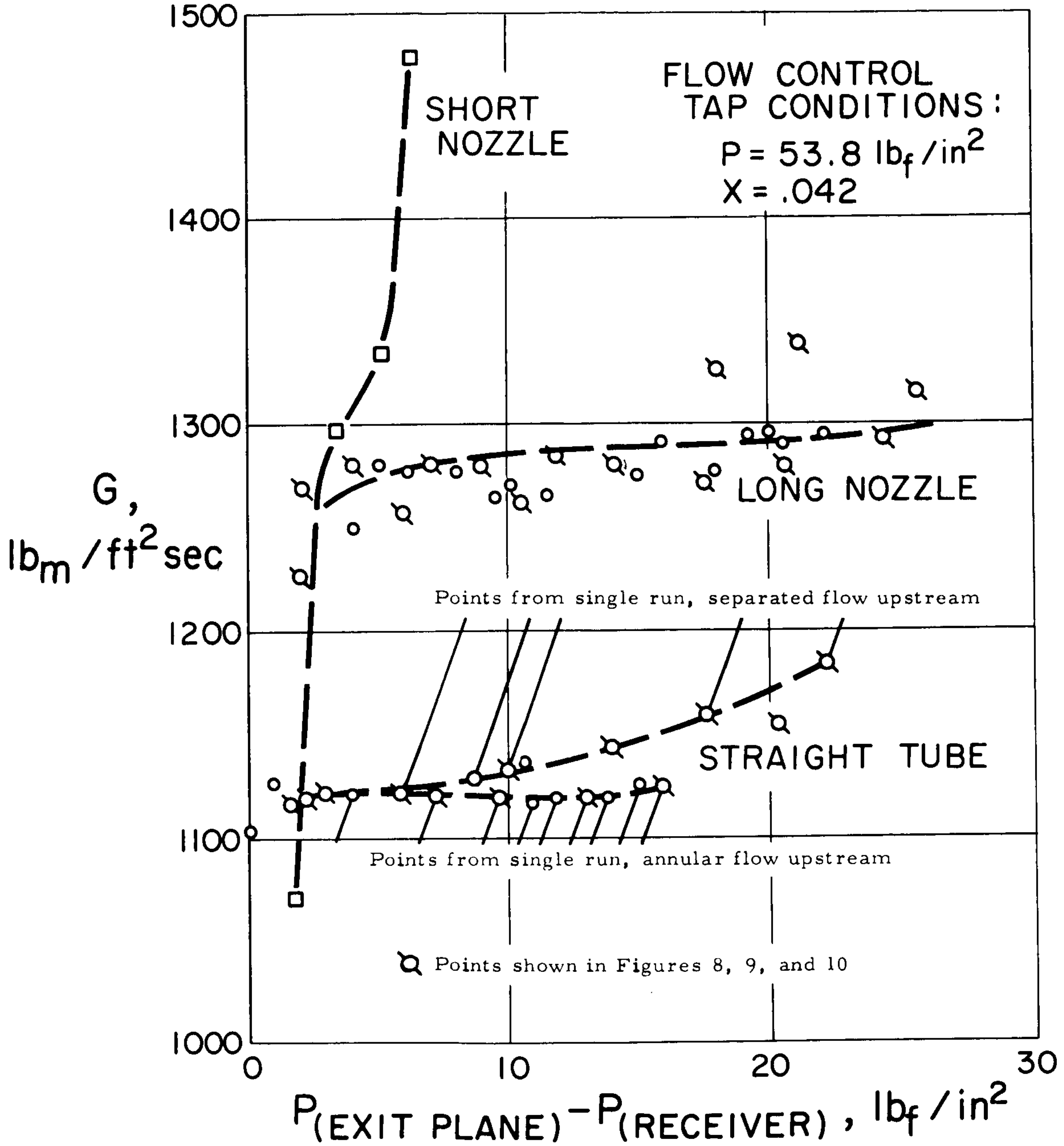

Figure 5. Mass Flow as a Function of Exit-Plane to Receiver Pressure Differential.

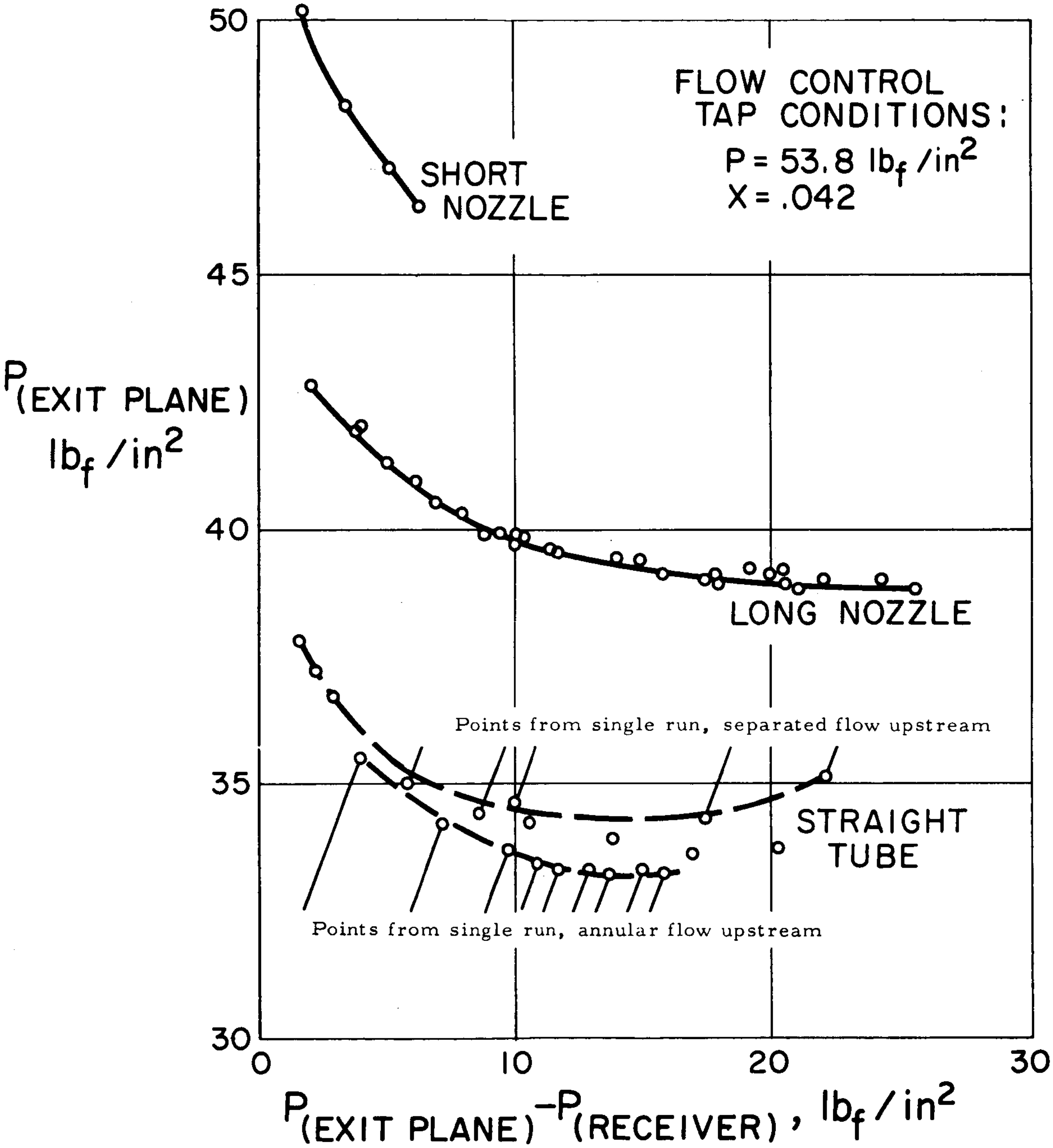

Figure 6. Exit-Plane Pressure as a Function of Exit Plane to Receiver Pressure Differential.

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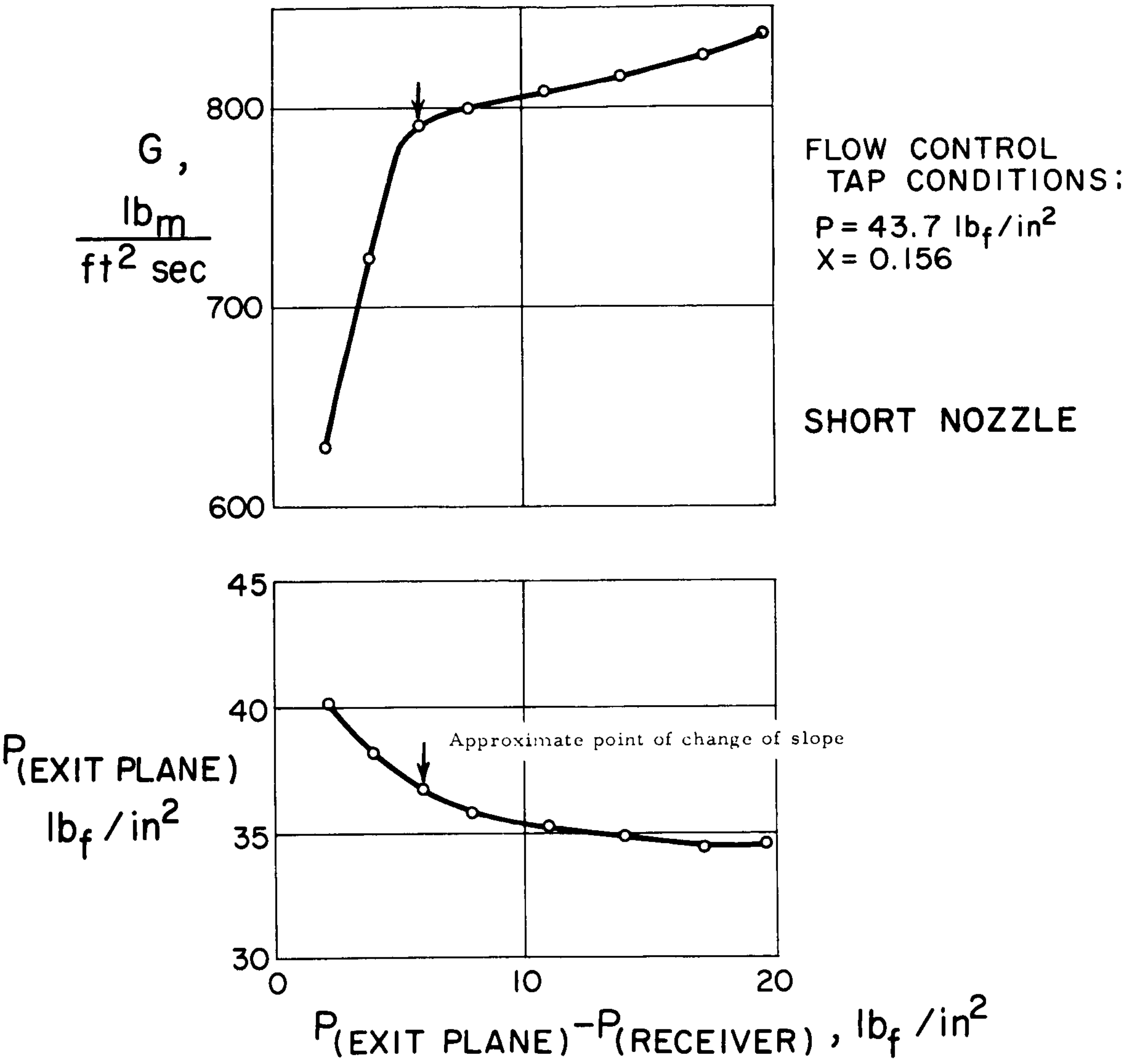

Figure 7. Mass Flow and Exit-Plane Pressure as a Function of Exit-Plane to Receiver Pressure Differential.

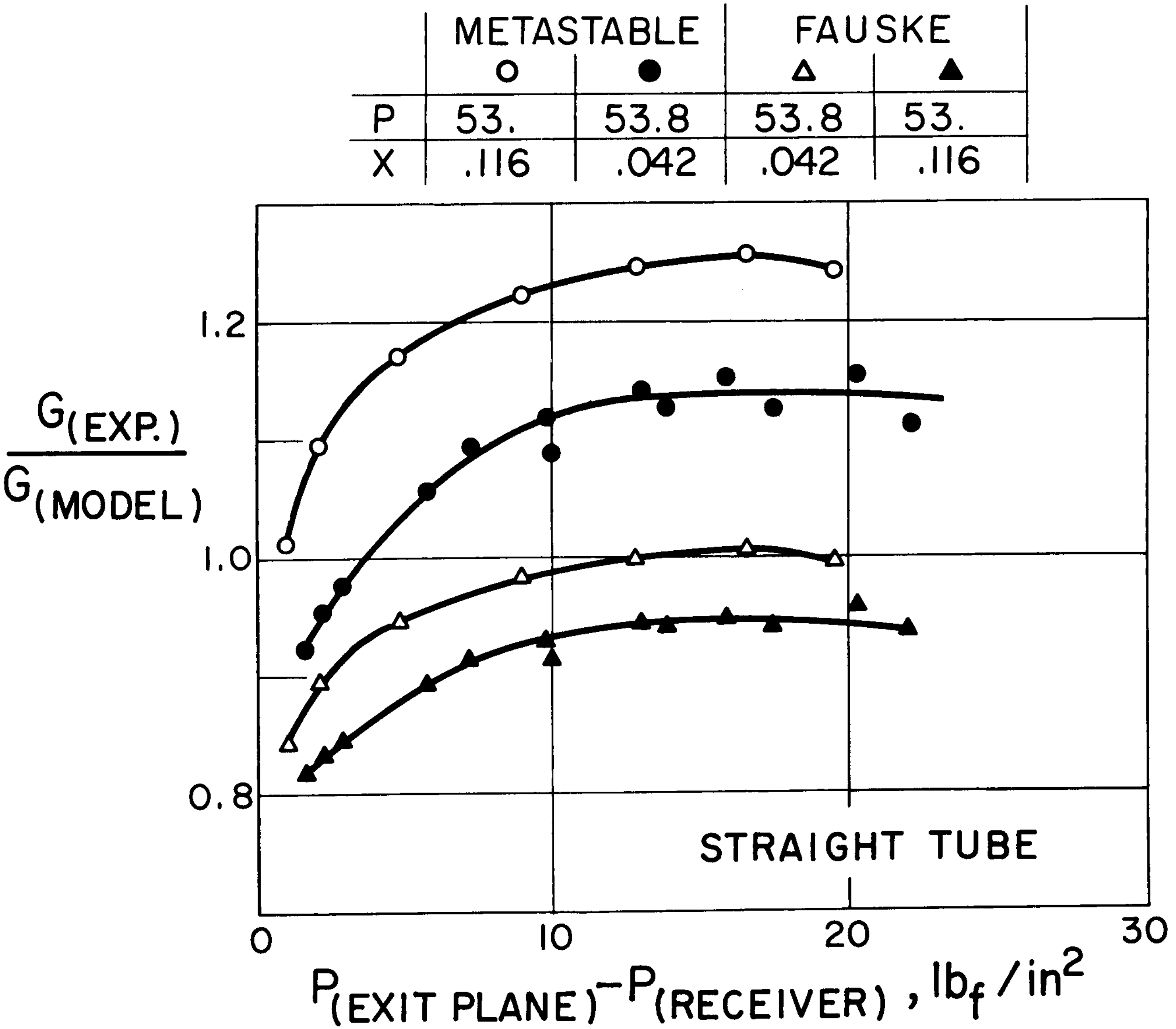

Figure 8. Mass-Limiting Flow Model Comparison

Pressure and quality are flow tap control conditions.

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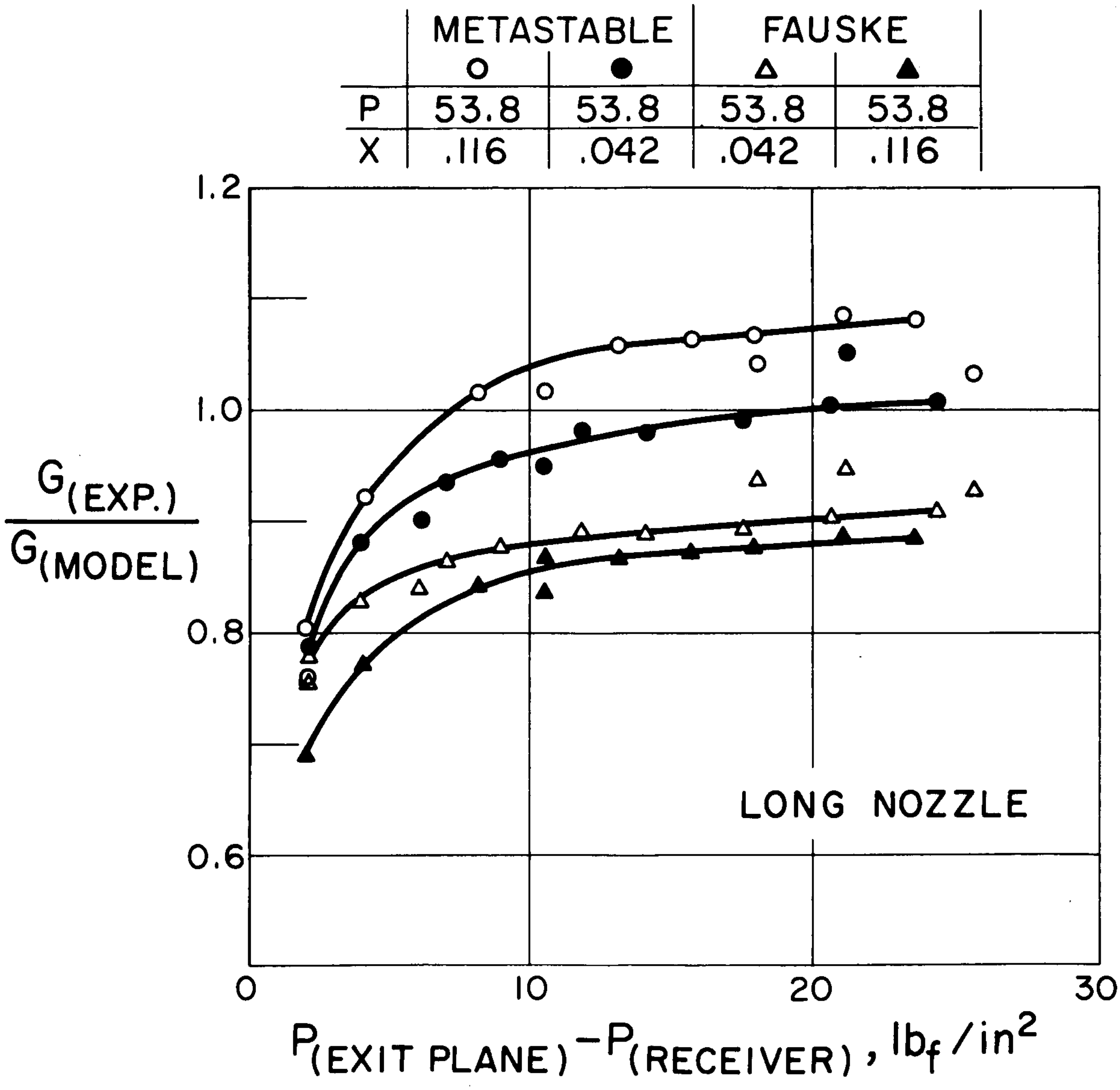

Figure 9. Mass-Limiting Flow Model Comparison.

Pressure and quality are flow tap control conditions.

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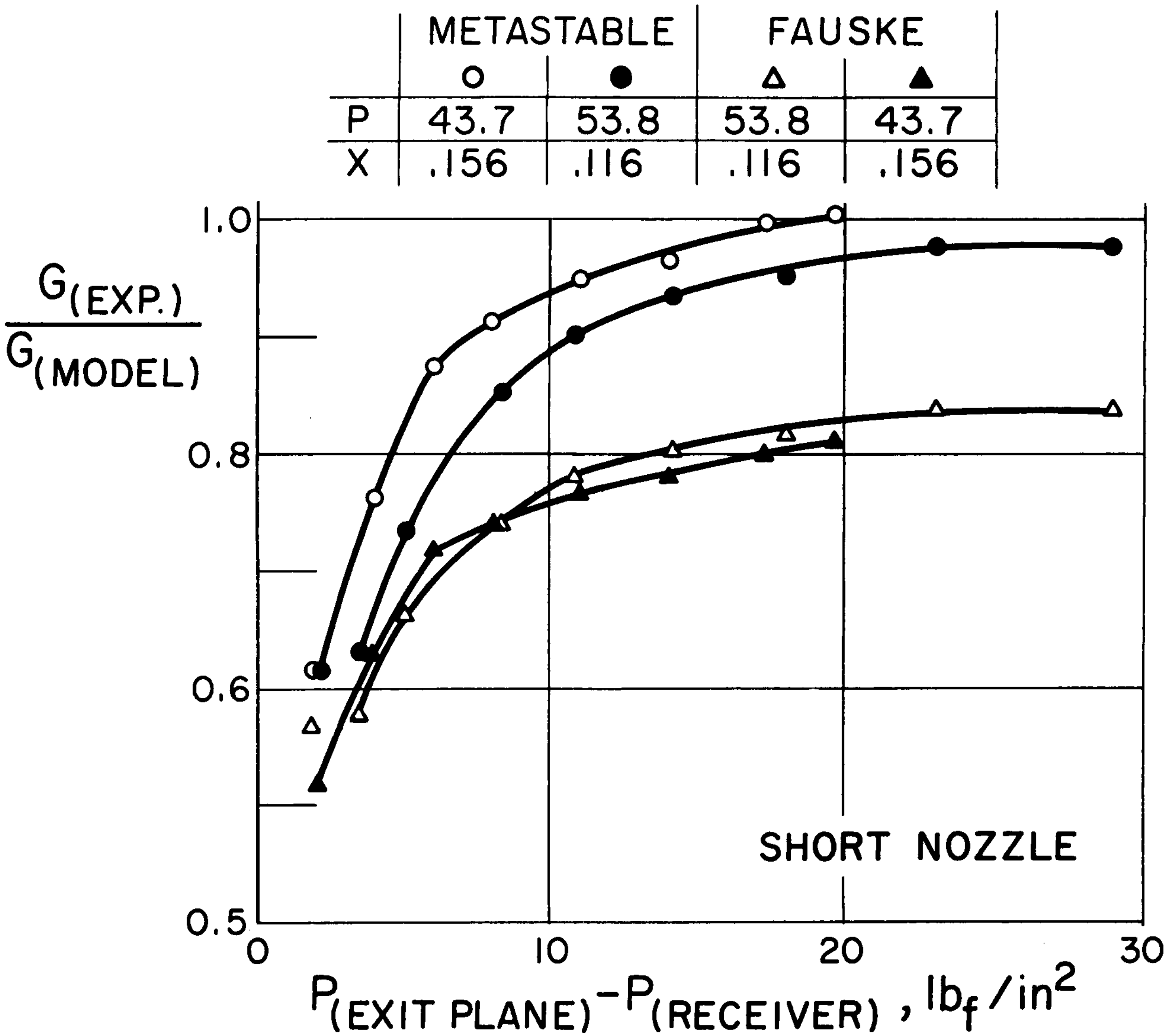

Figure 10. Mass-Limiting Flow Model Comparison.

Pressure and quality are flow tap control conditions.