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TECHNICAL NOTE

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MEASURED STEADY-STATE PERFORMANCE OF WATER VAPOR JETS FOR USE IN SPACE VEHICLE ATTITUDE CONTROL SYSTEMS

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SUMMARY

Measurements have been made in a vacuum environment to determine the steady-state performance of several nozzles having thrusts up to 1000 dynes for use in space vehicle attitude control systems. Water vapor was used as a propellant.

The results indicate that the trend of the variation of specific impulse and thrust coefficient with expansion ratio is predicted by calculations based on one-dimensional isentropic flow. The level of these quantities, however, is dependent upon the nozzle diameter. The specific impulse, for example, varies from about 30 percent to 80 percent of the theoretical value as the nozzle thrust is increased from about 10 to 1000 dynes.

INTRODUCTION

Various systems for precise attitude control of satellites have been studied at Ames Research Center. The results of analytical studies of one of these systems in which jet reaction provides the control torque are presented in reference 1. The required thrust of the jets was indicated to be of the order of several hundred dynes for a satellite, such as the orbiting astronomical observatory (see ref. 2). Nozzles which provide thrusts of this magnitude must either have a very small throat diameter or must operate at very low upstream pressures. In either event, the effects of viscosity would be expected to be large enough so that conventional nozzle theory, based on inviscid flow, would not provide adequate estimates of thrust and specific impulse. A search of the literature indicated no available experimental studies upon which design of low-thrust nozzles could be based. An experimental program was therefore initiated in which the performance of small nozzles was measured in a vacuum environment.

Two types of propellants have been proposed for low-thrust attitude control jets - condensible vapors and cold gas. Condensible vapors have a possible advantage over cold gas in that smaller volumes need to be stored and lower pressures are encountered, provided the proper choice of propellant is made. Oddly enough, water vapor is the best propellant among the condensible vapors from the standpoints of vapor pressure, corrosiveness, and theoretical specific impulse. Further, from a research standpoint, the properties of water vapor are well documented (see ref. 3) and it is easily removed from a vacuum environment by freezing. Water vapor was therefore chosen as the propellant in this study.

NOTATION

A_t area of throat, cm^2

C_d nozzle discharge coefficient - ratio of measured mass flow to theoretical mass flow for isentropic flow

C_F thrust coefficient, $\frac{\text{thrust}}{P_c A_t}$

d nozzle throat diameter, cm

g gravitational acceleration, 980 cm/sec^2

I_{sp} specific impulse, $\frac{\text{thrust}}{g\dot{m}}$, sec

$\frac{l}{d}$ ratio of nozzle throat length to diameter

$\dot{m}$ mass flow rate, gm/sec

P_c pressure in chamber behind nozzle, $dynes/cm^2$

R Reynolds number based on throat diameter; and velocity, viscosity, and density calculated from one-dimensional isentropic flow through the nozzle throat

T_c temperature of the vapor in the vapor generator, $^\circ C$

ϵ expansion ratio of nozzle, exit area divided by throat area

Subscript

isen performance parameters calculated for one-dimensional isentropic flow

APPARATUS

Balance System

A balance system was constructed to measure the thrust and mass expenditure of nozzles having thrusts up to 1000 dynes. Photographs of this apparatus are presented in figure 1. In essence, this system consisted of two remotely operable laboratory type balances, the balance used to measure thrust being mounted on an arm of the balance used to measure mass expenditure. Crossed flexures designed to achieve nearly zero restoring moment were used as the pivots for each of the balances. Additional flexures of silver foil, electrically insulated from the balance structure, were mounted between the crossed flexures to provide electrical circuits for operation of the solenoid valve and measuring devices. The force required to bring either of the balance elements to null was provided by a direct-current solenoid and permanent magnet.

The water was contained in vapor generators mounted on either side of the force measuring balance. The water was held by hollow cylindrical cellulose sponges contained in cups. Knife edges were machined integrally with the rim of the cups (see fig. 1(a)). The knife edges, which rested on agate bearings, were colinear with the flexure pivot axis, thereby preventing mass loss and uneven evaporation from appearing as spurious force readings. A precision thermometer that could be read to 0.1° C fit in the top of one of the vapor generators with its bulb in the hollow of the cellulose sponge, thereby shielding the bulb from external thermal radiation. An absolute reading pressure cell with a range from 0 to 5 psia was mounted in the top of the other vapor generator. The vapor generators were connected to a single line leading to the solenoid valve and nozzle. The nozzle was located so that the thrust vector was in a vertical plane containing the axis of the flexures of the balance that measured mass loss; therefore, that balance was not affected by thrust.

Both the thrust and the mass expenditure balances were calibrated in terms of solenoid current required for null when weights were placed either in the vapor generator cups or suspended on the thrust axis. The sensitivity could be adjusted to detect a change in thrust as small as 2 dynes and a mass loss as small as 0.02 gram.

It was intended to measure thrust and mass loss simultaneously on a continuous basis. However, during the time required for the mass loss to become significant, the thrust-off reading of the thrust balance was usually found to have shifted an intolerable amount. A measurement was made, therefore, to determine thrust in which the elapsed time between the thrust-off and thrust-on readings was of the order of a minute. During this period, shifts in the thrust-off reading of the balance were small. The mass-flow rate, needed to calculate I_{sp}, was determined from a separate measurement. For most of the mass-flow rates encountered, a binary water-vapor system existed within the vapor generator and the pressure could be determined from a knowledge of temperature. However, for the largest nozzle tested, the surface area available for evaporation was apparently insufficient and the vapor within the generator became superheated, as indicated by the measured pressure being slightly less than the saturation pressure which corresponded to the measured temperature. The heat content, or quality, of the vapor at the entrance to the nozzle was not determined except by indirect means which will be described later.

Nozzles

Four convergent-divergent nozzles were machined as well as several sharp-edged orifices (see fig. 2). The nozzles were designed to have a maximum expansion ratio of 100. The tolerance to which small holes of the size required can be drilled resulted in some deviation from this value, particularly for the smaller nozzles. The method used to measure the throat diameter was to stretch a copper wire, which was initially slightly larger than the throat, until it could just be passed through the nozzle. The wire diameter was then measured with a micrometer. The results obtained with this technique were more consistent than attempts to measure the diameter optically with a microscope. The excessively long throat section (four throat diameters) occurred by accident rather than design and was not discovered until the expansion ratio of two of the nozzles had been reduced to 1 by the progressive machining away of the exit cone. These nozzles were then modified to achieve a throat section that was one diameter long and had an expansion ratio of approximately 7.

Vacuum Chamber

The apparatus was placed in a vacuum chamber as shown in fig. 1(b). While the nozzles were operating, a mechanical vacuum pump and cold trap held the pressure within the chamber to 50 microns or less. The cold trap was refrigerated with dry ice which was sufficient to hold the partial pressure of the water vapor to about 8 microns. Heat lamps located external to the tank provided heat to the vapor generators. By varying the input voltage to the lamps, it was possible to regulate the temperature within the vapor generators from about 25° to 50° C.

CORRECTIONS TO DATA

The vacuum system was capable of maintaining the ambient pressure within the range from 30 to 50 microns while a nozzle was operating. A correction to the measured thrust to compensate for the pressure force on the nozzle exit is necessary if the results are to be applicable to a space environment. It is possible to obtain realistic results which can be corrected to zero pressure only if the pressure within the nozzle remains greater than ambient. The calculated exit pressure for a nozzle with an expansion ratio of 100 is in the range from 50 to 100 microns for the range of upstream pressures for which data were obtained. It was found experimentally that the corrected force coefficient was invariant with ambient pressure, provided the ambient pressure was less than 100 microns for a nozzle with an expansion ratio of 100 operating at the lowest inlet pressure for which data are presented. Since all results were obtained at an ambient pressure of 50 microns or less, the corrected results are considered to closely represent the force developed in an absolute vacuum environment. The applied correction was roughly 30 dynes for the largest nozzle tested ($d = 0.077$, $\epsilon = 98$). This correction is proportional to the exit area so that for many of the smaller nozzles the correction is insignificant.

The measured vapor pressure was corrected for the pressure drop through the valve. This correction was computed from the equivalent orifice diameter and discharge coefficients stated by the valve manufacturer. The correction is significant only when the nozzle throat diameter approaches that of the equivalent orifice representing the valve. For the largest nozzle tested the correction to the vapor pressure was roughly 2 percent.

RESULTS AND DISCUSSION

Ideal Nozzle Performance

One-dimensional isentropic flow is a convenient standard for comparison of nozzle performance. Well designed nozzles of the size usually used in rockets or turbines approach this performance within a few percent. The calculated variations of thrust coefficient and specific impulse with expansion ratio for isentropic flow of water vapor are presented in figure 3 for several states of the fluid entering the nozzle. As the vapor is expanded through the nozzle, first some liquid phase will be formed and entrained in the stream. As the pressure falls below the triple point, the solid phase will be formed. It was assumed, for purposes of calculation, that at a given point in the expansion, the stream contained either liquid and gas or solid and gas and, further, that both phases were at the same temperature. This cannot occur physically since insufficient time is available for heat to be transferred from the liquid or solid phases as the expansion proceeds. An alternative assumption, representing the opposite extreme, is that the liquid and solid phases remain at the temperature at which they were formed as the gas about them cools during the expansion. Neither of the two assumptions is realistic, but the difference between them in the calculated performance is only a few percent.

The results of calculations in which the flow is assumed to contain either liquid and vapor or solid and vapor all at the same temperature are presented in figure 3. The data shown are for an initial temperature of 48.9° C. Increases in saturation temperature will result in increases in specific impulse roughly proportional to the square root of the absolute temperature. The thrust coefficient does not vary significantly with temperature within the temperature range of the experimental conditions. The results of the computations indicate that significant departures from the dry saturated state cannot be expected to affect nozzle thrust, but that the presence of the liquid phase is detrimental to the specific impulse. Improvement in specific impulse might be realized by superheating the steam, but large increases in temperature would be required to achieve any large gain in performance.

Measured Nozzle Performance

Heat content of the water vapor.- In the experimental apparatus, the line leading to the valve and nozzle was not illuminated by the heat lamps and, in the absence of another heat source, was cooler than the vapor within it. This, of course, caused condensation within the line. The presence of condensate in the line was clearly indicated in several instances when the nozzle was blocked by ice shortly after the valve was opened. The ice was formed by evaporative cooling of the water droplets forced through the nozzle. This is obviously unacceptable performance if the nozzle is to supply torque for a control system. In such a system, it will be necessary for the vicinity of the valve and nozzle to be maintained at a temperature slightly greater than the rest of the system to insure against condensation in this region. In the experiment, the energy dissipated by the valve solenoid under steady-flow conditions proved to be an excellent method of providing the necessary heat. The two-position valve, which was closed when not energized, was designed to open for inputs from 8 to 10 watts. Once open, however, the valve remained open as the input was reduced to about 1/2 watt. The heat input to the valve, therefore, could be varied from about 1/2 to 10 watts. It was found that as the valve heat input was increased, the mass-flow rate decreased rapidly until an input of several watts was reached. This decrease was assumed to result from conversion of water droplets entrained in the flow to steam. Further increases in heat input resulted in no further reductions in mass-flow rate. For test purposes, the valve was operated at about 5 watts. Under these conditions the water vapor was considered to be dry saturated or slightly superheated steam. Since superheating the steam by modest amounts has been shown to have little effect on the ideal performance (see fig. 3), the data in this report can be considered to be representative of the performance of nozzles using dry saturated steam.

Effect of nozzle shape.- Typical results of thrust and mass-flow rate measurements are presented in figure 4. The mass-flow rate, as might be expected, was independent of expansion ratio. (See results for d = 0.027 and 0.051 cm in fig. 4(b).) There was considerable scatter between the individual measurements, particularly those of nozzle thrusts less than about 30 dynes. It was assumed, for purposes of calculation, that the mass-flow rate and thrust varied as the upstream pressure raised to some power. A least-squares procedure was used to find the most probable curve of this description to fit the data. The root-mean-square deviation of the individual thrust measurements from the most probable value was about 3 dynes for the smallest nozzle and about 30 dynes for the largest. The rms deviation of the mass-flow rate was about 2×10^{-5} gm/sec for the smallest nozzle and 2×10^{-4} for the largest. The corresponding rms deviations from the most probable value of specific impulse varied from about 10 seconds for the smaller nozzles to 7 seconds for the largest.

The performance at an upstream temperature of 48.9° C has been chosen to illustrate the effects of nozzle shape on performance. The values of specific impulse and thrust coefficient calculated from probable values of thrust and mass-flow rate at this temperature are shown in figure 5. (The rms deviation from this value has also been shown at each data point.) The variation of the performance parameters with increasing expansion ratio is approximately that predicted for isentropic flow in that, for a given nozzle diameter, the percentage of the isentropic performance achieved is nearly independent of expansion ratio. Since the nozzles are intended for use in a vacuum environment where the flow cannot be overexpanded, it is concluded that the expansion ratio should be at least 100.

As noted previously, the original nozzles had a throat length four diameters long. (See fig. 2.) After conclusion of the tests to establish the effects of expansion ratio, two of these nozzles were modified to have a throat length one diameter long and an expansion ratio of roughly 7. The effect of this change in throat length and of using a sharp-edged orifice, which can be considered to have a throat length of zero, can be seen from the results of figure 5. These results indicate that specific impulse is less sensitive to changes in throat geometry than is the thrust coefficient. This is to be expected since an increase in the discharge coefficient will invariably increase the thrust coefficient because it is dependent upon the product of mass-flow rate and exit velocity, whereas the specific impulse is primarily dependent upon exit velocity. The decrease in the length of the throat section of the 0.027-cm-diameter convergent-divergent nozzle did not improve the specific impulse but increased the thrust coefficient by roughly 25 percent. The measured thrust of the 0.051-cm-diameter nozzle with the shortened throat appears to be low since a decrease in specific impulse is indicated with very little increase in thrust coefficient. Use of a sharp-edged orifice, or effectively a throat length of zero, increased the specific impulse over that for a nozzle having a throat length four diameters long and an expansion ratio of 1 by roughly 10 percent. The corresponding increase in thrust coefficient was about 30 percent for the 0.051-cm-diameter nozzle and about 45 percent for the 0.027-cm-diameter nozzle.

<u>Correlation of results</u>.- The variation of the nozzle performance parameters with nozzle diameter suggests that the results might correlate in terms of Reynolds number. Such a correlation would be desirable in that it would permit the results to be applied to nozzles using other fluids as propellants. Since data for a wide range of pressures and, hence, fluid densities are available (see fig. 4), a range of Reynolds numbers was covered for each nozzle. The Reynolds number chosen for the correlation was based on the throat diameter and the velocity and density within the throat corresponding to isentropic flow. The most probable values of specific impulse, thrust coefficient, and discharge coefficient calculated from the least-squares data analysis described above are presented as functions of this Reynolds number in figure 6. It can be seen that a reasonable correlation is obtained for the discharge coefficient, but that no correlation is obtained for either specific impulse or for thrust coefficient. The correlation of the latter quantities could be improved only slightly if the measured mass flow were used in the determination of Reynolds number. The lack of correlation of thrust coefficient and specific impulse in terms of Reynolds number implies that the flows through two different sized nozzles operating at the same Reynolds number are not similar even though the nozzles are geometrically similar. In particular, from the variation of specific impulse and thrust coefficient, it is obvious that the exit velocity is lower for smaller nozzles which implies that viscous effects cause the expansion of the flow to lower pressures to be progressively more retarded as the throat diameter is decreased.

An empirical correlation was found between specific impulse and mass-flow rate. Such a correlation is shown in figure 7 for nozzles with expansion ratios greater than 50. The specific impulse was normalized by dividing by the value for isentropic flow in order to account for the differences in expansion ratio between the various nozzles. The specific impulse was calculated from each thrust measurement and the mass-flow rate determined from the least-squares data analysis. This correlation places most of the results for a given mass-flow rate in a band which is about 10 percent of the theoretical specific impulse in width. The effect of a change in throat geometry on this correlation is shown in figure 8. In this figure, the results are shown for nozzles having no expansion cone and a throat four diameters long, and for a sharp-edged orifice ($l/d = 0$). When these data are correlated in terms of mass-flow rate, there appears to be no difference in the specific impulse within the accuracy of the measurements.

The last result indicates that the specific impulse and, therefore, also the thrust of convergent-divergant nozzles of any reasonable throat geometry which use steam as a propellant can be estimated from figure 7 if the mass-flow rate is known. The mass-flow rate can be determined by direct measurement or by knowledge of the nozzle throat area and discharge coefficient. Measurements of the throat area of nozzles of this size can easily be in error by as much as 10 percent, and it would seem likely that microscopic differences in construction could cause the discharge coefficients of seemingly identical nozzles to differ. For these reasons, it is believed that more reliable results will be obtained if the mass-flow rate is determined by direct measurement.

Ames Research Center
National Aeronautics and Space Administration
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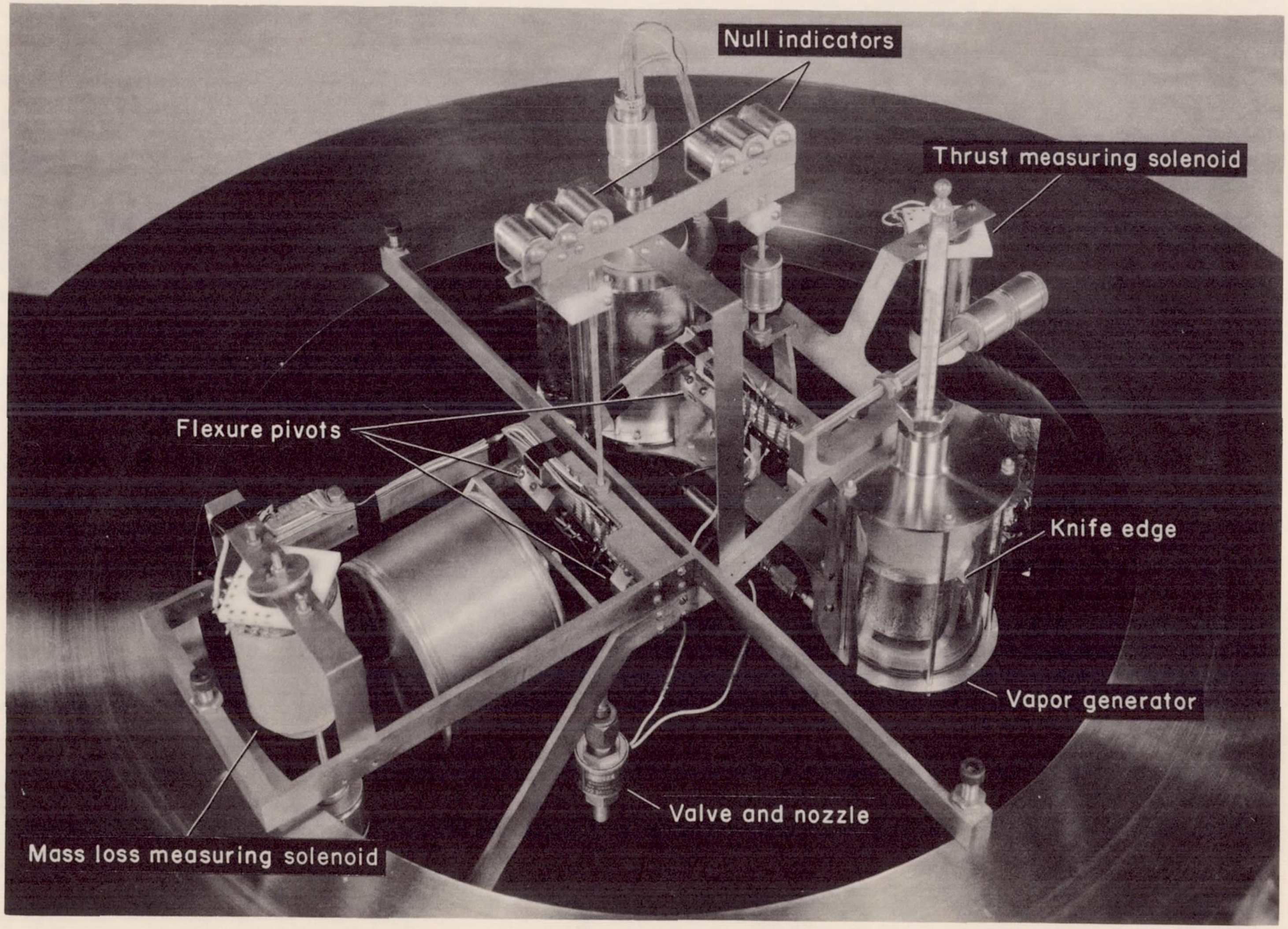
2. Triplett, William C.: Design Considerations for an Orbiting Astronomical Observatory. ARS Preprint 1184-60, 1960.

3. Keenan, Joseph H., and Keyes, Frederick G.: Thermodynamic Properties of Steam; Including Data for the Liquid and Solid Phases. John Wiley and Sons, Inc., 1936.



(a) Vapor-jet balance.

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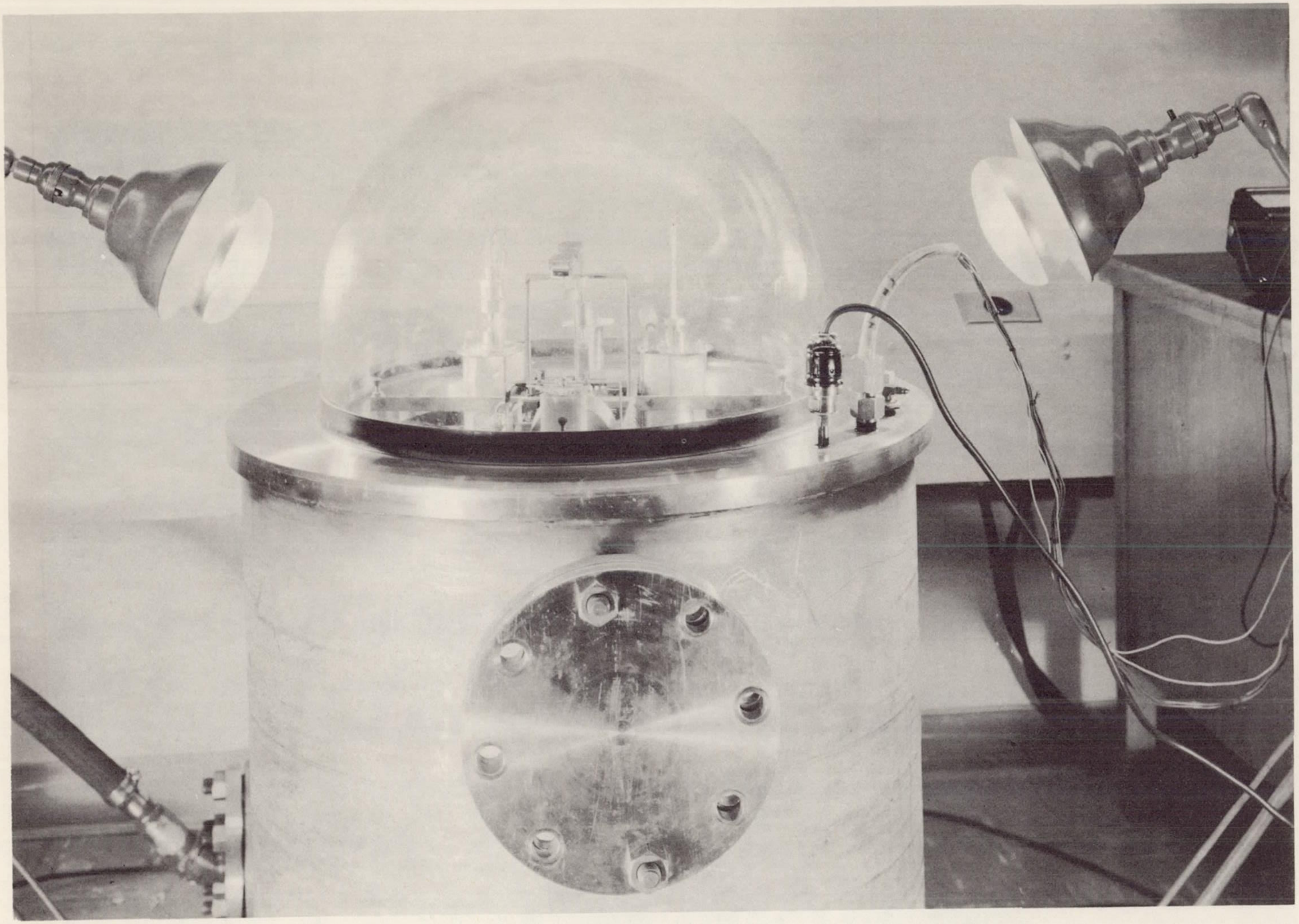
Figure 1.- Experimental apparatus.



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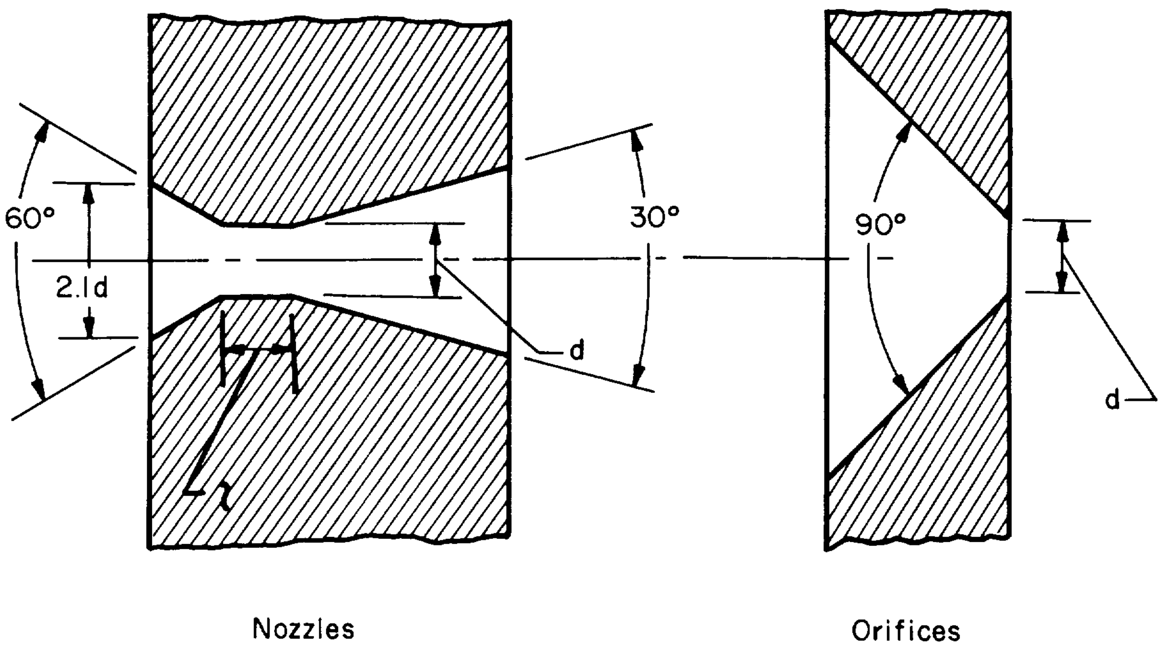
(b) Vacuum tank with balance installed.

Figure 1.- Concluded.



	d, cm	l/d	
Nozzles	0.018	4	53
	0.027	4	81, 55, 10, 3 & 1
	0.027	1	7.8
	0.051	4	99, 60, 10, 3 & 1
	0.051	1	6.3
	0.077	4	98
Orifices	0.027	—	—
	0.051	—	—

Figure 2.- Dimensions of nozzles and orifices.

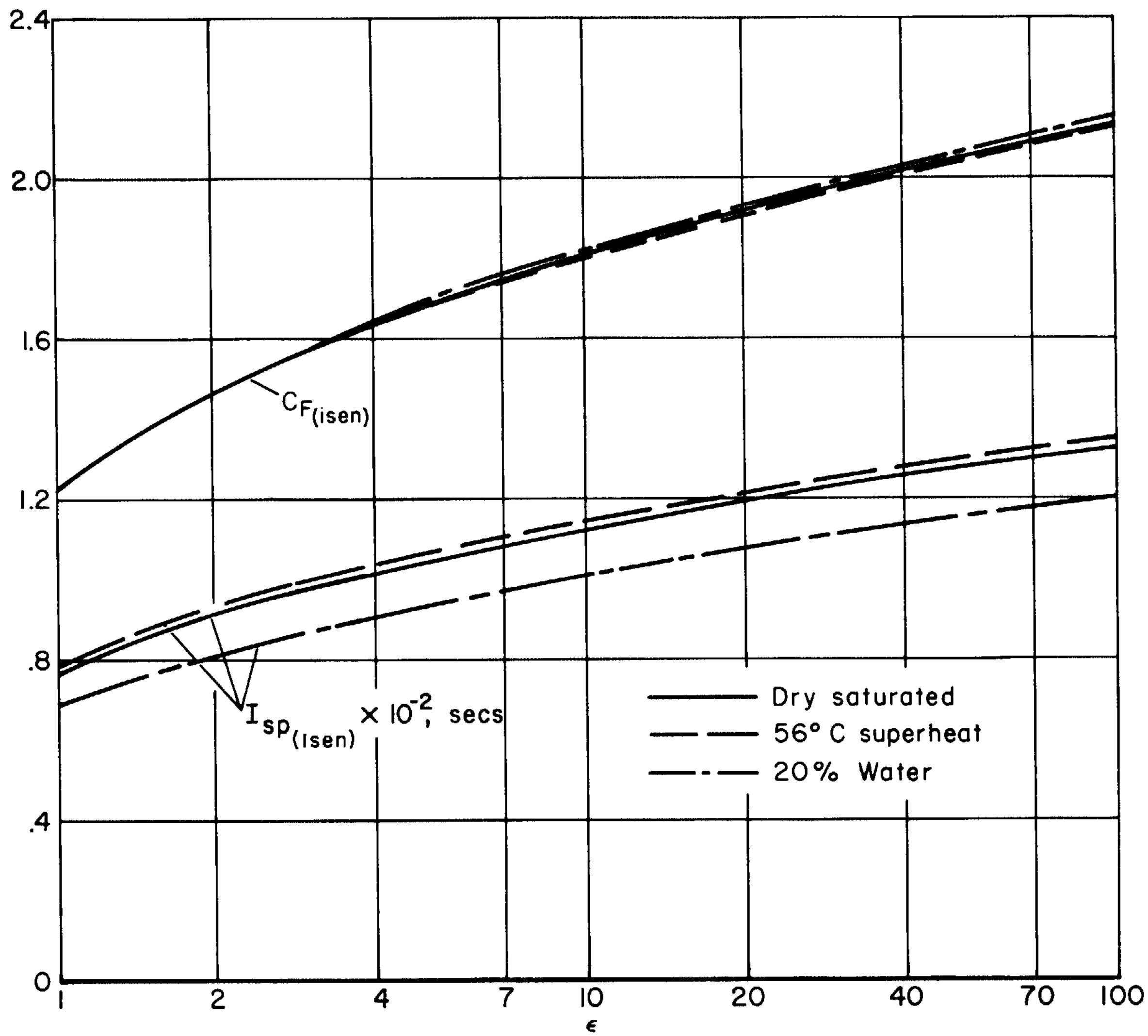
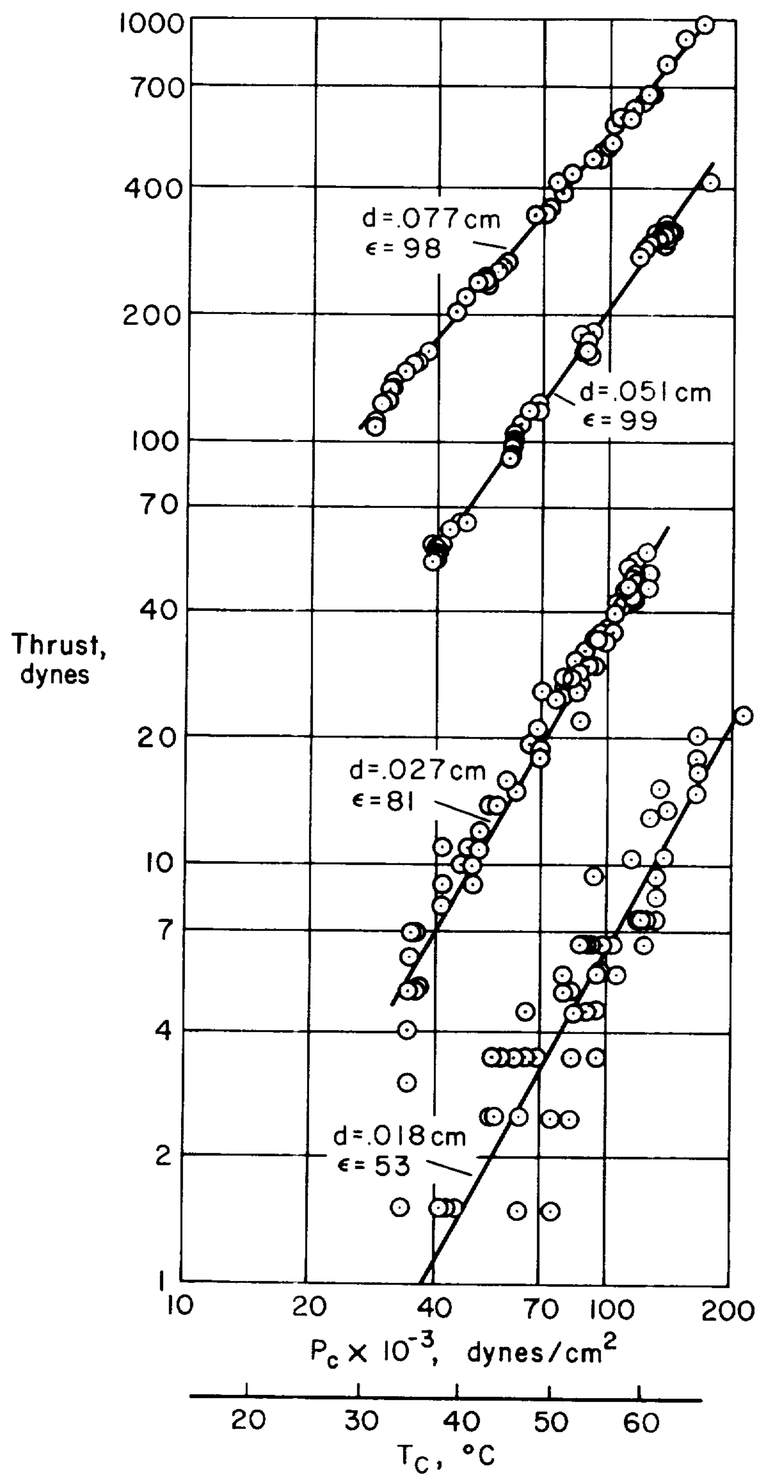


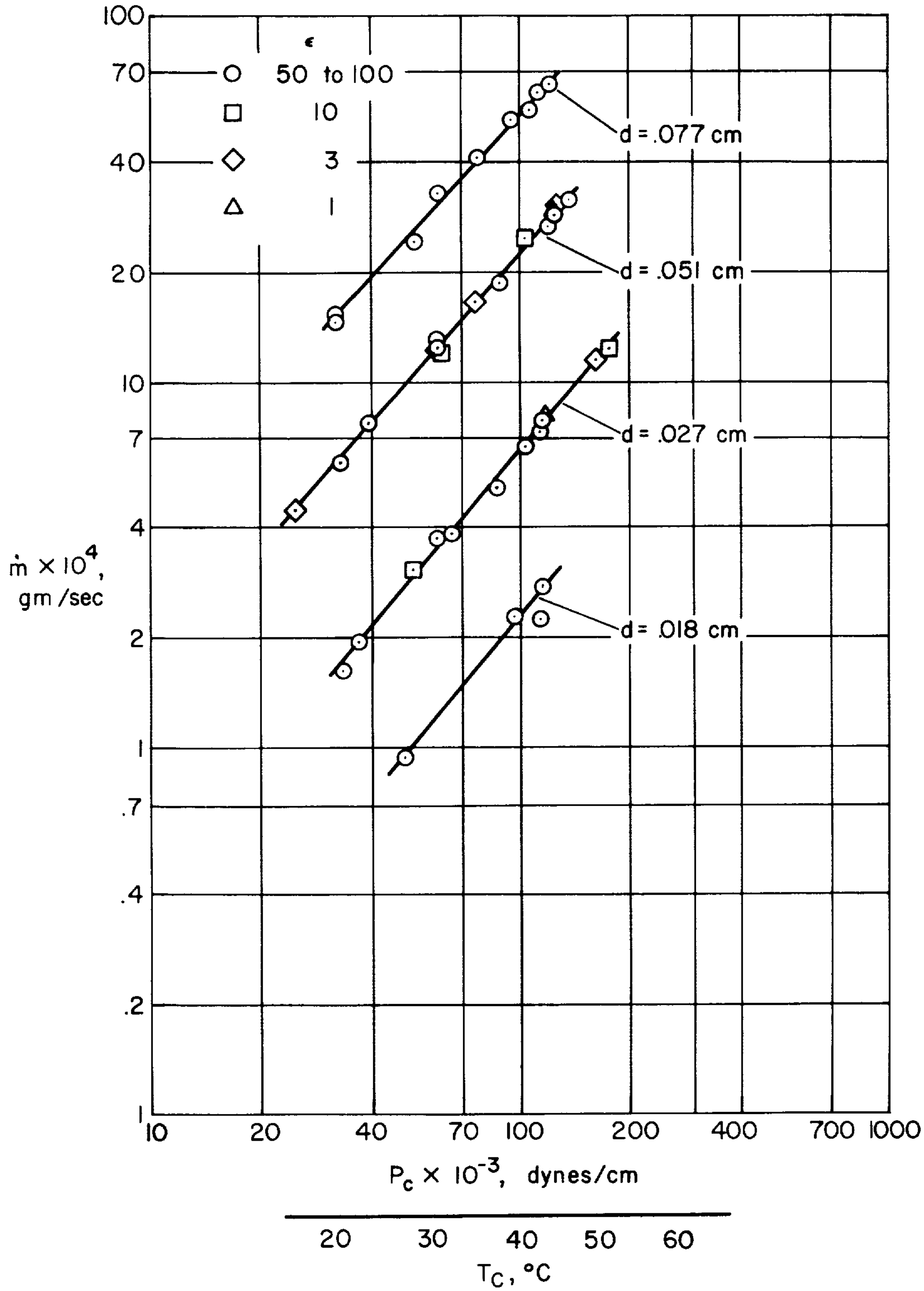
Figure 3.- Calculated performance of nozzles for isentropic flow for a vapor generator temperature of 48.9° C.

A 5 7 9



(a) Thrust.

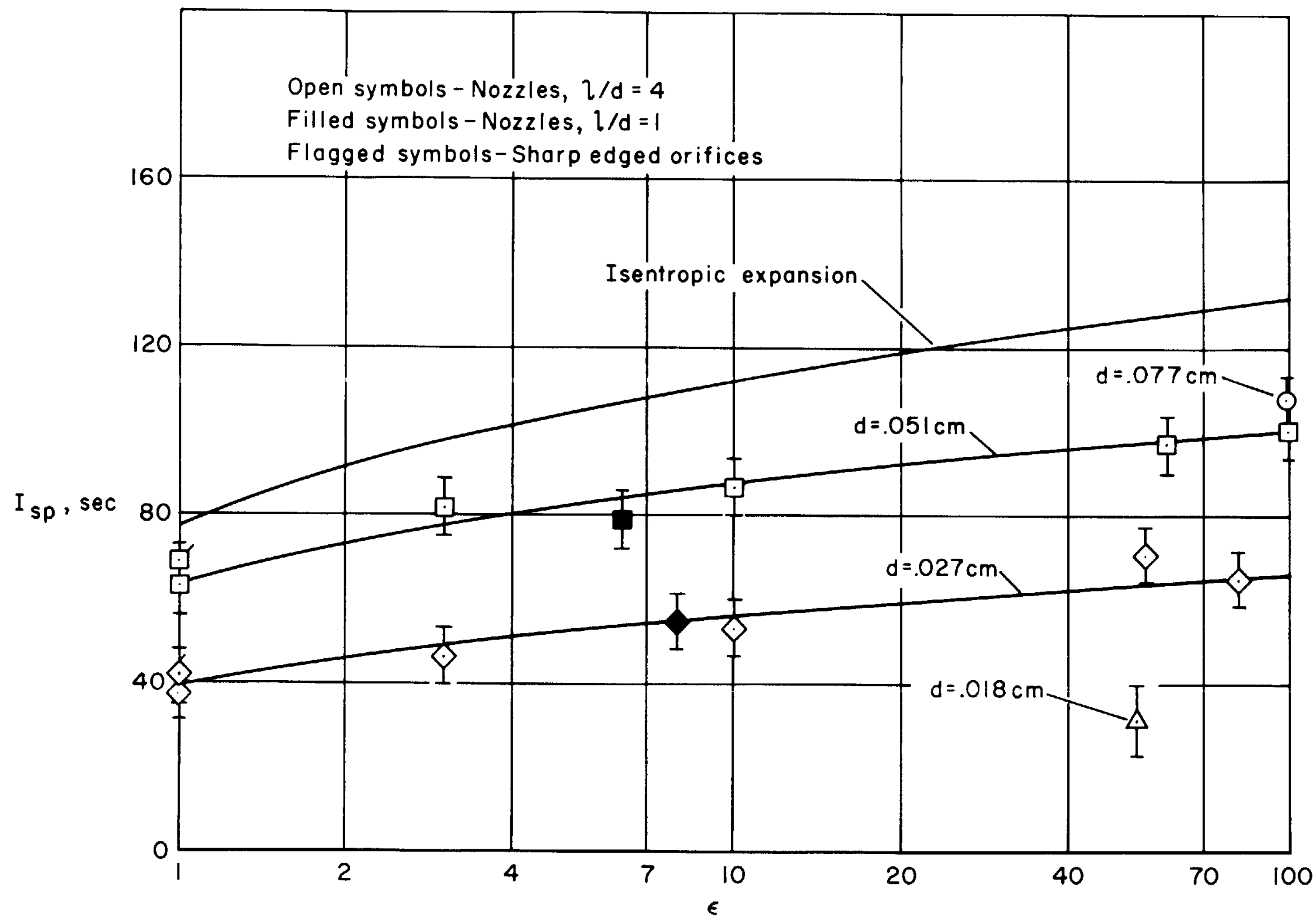
Figure 4.- Typical test results for convergent-divergent nozzles; $l/d = 4$.



(b) Mass-flow rate.

Figure 4.- Concluded.

A
5
7
9

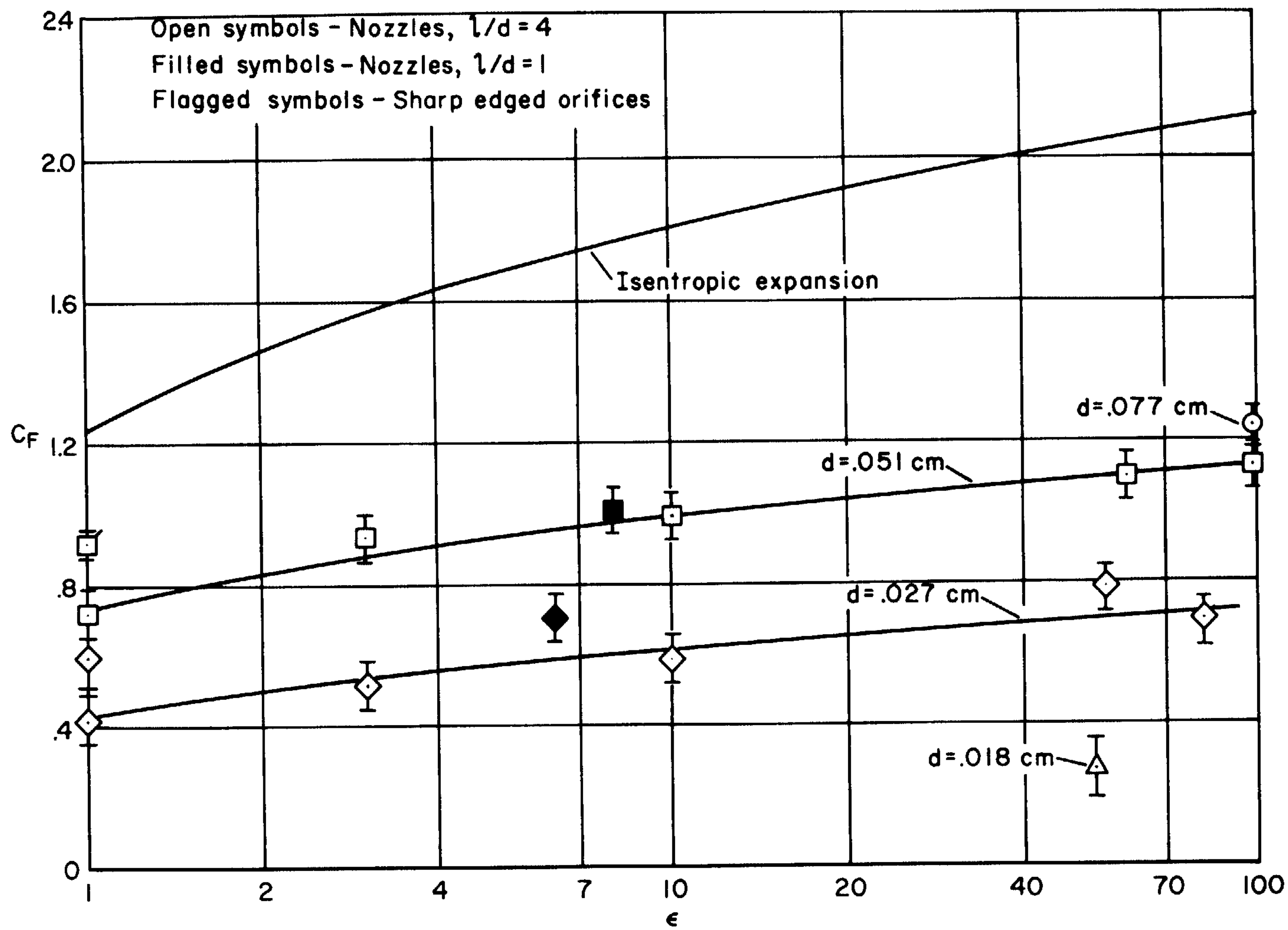


(a) I_{sp} vs. ϵ

Figure 5.- Variation of measured performance parameters with expansion ratio; T_C = 48.9°.

A 5 7 9

2D



(b) C_F vs. ϵ

Figure 5.- Concluded.

A
5
7
9

A
5
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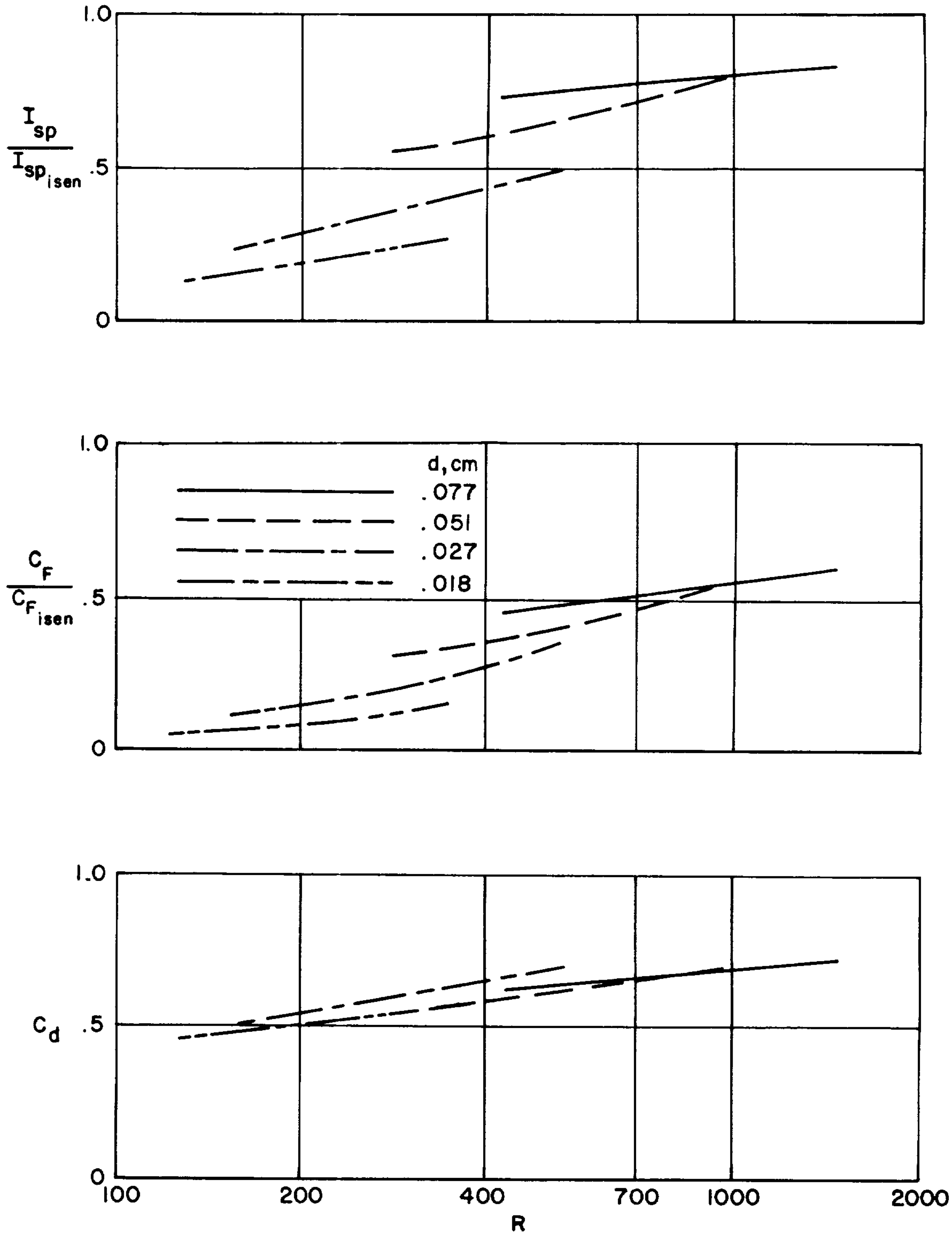

Figure 6.- Correlation of results as a function of Reynolds number; $l/d = 4$, $\epsilon = 55$ to 100.

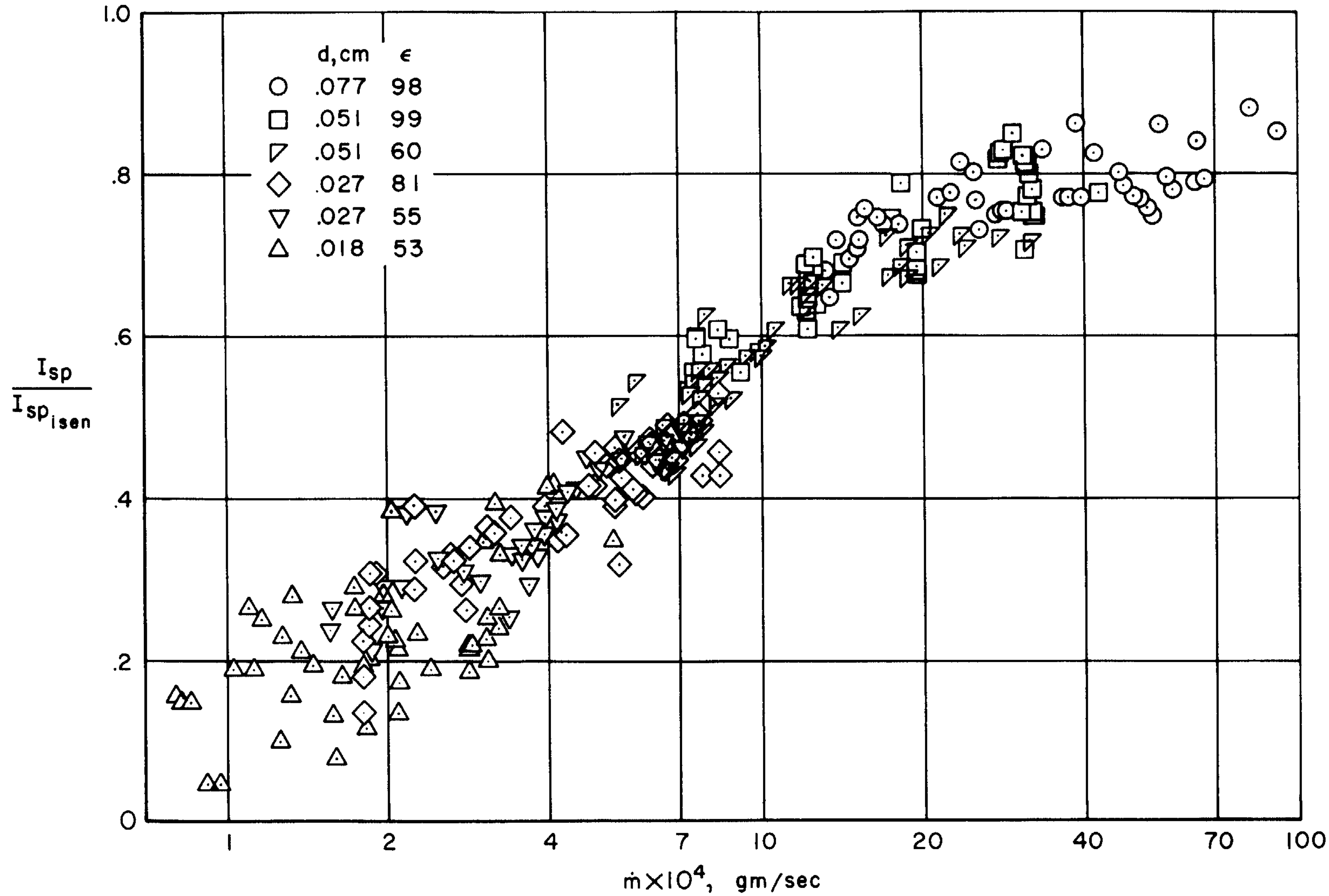

Figure 7.- Correlation of specific impulse with mass-flow rate.

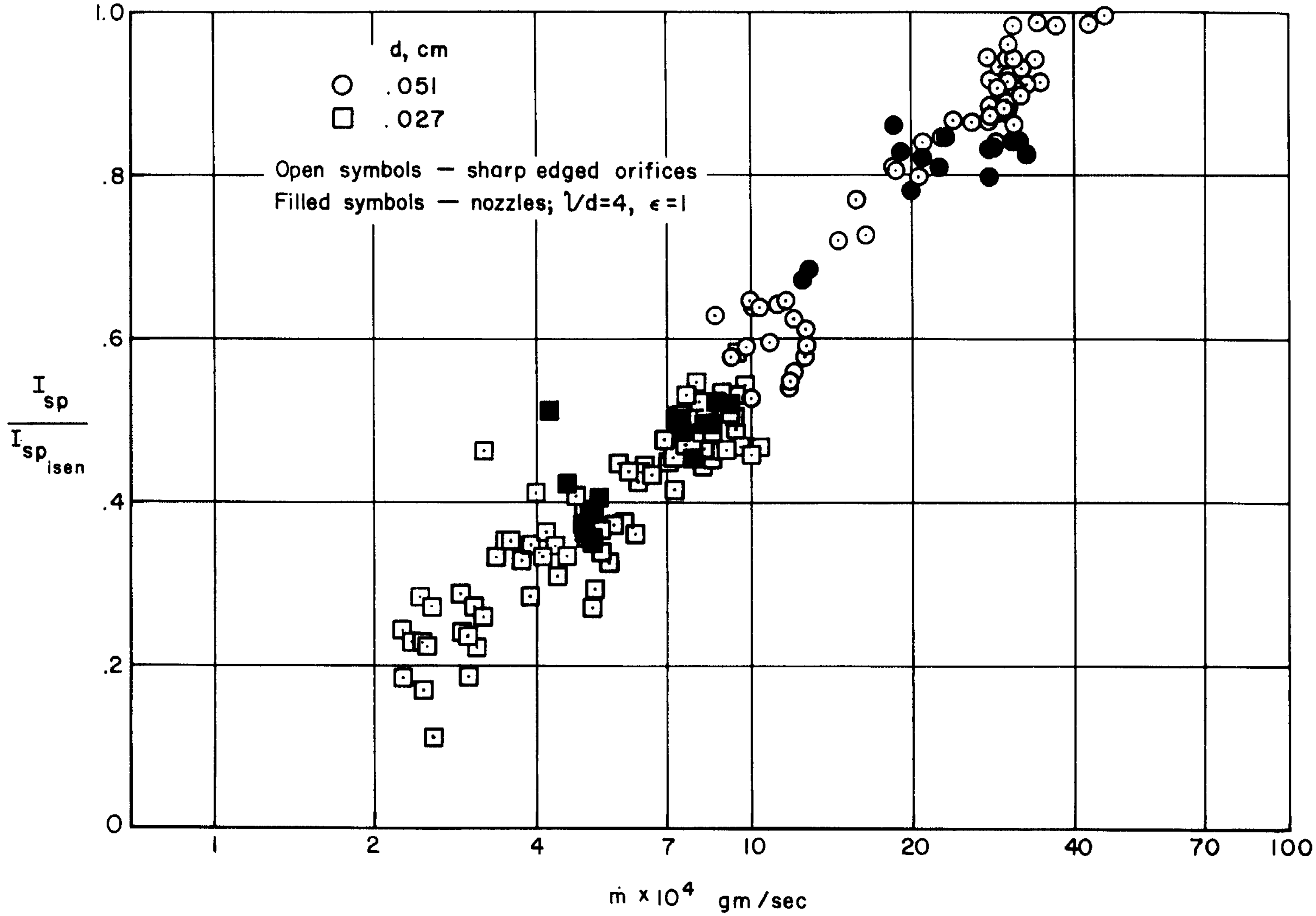

Figure 8.- Effect of throat geometry on correlation of specific impulse with mass-flow rate.

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