THE UNIVERSITY OF MICHIGAN
College of Engineering
Department of Mechanical Engineering
Cavitation and Multiphase Flow Laboratory

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SCALE EFFECTS INCLUDING GAS CONTENT UPON CAVITATION IN A FLOWING SYSTEM

by: Frederick G. Hammitt
David M. Ericson, Jr.

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ABSTRACT

The cavitation scale effects relating to gas content, throat velocity, throat diameter, and temperature are examined for a cavitating venturi using water and mercury as test fluids. The prediction of variation of cavitation number in terms of these variables is discussed.

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I. INTRODUCTION

The pressure and temperature conditions under which cavitation is initiated in a flowing system such as a centrifugal pump or hydraulic turbine is strongly influenced by the gas content in the liquid. Entrained gas is thought to be the primary factor is determining the conditions necessary for bubble nucleation to a size necessary to produce observable cavitation. While the entrained gas content is not necessarily proportional to total gas content, it is certainly strongly influenced by it. The effects of fluid properties, velocity, passage geometry (including roughness), and gas effects comprise the "scale effects" which make the precise prediction of the behavior of cavitating prototype fluid machines from model tests, very difficult.

A detailed basic determination of the effects of gas upon cavitation initiation in the presence of the variation also of other parameters requires measurements of actual gas nuclei spectra in the fluid, as well as the trajectory of such nuclei through the fluid in a given flow regime. While some basic work on gas particle trajectories and their effect has been reported (1, 2), and our own laboratory and others are engaged in attempting to measure particle spectra (3), at present it is necessary to base predictions on the total gas content as well as the previous history and treatment of the water, since only these quantities may be measured or described in the usual facility.

The present paper reports on observations of cavitation initiation in geometrically similar venturi test sections using both water and mercury as test fluids. Cavitation number for initiation is presented as a function of velocity and gas content in geometrically similar venturis of different throat diameter. Some theoretical interpretation of the data is presented in hopes of assisting in the formulation of scale effect relationships for flowing machines.

II. EXPERIMENTAL FACILITIES AND TECHNIQUES

Two closed-loop venturi facilities (4) were used: one for water to 150° F and 220 fps and one for mercury to 600° F and 55 fps. Both systems have some degassification capability as well as devices for increasing the total gas content above normal saturation.

Geometrically similar venturis (Fig. 1) were used for all tests, with throat diameters ranging from 1/8 to 3/4 inch. The length to diameter ratios of the cylindrical throats, and the converging and diverging cone angles in the vicinity of the throat, were the same for all venturis. Pressure taps are located near the inlet and exit of the throat as well as being suitably spaced along the diffuser. In general, plexiglass venturis were used for the water tests and for the room-temperature mercury tests. For the high-temperature mercury tests (270 and 400° F), stainless steel venturis were used. The total gas content for both fluids was measured using an adaptation of the standard Van Slyke apparatus. No separate entrained gas measurements were attempted.

Only air was used in the water tests, while injected argon was mixed with the irreducible air residue in the mercury tests. For both systems the mean radius of entrained bubbles observed photographically in the region of the venturi throat discharge, but just upstream of the start of cavitation, was 0.1 to 0.2 mm. More complete details of the equipment and test procedures are given elsewhere (5, 6).

Results are presented in terms of cavitation number defined as in eq. (1):

$$\sigma_c = \frac{(p_{min} - p_v)}{\rho V_t^2/2} \quad \text{- - - - - - - (1)}$$

In all tests the axial pressure profiles were measured, to establish the minimum pressure for eq. (1). In most cases this was the lowest measured pressure which was usually that at the last tap in the cylindrical throat just slightly upstream of the start of the diffuser. For cavitation inception which is the subject of these tests, the minimum pressure presumably occurs near the wall discontinuity marking the entrance to the diffuser. Pressure measurements with similar venturis have also been taken for more fully developed cavitation (5, 7) and it has been observed that the pressure minimum sometimes occurs within the diffuser. In some of the present measurements, as explained later, it was assumed that the pressure gradient in the cylindrical throat, presumably due largely to friction, will continue linearly to the diffuser entrance. Thus an extrapolated minimum pressure at this point was used in these cases.

It has sometimes been reported in water tunnel tests (8, e.g.), that there is a cavitation "hysteresis" between "incidence" (inception) and "desinence" (disappearance). This effect was not observed in the present tests.

III EXPERIMENTAL RESULTS

A. Water Tests

1. Water History Effects

It is generally supposed that nucleation in cavitation or boiling is largely the result of permanent and/or gas "nuclei" which grow under the reduction of pressure or addition of heat beyond a critical radius, such that subsequent growth becomes "explosive" and visible or audible bubbles appear. It is clear that for a given total gas content the ambient size and number of such nuclei depends upon the previous pressure history of the liquid which affects the distribution between entrained and dissolved gas quantities. This dependence upon liquid prepressurization has been observed in the past by other cavitation investigators (8,9) and experiments are presently continuing in our own laboratory (10). Fig. 2 (5,6) presents data from our water venturi showing the effect of prepressurization to 20 atm. for several hours. One to two hours of loop operation are required for the effect of the prepressurization to disappear, and it can affect the cavitation number quite substantially.

2. Cavitation Number vs. Velocity and Gas Content

Tests were made in geometrically-similar venturis with throat diameters ranging from 1/8 to 3/4 in. (1/8, 1/4, 1/2, and 3/4 in. were used), but the majority of the measurements were in the 1/2 in. section, with a substantial number at 1/4 in. Hence, these portions of the data are emphasized. In most cases, the minimum pressure was assumed to be the minimum measured pressure, i.e. the pressure at the last pressure tap in the cylindrical throat. In some cases, to be discussed, a linear extrapolation of pressure was made in the cylindrical throat to the diffuser entrance, and this extrapolated pressure considered as the minimum value. While this procedure may give a useful correction, it cannot be verified experimentally or theoretically (unless friction effects alone are important), and hence was not used in general.

Fig. 3,4, and 5 are typical of the data obtained. Fig. 3 is for the 1/2 in. venturi where the cavitation number is defined in terms of the minimum measured pressure, while Fig. 4 is for the case where the minimum pressure is extrapolated. Fig. 5 is analogous to Fig. 3, but for the 1/4 in. venturi. Generally all figures show an increasing cavitation number with increasing gas content.

Fig. 6, 7, and 8 are cross-plots of these data sets, respectively. The data has been extrapolated to estimate the approximately zero gas content condition, and in each case shows the variation of cavitation number with throat velocity as a function of air content. All these curves show, for high gas content, a decrease to a minimum in cavitation number, and then an increase. In some cases, for very low gas content, a continual increase of cavitation number with velocity is indicated. The results are quite similar to some obtained earlier by Ripken and Killen (11) for an ogive in a test section, and the high gas content results are similar to some previously reported by Jekat (12) for a cavitating inducer. While the present venturi curves (Fig. 3,4,5) are generally similar to each other, they are not identical as is indicated by Fig. 9, which compares the 1/4 in. and 1/2 in. results at selected gas contents.

3. Cavitation Number vs. Reynolds Number

It has often been supposed that differences in size and velocity effects in cavitation inception measurements might be resolved by plotting against Reynolds number. This hypothesis is at least partially justified on theoretical grounds since turbulence levels and boundary layer effects are functions of Reynolds number, and some limited success with such plots has been achieved in the past (7, 12, 13, e.g.). Fig. 10 shows such a Reynolds number plot for the present water data for all the venturi sizes. It is noted that Reynolds number does not succeed in grouping all this data into a single curve.

B. Mercury Tests

The mercury tests were conducted in a similar fashion to the water tests, although the results were quite different. The difference may be partly due to the added experimental difficulties with mercury in obtaining good measurements of gas content as well as maintaining homogeneous gas-liquid mixtures. However, different results might also be expected because of the vastly different ratios of entrained to dissolved gas to be expected with mercury, or indeed with any liquid metal, since the solubility for the gases used (air or argon) in mercury are essentially nil as compared with the solubilities in water. Nevertheless, the total gas contents used were of the same order of magnitude. Fig. 11 shows results for a 1/2 in. venturi in room temperature mercury in the format analogous to Fig. 6, 7, and 8 for water. As expected, the cavitation number is generally higher for higher gas contents.

However, for low velocities it rises sharply for increasing velocity for almost all gas contents (as opposed to the water results). It does become more similar to the water results for high velocities. More complete details of the mercury tests are reported elsewhere (5,6).

IV. DISCUSSION OF RESULTS

A. Gas Partial Pressure Model

The composite water results as shown in Fig. 6, 7, and 8 can in part be approximately justified if it is assumed that the nuclei giving rise to cavitation nucleation contain some partial gas pressure in all cases which is proportional to the total gas content.* Assuming the number and size of bubbles also increases with total gas content, which appears visually to be the case, the entrained portion increases more than proportionately to total gas volume as the total volume is increased. Using the approach suggested by Holl (6) in interpreting his experimental data for a submerged body in a water tunnel, a partial cavitation number based on the gas pressure alone can be defined. To obtain the total cavitation number, this partial number must be added to that for zero gas content.

$$\sigma = \sigma_o + \sigma_\alpha$$
$$\sigma_\alpha = p_a/(\rho V_t^2/2) \qquad \text{- - - - - - - - - (2)}$$

This model is approximately consistent with the data shown in Fig. 6, 7, and 8. It is closely consistent (6) with that of Fig. 7, for which the cavitation numbers were taken from a pressure profile extrapolated to the diffuser entrance from the existing taps in the cylindrical throat. Fig. 12 shows the comparison between measured and computed gas cavitation numbers if these are made to coincide at a throat velocity of 200 f/ s. From Fig. 7 it can be computed that the gas pressure for all test conditions in the cavitating region is approximately 1.50 psi per volume percent of total gas, at standard temperature and pressure (STP), i.e., the gas pressure computed from this data is always proportional to total gas content. It can also be seen in Fig. 7, comparing data at 100 and 200 f/s, that the gas cavitation number is closely proportional to velocity squared as it would be if the gas pressure were constant as assumed.

Fig. 6 and 8 give results generally similar to Fig. 7, although in Fig. 6 the gas cavitation number is more than proportional to velocity squared between 100 and 200 f/s (ratio is about 6 rather than 4 as required). On the other hand, Fig. 8 is closely consistent with the hypothesized in this respect. An estimate of the gas pressure in the nuclei in the cavitating region from Fig. 6 for the 1/2 in. venturi (using the actual measured pressure near the throat exit to compute cavitation number) gives about 1.0 psi, while an estimate for the 1/4 in. venturi (Fig. 8) computed in the same way gives 0.34 psi. (Table I).

The hypothesized model is clearly not consistent with the mercury data shown in Fig. 11, since the gas cavitation number therein first increases with velocity and then decreases. However, the gas pressure can be estimated for the maximum gas effect which occurs at 33 f/s. It is then found (Table I) that the gas pressure per percent total gas volume is considerably larger than for the water cases (5.8 psi). This seems reasonable since relatively very little of the gas can be in solution in mercury.

As shown in Table I, k varies widely for the different conditions but averages about 0.9 psi/percent total gas volume STP for water and 5.8 for mercury. The variation between water tests is partly due to the different methods used for computing cavitation number, and also because of inadvertently different pretreatment (pressurization, settling, etc.) of the water for different tests. A scale effect may also be involved between the 1/2 and 1/4 in. venturis since the time for passage and bubble growth differs between the cases.

B. Scale Effects for Cavitating Venturi

The foregoing discussion indicates that at least for water the division of the overall venturi cavitation number into two additive portions is a reasonably realistic model. That is, we assume one part is the result of a gas pressure within the bubbles in the cavitating region that is only a function of total volumetric gas content to which it is proportional for a given test. The other part is presumed to be a cavitation number which would be obtained for substantially zero gas content, and that is a function of velocity, throat diameter, temperature, etc. The constant of proportionality, k between gas pressure and total volumetric gas content depends upon previous pressure history of the water, probably temperature and other variables. Presumably it must be measured for a given test set-up. Unfortunately, however, the model is not applicable to the mercury tests.

What remains then is to delineate the scale effects relating to zero gas content for a given test arrangement in order to obtain an estimate of the full variations of cavitation number for the venturi. It is to be expected (5) that this will be a function of various parameter groupings such as Reynolds number, thermodynamic parameter, B (14, 15, e.g.), Weber number, and also time of exposure to underpressure. Unfortunately, however, extensive regression analyses have failed to show any good correlations for the present data set in these terms (5). Attempts to show the individual effects of temperature, throat diameter, and velocity (or Reynolds number), using computerized regression analyses, have previously been reported (6), and also did not give really satisfactory results.

An examination of Fig. 6, 7, and 8 (which summarize the water results) indicates the difficulty. In Fig. 6 the zero gas cavitation number rises slowly with velocity (concave upward). In Fig. 7, it rises sharply with velocity but is concave downward; while in Fig. 8 it falls at a decreasing rate with velocity. Hence the velocity effect cannot be simply isolated. Between Fig. 6 and 7 on one hand and 8 on the other, there is a decrease in throat diameter by a factor of 2, but the effect of this size variation cannot be isolated from the velocity effect. Previous work (6), based on a statistical analysis of a large body of data, did show an increase by a factor of about 7 in cavitation number for low gas content as throat diameter is increased (1/4 to 1/2 inch). In the present data the 1/2 inch zero gas cavitation number is about 2 times that for 1/4 inch at 100 f/s throat velocity (i.e. zero gas cavitation number is proportional to diameter) and about 30 times it at 200 f/s (which is perhaps an unreliable estimate since the 1/4 inch cavitation number is near zero at this condition). Thus it might be assumed, but only as a very rough approximation, that zero gas cavitation number is proportional to throat diameter.

Previous work (5) has indicated that zero gas cavitation number is a weak function of the thermodynamic parameter (14, 15, e.g.), varying approximately as the 1/4 power of this function.

The trends summarized above can be assembled into a very rough predicting equation for cavitation scale effects for a venturi. In lieu of more precise information, it may be assumed that this will apply very roughly also to hydraulic machinery.

$$\sigma = \sigma_a + \sigma_o \simeq \frac{k\alpha}{\rho V_t^2/2} + C_1 \left[D_t \, B^{1/4} f(V_t) \right] \quad \text{- - (3)}$$

$$\frac{\sigma_{o_1}}{\sigma_{o_2}} \simeq f\left(\frac{V_{t_1}}{V_{t_2}}\right) \frac{D_{t_1}}{D_{t_2}} \left(\frac{B_1}{B_2}\right)^{1/4} \quad \text{- - - - -(4)}$$

In the present state of knowledge $f(V_t)$ must be measured for a given case using well-degassed fluid (to approximate the "zero gas" condition). If C_1 and k are determined experimentally, then eq. (3) or (4) could be used to predict cavitation number for other reasonably similar configurations or test parameters.

V. CONCLUSIONS

The effect of gas content in a cavitating venturi has been found to be closely predictable in terms of the assumption of a gas pressure within a cavitation nucleus which is proportional to the total gas content of the liquid. This result infers that the ratio between entrained and total gas increases considerably as total gas is increased in a typical case, since the total number of bubbles also increases with total gas content.

The proportionate gas content of a cavitating mercury bubble was found to be much greater, though the general model was not applicable.

The effects of throat velocity, throat diameter, and temperature were found to be less clear-cut, but methods for predicting scale effects in terms of these variables are discussed.

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NOMENCLATURE

σ_c - - - - - Cavitation Number-defined by eq. (1)

p_{min} - - - - Minimum pressure

p_v - - - - - -Vapor pressure

ρ - - - - - -Density

V_t - - - - - - Throat velocity

σ_o - - - - - -Cavitation number for approximately zero gas content - defined by eq. (2)

σ_a- - - - - -Partial cavitation number due to gas content-defined by eq. (2)

p_a - - - - - Gas partial pressure in cavitation nuclei

α - - - - - - Volumetric percent gas content at standard temperature and pressure

k - - - - - - Proportionality constant between p_a and α-defined by eq. (2)

STP - - - - - Standard temperature and pressure (1 bar at 20^o C)

B - - - - - - Thermodynamic cavitation parameter-defined ref. 14 and 15, e.g.

D_t- - - - - - Venturi throat diameter

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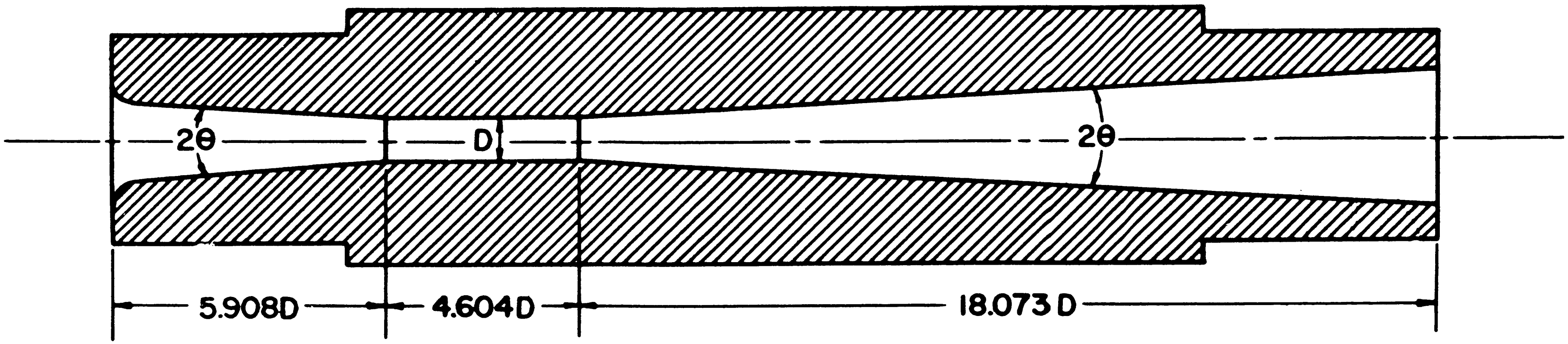
TABLE I

Fluid	Venturi Throat Diameter (Inches)	k / psi/ %vol. gas
Cold Water	1/2 (Fig. 6)	1.50
	1/2 (Fig. 7)	0.96
	1/4 (Fig. 8)	0.34
Cold Mercury	1/2 (Fig. 11)	5.80



$$2\theta = \frac{5^\circ 54'}{6^\circ 04'}$$

D = 1/2 - INCH

Fig. 1. Venturi Flow Path

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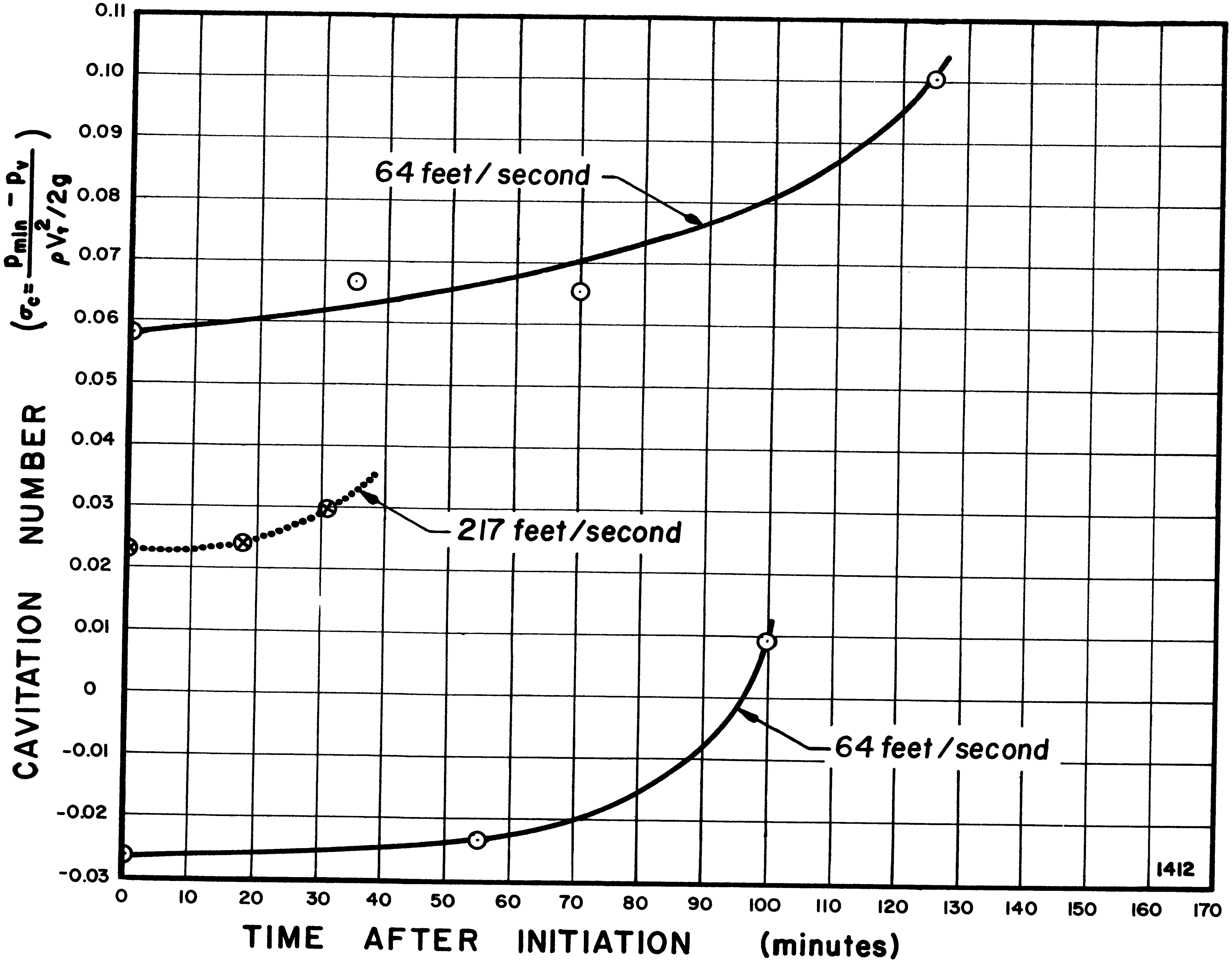

Fig. 2. Prepressurization Effects of Cavitation

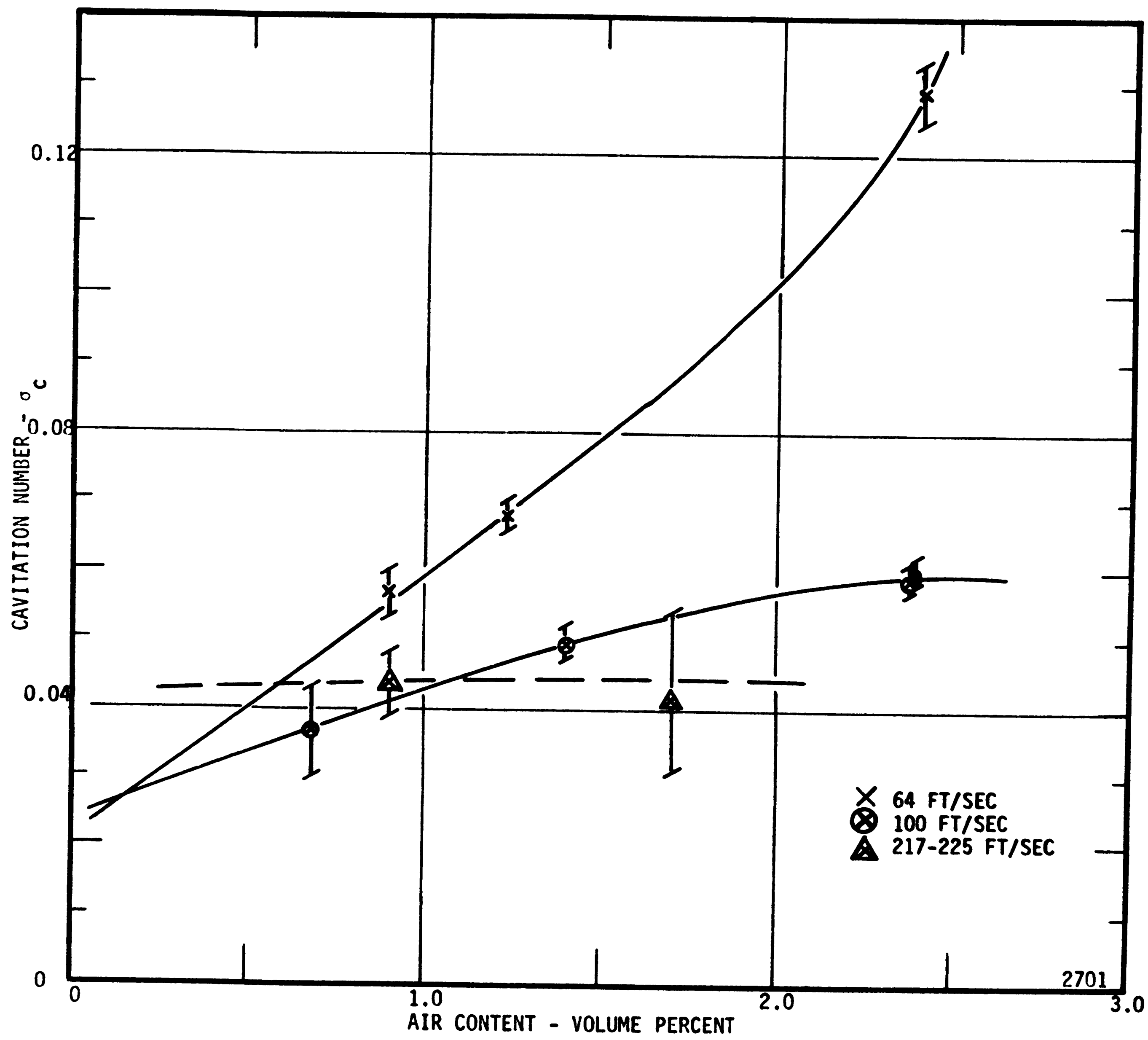

Fig. 3. Cavitation Number for 1/2 Inch Throat Venturi with Water (Using Pressure at last throat tap for minimum pressure)

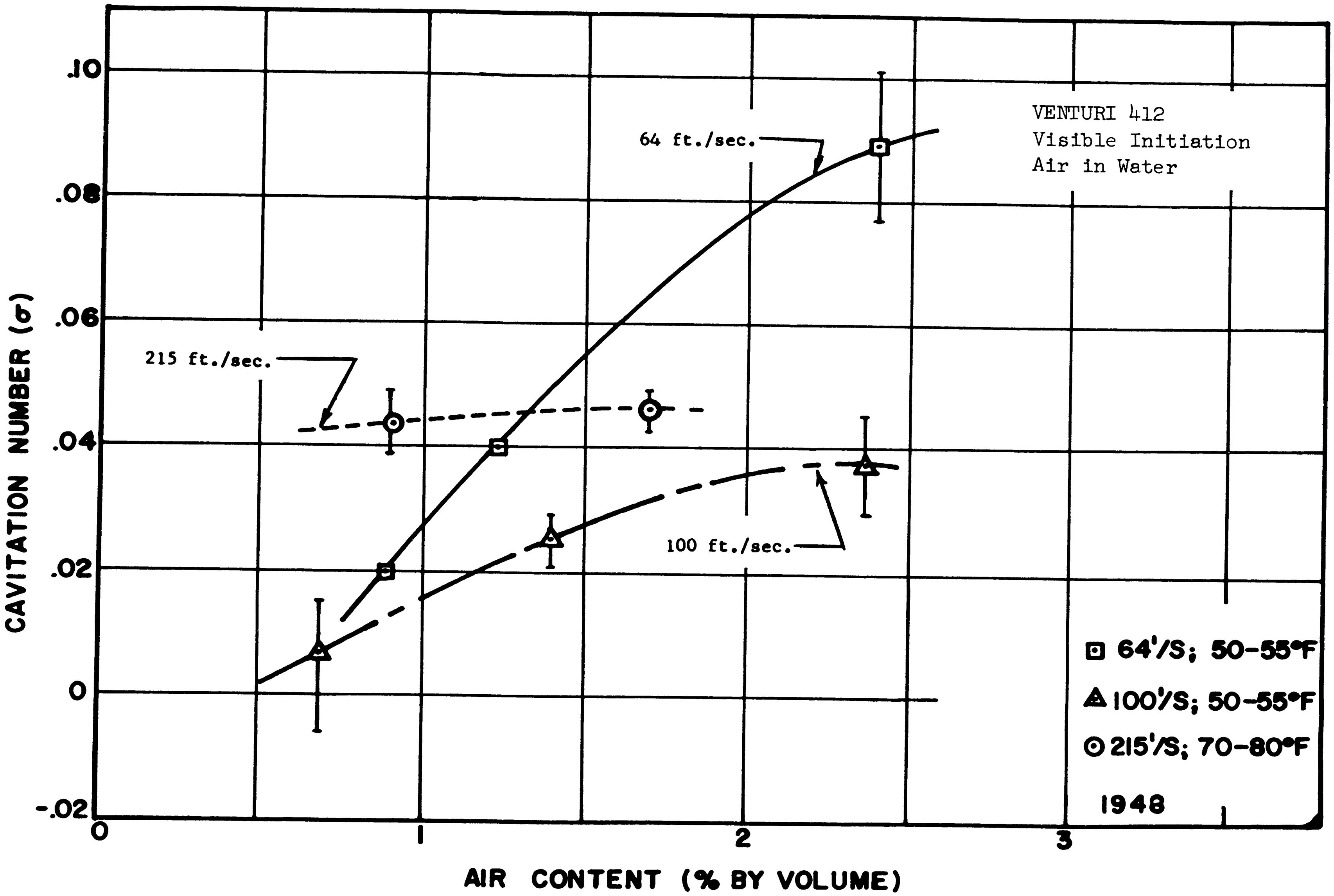

Fig. 4. Cavitation Number for 1/2 Inch Throat Venturi with Water (Using extrapolated minimum pressure)

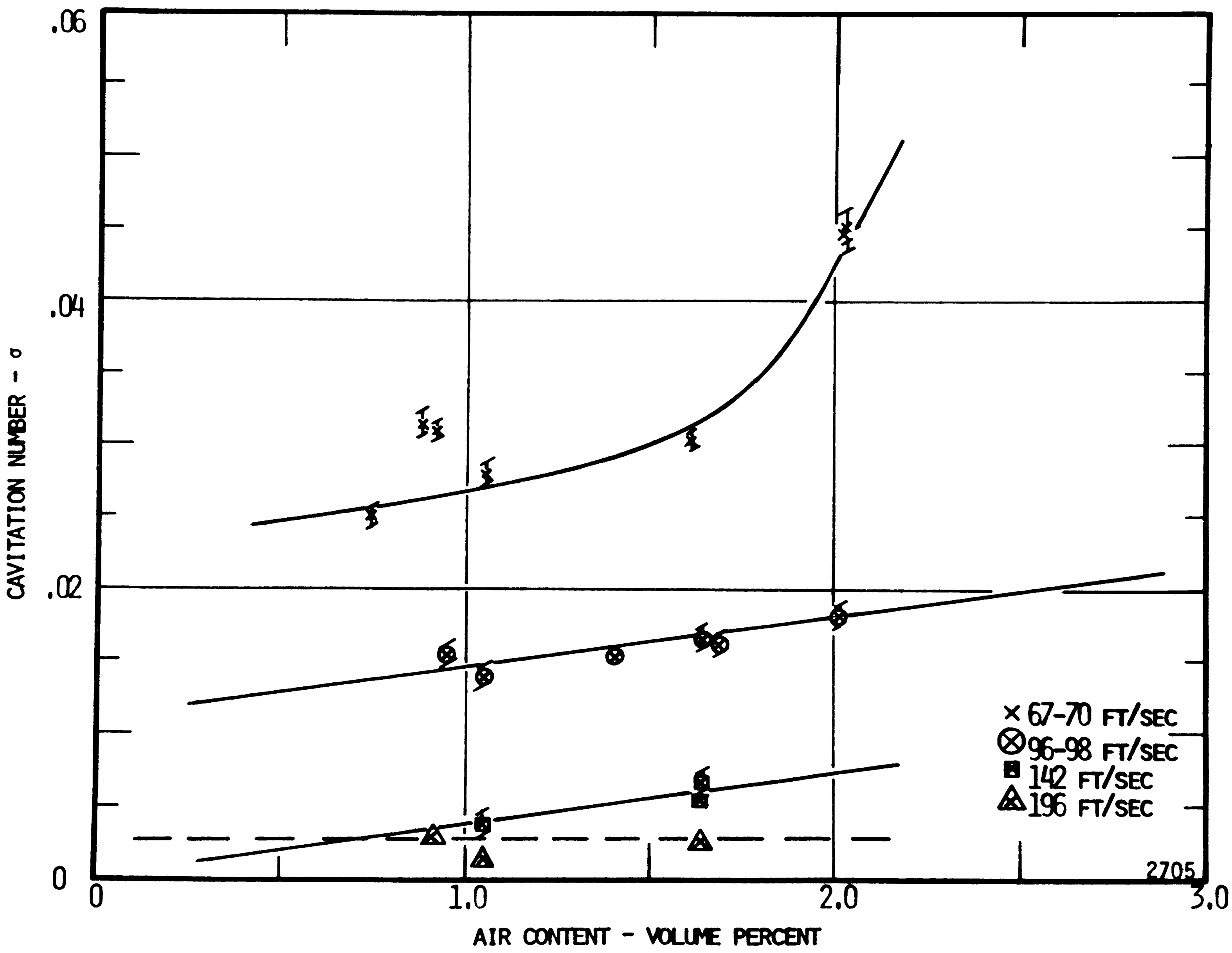

Fig. 5. Ibid., 3 -- with 1/4 Inch Throat Venturi with Water

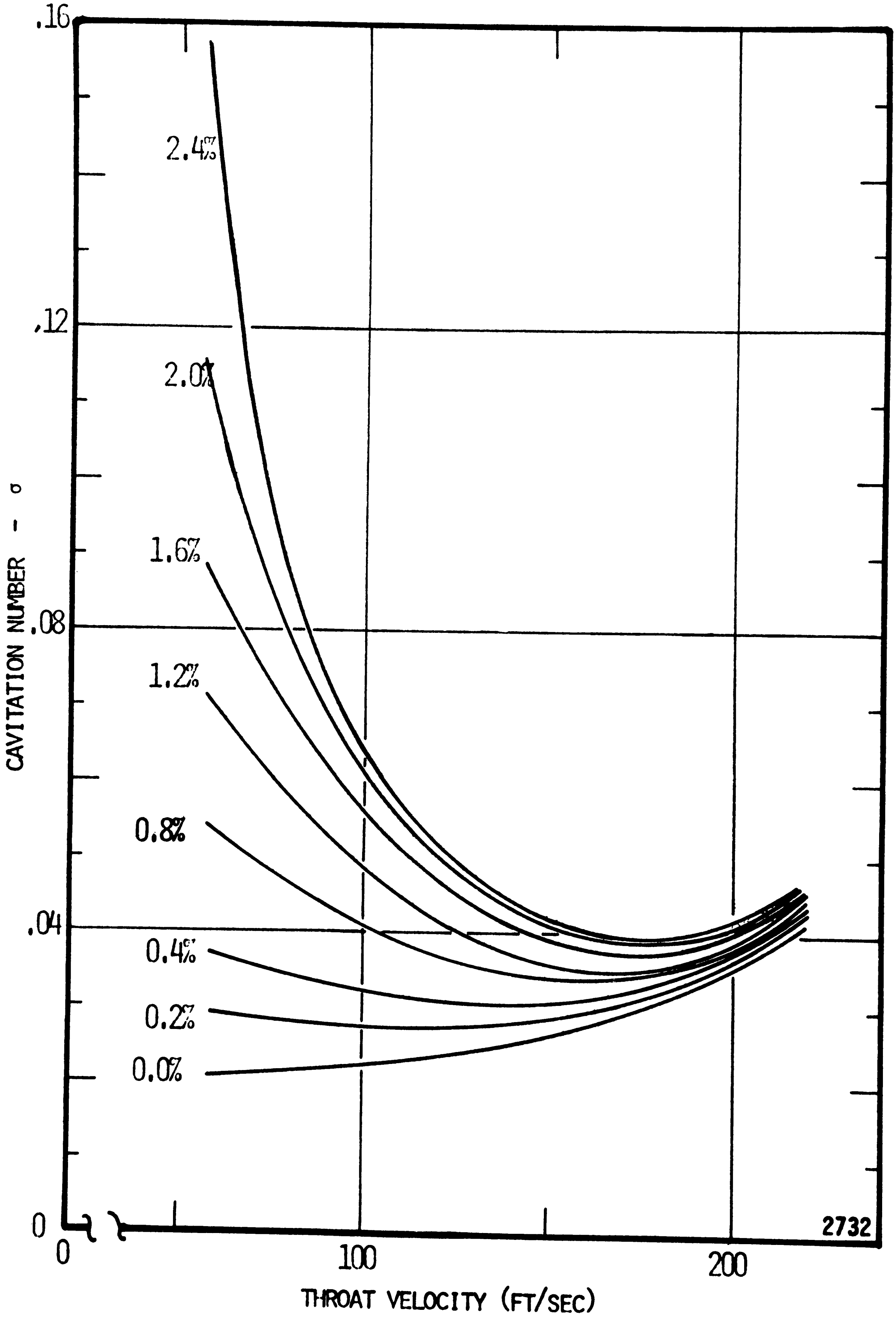

Fig. 6. Cavitation Number vs. Throat Velocity (H_2O) 1/2 Inch Venturi (Cross-plot of Fig. 3 data)

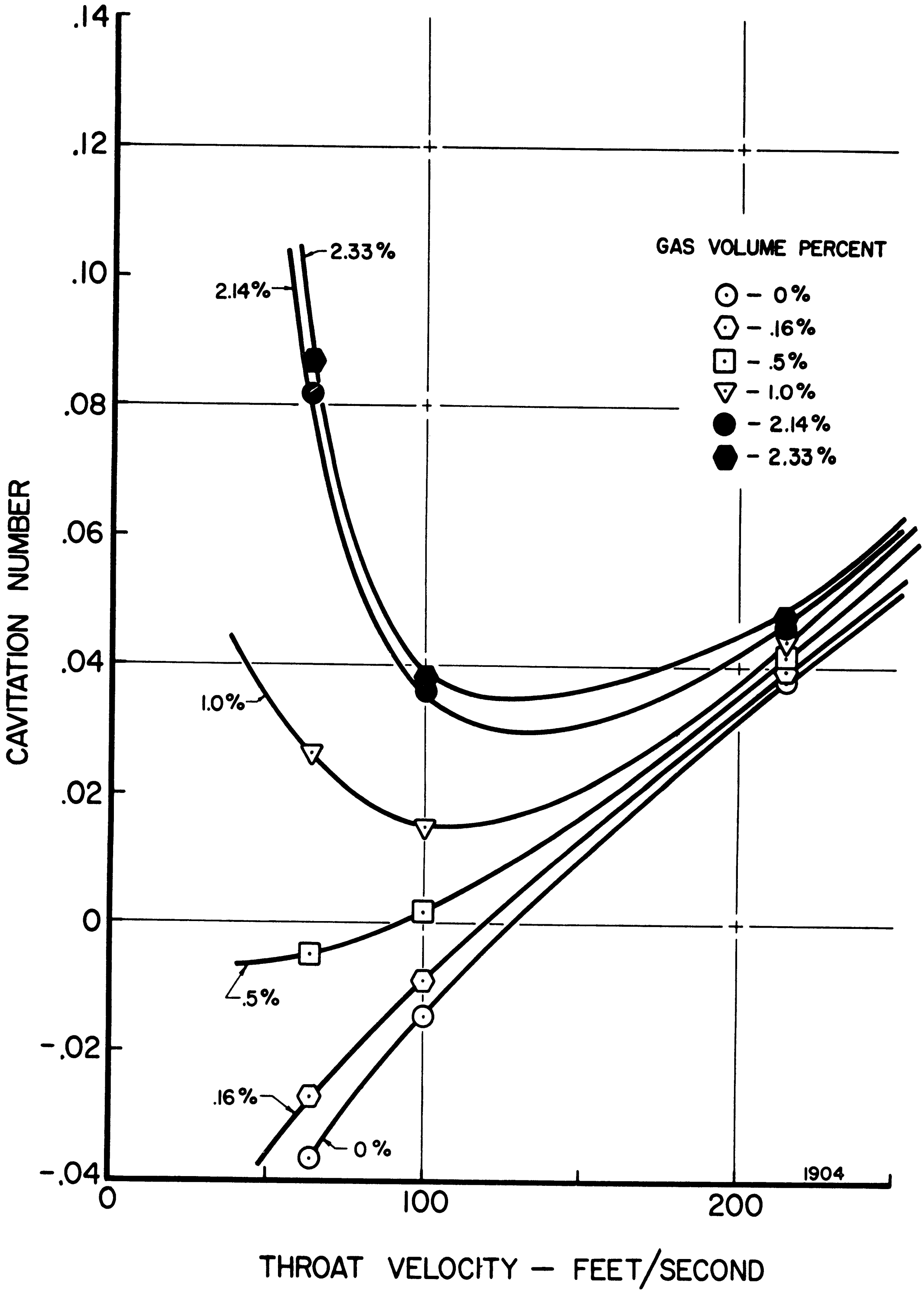

Fig. 7. Ibid., #6 (Cross-plot of Fig. 4 data)

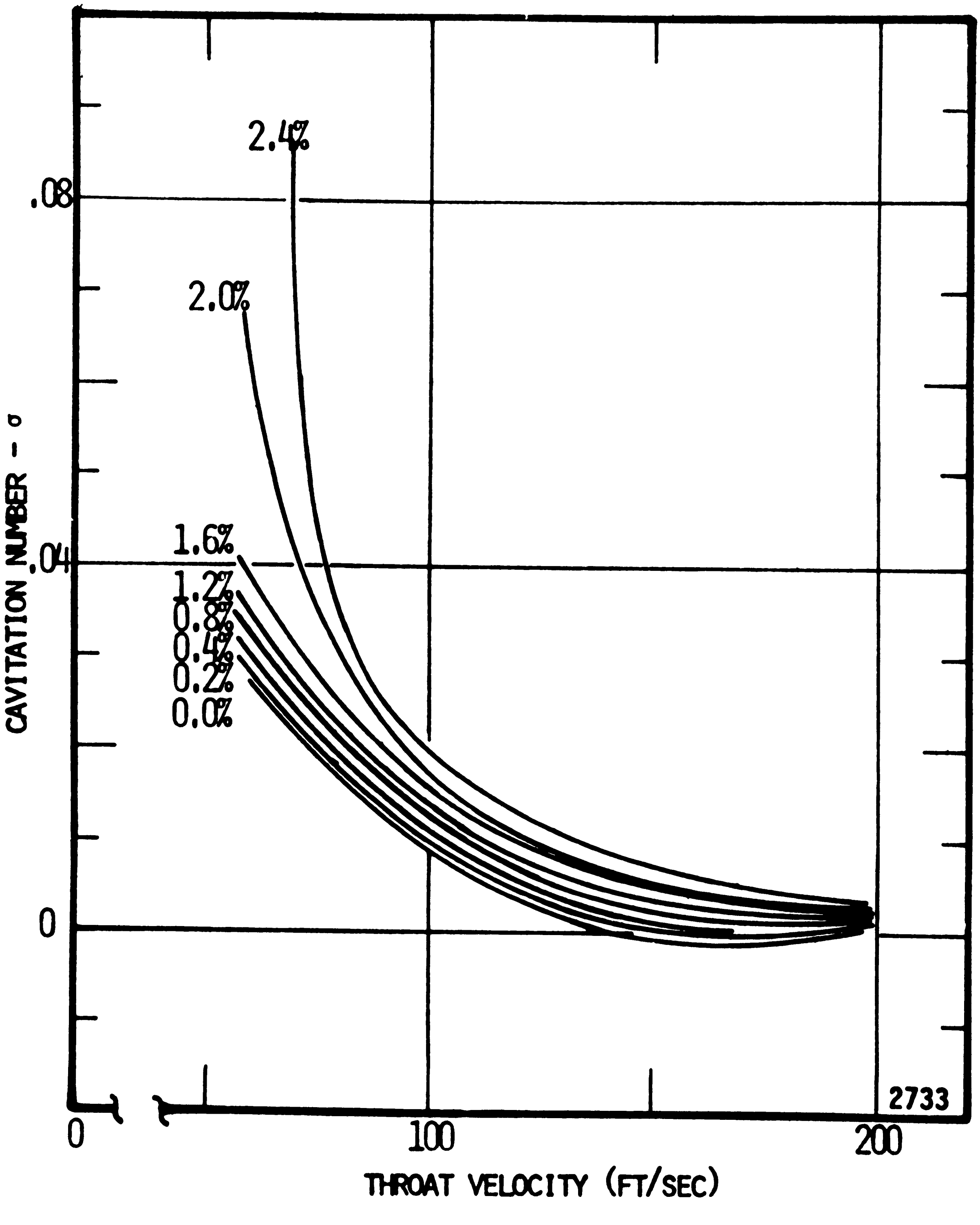

Fig. 8. Ibid., #6, 1/4 Inch Venturi (Cross-plot of Fig. 5)

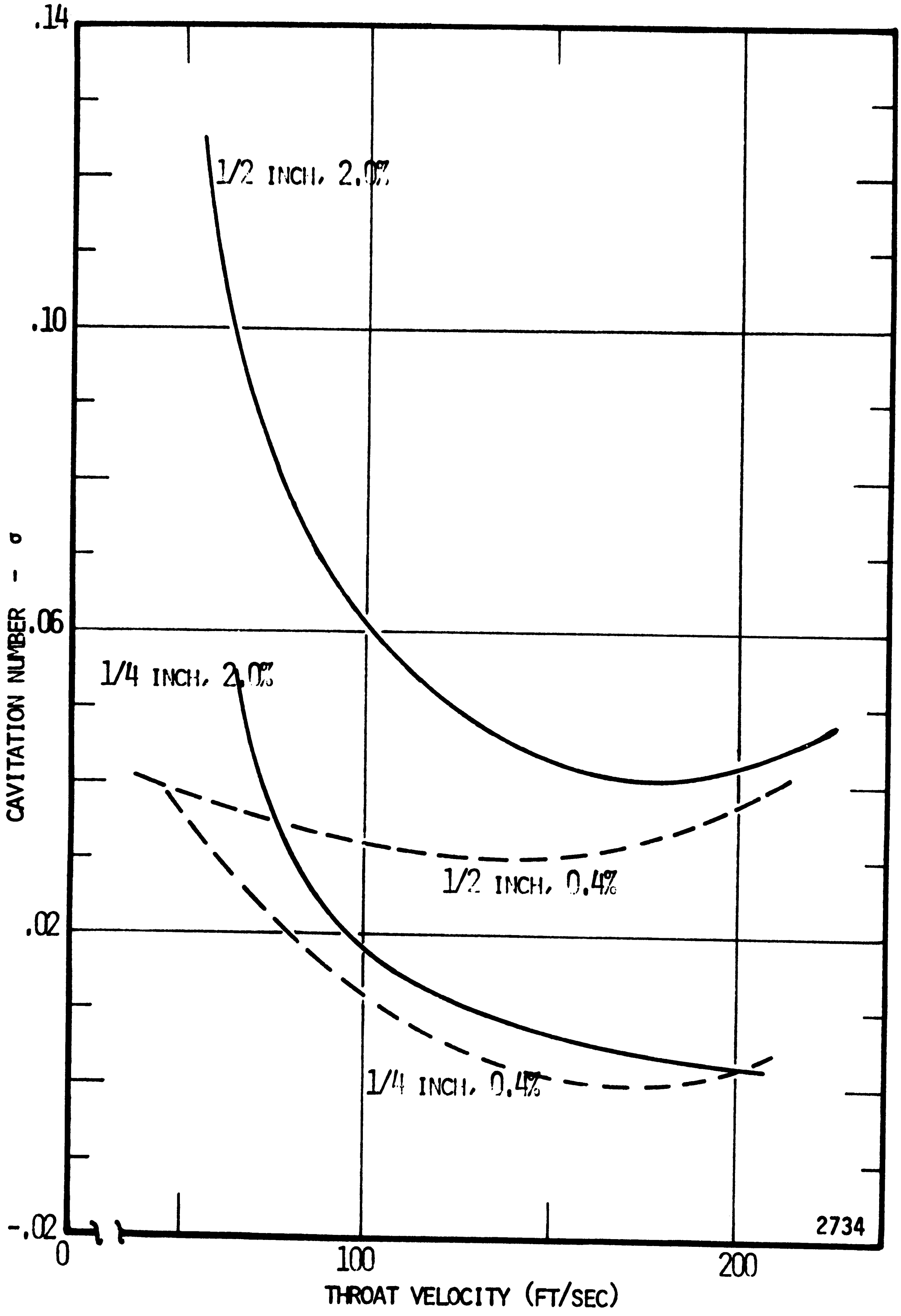

Fig. 9. Cavitation Number vs. Throat Velocity (H_2O) 1/2 and 1/4 Inch Venturis at Selected Gas Contents

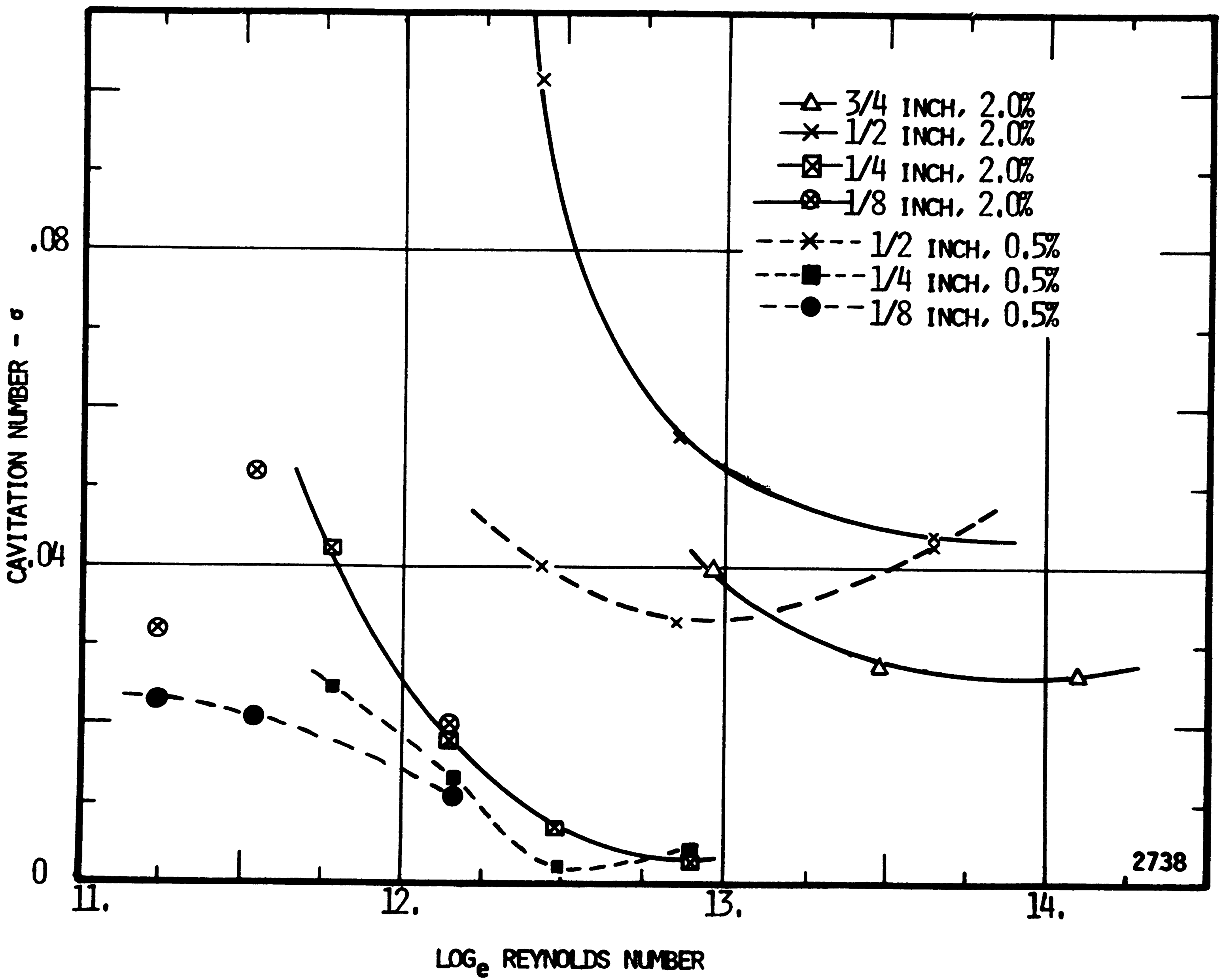

Fig. 10. Cavitation Number vs. Reynolds Number, 1/8 to 3/4 Inch Venturis, H_2O

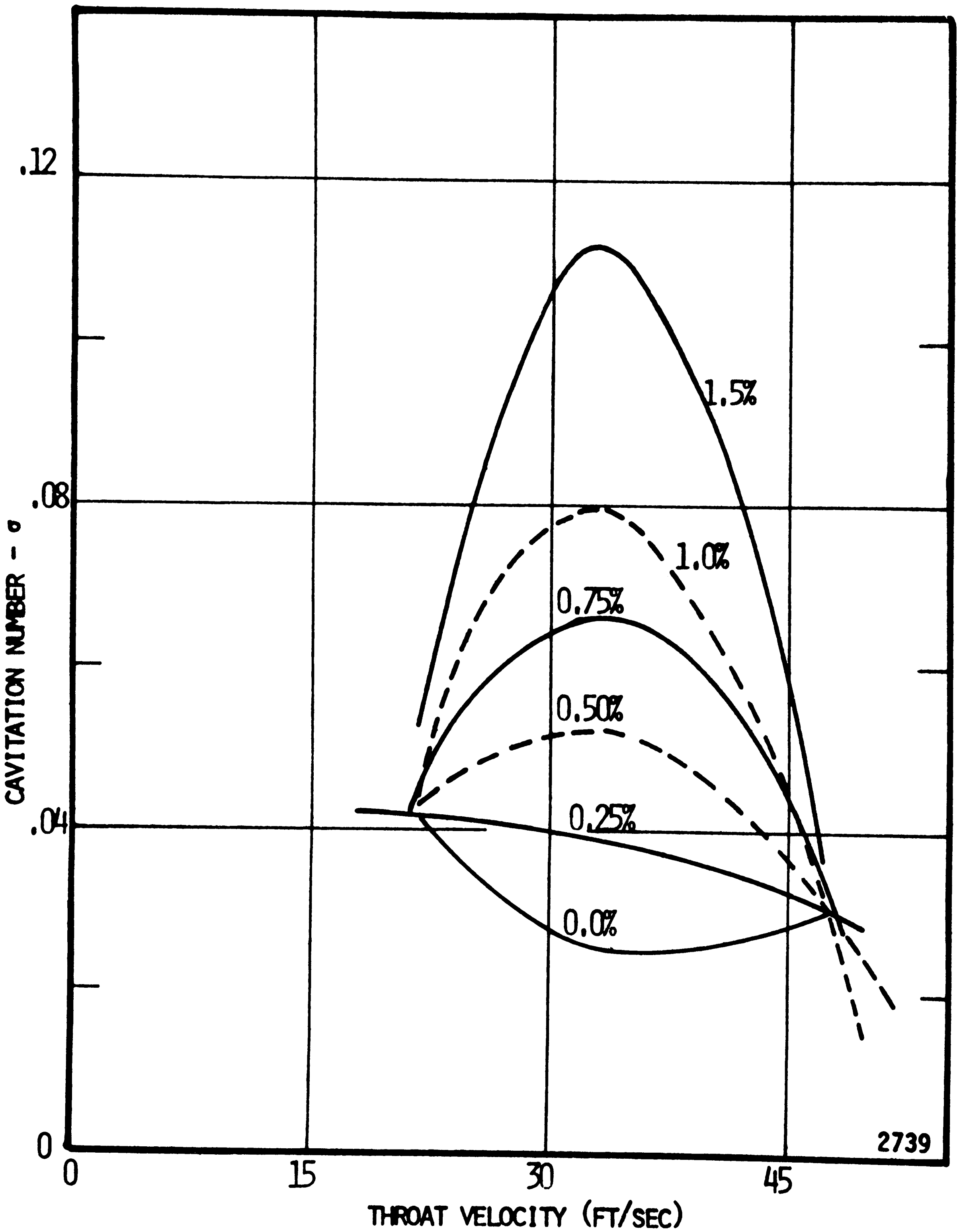

Fig. 11. Cavitation Number vs. Throat Velocity (cold Hg), 1/2 Inch Venturi (Using pressure measured at last throat tap as minimum pressure)

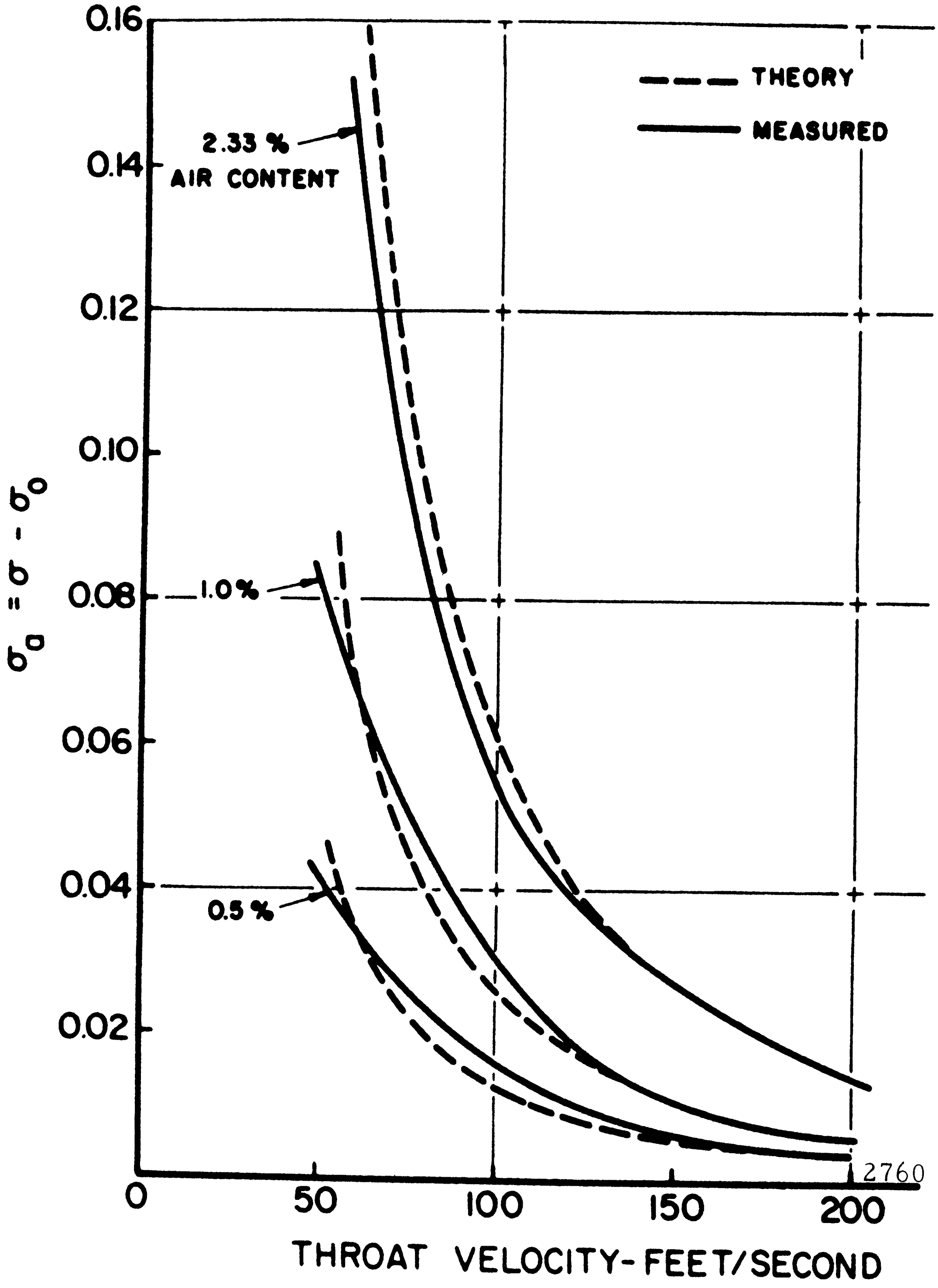

Fig. 12. Comparison of Measured Cavitation Number with Theoretical from Gas Partial Pressure Model