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EFFECTS OF GAS CONTENT UPON CAVITATION INCEPTION, PERFORMANCE, AND DAMAGE

(Summary Report for Working Group No. 1 of
Section for Hydraulic Machinery,
Equipment and Cavitation of IAHR)

by

Frederick G. Hammitt

Submitted to IAHR for publication, December 1971

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[*] Professor-in-Charge
Chairman of Working Group No. 1, Hyd. Mach. Sect., IAHR

SOGREAH Report NT. 1660, Grenoble, France

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ABSTRACT

The major past and on-going studies of the effects of gas content upon cavitation are reviewed. Those studies are considered first which provide information directly applicable to the estimation of air content effects upon cavitation inception sigma or other performance parameters. Next, studies are considered which are of a more basic nature. Finally, those studies pertinent to a prediction of the effects of gas content upon cavitation damage are discussed. In view of the overall situation as it appears at present, conclusions where possible and recommendations for future directions of research are appended.

SOMMAIRE

On a considéré les études actuelles et antérieures des effets de la teneur en gaz sur la cavitation. On considère tout d'abord les études qui donnent des renseignements applicables directement à l'estimation des effets de la teneur en gaz sur le σ de début de cavitation ou d'autres paramètres de performance des machines. Ensuite, on considère les études plus fondamentales, et enfin les études des effets de gaz sur l'érosion de cavitation. Des conclusions et recommandations pour les recherches futures sont incluses quand cela est possible.

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I INTRODUCTION

Nucleation thresholds of liquids, whether in cavitation or boiling, depend very strongly on the population and size spectrum of microbubbles (or gas "nuclei", "germes" in French) in the liquid. In addition, the violence of collapse of cavitation bubbles appears also to be strongly influenced by the quantity of gas (free or dissolved) in the liquid. Cavitation damage is thus usually found to be reduced for "gassy" liquids. While the existance of substantial effects of gas (or air) content upon both the inception of cavitation (or boiling) and cavitation damage has long been recognized, no full understanding of these effects, or any simple and reliable method for their prediction, has as yet emerged. A large quantity of pertinent, sometimes conflicting, technical literature exists. It was the purpose of the study upon which this article is based to review the most important of these past studies, and then to present whatever definitive information and trends seem justified at this time. Due to the considerable quantity of literature existing on this subject at this time, a reasonably complete report is far too voluminous for presentation in this journal. Such a report has been published (1) in the Proceedings of the IAHR Paris Congress (1971), and thus is available for the reader interested in details beyond those here included. However, due to the rather limited distribution of these Proceedings, it was felt desirable to make the present article available in this journal.

The study upon which this article and the full report (1) are based was conducted as a first task of Working Group No. 1 of the Section for Hydraulic Machinery, Equipment and Cavitation of IAHR, of which the writer of this article is the present Chairman. While the compilation of these reports is my own work, much thanks are due many of the members of Working Group No. 1 who forwarded information at their disposal or called my attention to articles of which they were aware. The conclusions regarding the overall trends indicated by the existing data are the author's own.

II AIR CONTENT EFFECTS

A. General

The effects of air content (or gas content in general) upon cavitation can be considered under 3 main headings, of which the first is probably the most important, i.e.,

1) Cavitation inception sigma

2) Flow regime, torque, power, head, efficiency, noise, vibration, etc., for well-developed cavitation

3) Cavitation erosion

There is evidence of important air content effects under each of these 3 headings. However, a major portion of the research has been concentrated under the first, and theoretical treatments are more possible in that category than in the others.

The available information can also be divided as follows:

1) That which is directly applicable to the prediction of field and laboratory performance.

2) That which is primarily of the nature of basic research, which can hopefully be used to clarify the observed trends or make meaningful predictions from observed data not directly applicable.

The above division of material is followed in the present article, and damage effects are considered separately.

B. Data Directly Applicable to Sigma and Performance Effects of Air Content (Damage not Considered)

There have been numerous fairly systematic and comprehensive studies of the effects of air content upon cavitation inception sigma, and also upon its effects, after initiation, upon overall performance parameters such as efficiency, power, etc. However, it is difficult to apply this information in general because of the large number of independent parameters having an apparently very important influence upon the results. The importance of some of these has not been recognized until recently, and it seems probable that even now insufficient understanding of the overall phenomena exists to define and construct a basic test which would provide data entirely applicable to the various prototype or model devices at this time. There are two primary reasons for this:

1) Experimental Difficulty -

No readily practical and usable method exists as yet for the measurement of the number, size, and location distribution of the very small entrained gas "nuclei" in the flow from which the audible and visible cavitation develops, the effects of which are measurable upon machine performance, etc. These "microbubbles" probably cover the diameter range of 10^{-5} - 10^{-3} cm, thus being invisible to the unaided eye. Knowledge of the total gas content is insufficient in itself.

2) Theoretical Difficulty -

It is not possible to describe in sufficient detail actual flow patterns in order to delineate the pressure and velocity history, or the trajectory, of a given gaseous "nucleus", assuming that its position and condition at a given instant of time were known by such a measurement as that discussed under (1) above. The realistic problem is 2 or 3 dimensional (depending upon the type of device), essentially biphasic in nature (even if only a question of cavitation inception), since the trajectory of the low-density entrained nuclei is not even approximately that of the liquid, if important pressure or velocity gradients exist. Finally, turbulence must be considered, since turbulent fluctuations importantly influence gas diffusion effects into and from the nuclei, as well as affecting the likelihood of cavitation inception through the application to the gas nucleus of instantaneous pressures, which may be considerably below the time-mean pressure.

Thus a complete solution of the air effects problem seems precluded at the present time. However, an improving theoretical understanding of the phenomena, the increasing availability and economy of large computers, and the continuing development of instrumentation techniques continues to substantially reduce the gap between the possibilities of basic investigations and their direct application to model and prototype devices. Thus comprehensive experimental programs planned today are likely to be considerably more fruitful in providing information of more general applicability than those planned and conducted many years ago. Of course, the earlier investigations proved the existance and importance of air effects upon cavitation, and thus motivated the continuing study of this problem. Such studies appear to date from the 1930(s). These are considered in the following and in more detail in the original report (1) under the continuing efforts of various institutions, universities, companies, etc, rather than as isolated papers by individuals. Of course only a few key people are generally associated with each such group.

1. F. Numachi and T. Kurokawa, Institute of High Speed Mechanics, Tohoku University, Sendai, Japan (2-7).

This group in the late 1930(s) apparently conducted the earliest comprehensive investigations of the effects of total air content upon cavitation sigma. Both a venturi test section and an isolated profile were used. Tests were in distilled water, tap water, and salt water (2-6). Water temperature covered the range 10 - 40°C, and air content 0.3 - 1.3 saturation at STP measured by Van Slyke[*]. In general, they obtained a fairly linear

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[*] Ref. 38 gives an excellent description of this and other systems for measurement of air or gas content.

rise of inception sigma with air content, with more effect noted at lower temperature. The change in sigma was considerable, ranging from up to 10-fold in the venturi to 20-50% for profile tests. Fig. 1 is typical of their results.

2. H. Edstrand, H. Lindgren, and C. A. Johnson, Swedish State Shipbuilding Tank, Goteborg, Sweden (8-10).

This group has reported a very comprehensive series of experiments on the effects of air content on inception sigma and other performance parameters of marine propellors in both tap water and sea water (1946-1950, Ref. 8 and 9). Recent data from the same installation is found in Ref. 10. They noted a substantial effect of relative air content (i.e., relative to saturation at STP) with efficiency ranging between 0.23 and 0.73, as relative air content drops from 0.62 to 0.46 for a given advance coefficient and sigma. Fig. 2 is typical. Their results differ considerably from those of Numachi, et al (2-7), though admittedly the geometries tested are very different. Again some difference between tap water and sea water was found, although not nearly so great as that noted by Numachi. This comparison is shown in Fig. 3. They also noted a considerable effect upon inception sigma of the rate of lowering of pressure to obtain cavitation (10). It is thus confirmed that inception sigma is not determined soley by the flow parameters and total air content. Finally they found that the type of cavitation influenced the magnitude of the air content effect. For inception, they found large effects for "laminar cavitation" (presumably involving relatively steady-state cavities). Also the variation in performance parameters such as torque, thrust, and efficiency was little affected by large differences in total air.

3. Escher-Wyss and I. Vuskovic (11).

A relatively comprehensive series of tests on air content effects upon both performance and erosion in a Kaplan turbine was reported by Vuskovic working at Escher-Wyss (11) in 1940. The damage portion will be discussed later. However, the effects upon the performance of the turbine are some-

The work of these various institutes pertinent to the present discussion has centered upon the observed difference in sigma between incidence and "desinence", so named by Holl (18). It was generally found that desinent sigma exceeds inception sigma, so that a "hysteresis" exists. This difference appears to decrease with increased velocity or size, so that it is actually a "scale effect". It was further found that desinent sigma data exhibits much less scatter than incident. Inception sigma depends upon rate of lowering of pressure, as previously discussed herein concerning the work of Lindgren and Johnson (10).

All the above effects appear closely connected with the details of the nucleation process from entrained or stationary "nuclei". Hence, knowledge of the distribution and size spectra of these nuclei is needed. Work at U - Minn over the past decade has been aimed in this direction. Ripken and Killen (19) found an equilibrium of entrained gas nuclei to be attained in a closed tunnel for given tunnel conditions. They also found no hysteresis if the free gas conditions were maintained the same, so that hysteresis ceases to be a scale effect under these conditions. The U - Minn investigators also developed a method for the continuous monitoring of the free gas distribution, using its effect upon velocity of propagation of a pressure pulse (20 - 23).

6. Bassin d'Essais des Carènes, Paris (25 - 27).

A comprehensive series of tests has been conducted by Bindel, et al. on the effects of the variation of total air content upon inception sigma for various ogives, hydrofoils, and propellors (25 - 27). In agreement with Vuskovic at Escher-Wyss (11) and Edstrand, et al,(8 - 10) in Sweden, they found that the effects of velocity and total air content upon sigma depend strongly on the type of cavitation. They observed bubble (or "burbling") cavitation, cavitation by lamina (steady - cavity), and vortex cavitation, although all types did not appear in all tests. Fig. 4 is typical. In general, an increase of air or velocity reduces sigma. Their results are qualitatively similar to those of both Edstrand and Vuskovic, in that they found large effects of air for vortex cavitation, and little effect with laminar cavitation. The data for "burbling cavitation" are less consistent between Bindel, et al. and the others.

A further result of Bindel, et al. is that velocity and air content effects are not independent. In all cases where there is an effect of air content, an increase therein favors the apparition of cavitation. However, the effect of velocity increase upon sigma is not consistent in direction, and depends upon other conditions.

7. National Physical Laboratory Water Tunnel Tests (28).

Propellor performance tests are reported by Silverleaf and Berry (28) in which total air content was varied. An ultrasonic transmission method was tried unsuccessfully to distinguish entrained from dissolved gas. Again it was found that the development of cavitation is favored by an increase of air content.

8. Colorado State University Water Tunnel (29).

Tests upon cavitating orifices ranging in diameter from 1 to 40 in. are reported by Tullis (29) for a once-through pipe system in which air content was not measured. Size scale effects were found as expected, but there was little evidence of effect upon inception sigma of probable large variations in total air and entrained air content in these tests.

9. SOGREAH - Grenoble, France (30 - 34 and 36 - 38)

A series of tests has been reported (30 - 35) from SOGREAH upon cavitation in regions of strong shear such as the wake region downstream of an orifice wherein air content, velocity, and temperature were varied (to increase Reynolds Number variation). A substantial effect upon sigma of total air content was found (Fig. 5), particularly in the range of moderate air contents (30 - 60% saturation at STP). Also a strong effect of the previous pressure history of the water was found, again indicating the necessity of a more detailed specification of entrained air content than that provided by total air content. The development of techniques for this purpose have been the subject of continued work at SOGREAH.

This latter effort has included the use of standardized cavitating test sections ("veines étalons") to calibrate the "cavitatability" of the water in a given instance, and the development of a "bubble microscope" (36, 37) for the direct observation and photography of the entrained gas nuclei. This last approach is not entirely convenient, since only a very small field can be sampled, and counting and classification of particles is very tedious.

10. University of Michigan - Venturi Studies (34, 39 - 42).

A relatively long and comprehensive study of both damage and performance effects in venturi test sections has been made in the writer's laboratory at the University of Michigan (34, 39 - 43, e. g.). While the damage work has not involved air content effects, considerable work on gas effects on cavitation sigma for both water and mercury has been done. The inclusion of liquid metals is of interest because gas solubility effects are greatly reduced in such fluids. The cavitation sigma studies have been in two parts:

1) Cavitation venturi tests for geometrically similar venturis over 1/8 to 3/4 in. diameter throat (6° total divergence angle) for water and mercury with considerable variation of temperature and velocity (39 - 42, e. g.).

2) Development of modified Coulter-Counter (38) system for measurement of gas nuclei size and population distribution (35), and correlation with sigma. Early measurements have shown that typically the entrained gas volume is only about 10^{-6} of the total. The effects of gas content and velocity are substantial (Fig. 6). For high gas contents, sigma decreases strongly with velocity, passes through a minimum, and then increases. This behavior is similar to that found by Jekat (44) in an axial-flow centrifugal pump for air-saturated water. For low gas content, sigma increases monatonically with velocity. The separation between sigma curves is much greater at low than at high velocity, consistent with work by Holl (18) and Bindel (25 - 27). Since this separation is approximately inversely proportional to kinetic head, it appears that the gas pressure in the bubbles is constant over the range tested. Following the approach suggested by Holl (19):

$\sigma = \sigma_o + \sigma_{gas}$; $\sigma_{gas} = \dfrac{kp_{gas_{SAT}}}{\rho V_t^2/2}$; $p_{gas_{SAT}}$ = gas pressure to which water is exposed.

k = Proportion of saturation pressure actually in bubble, and can be computed from the data, but with considerable scatter. This is presumbly largely due to the differing pressure histories of the water. Fig. 7 shows this effect. However, for water k averages 0.009, and for mercury 0.058 in the present tests.

11. Swedish State Power Administration (45).

Fig. 8 shows data by Fallström (45) from tests upon a Kaplan turbine. The results are consistent with those of Vuskovic (11) upon a Kaplan turbine (already discussed). It is Fallström's opinion (45) that air content within the range tested affects only the initial appearance of bubbles in this type of machine, and thus its variation presents a problem only of academic interest.

12. Technischen Hochschule, Darmstadt, West Germany.

A very recent doctoral dissertation by P. Gast (76) from Darmstadt reports on experiments involving cavitation upon a submerged object in a water tunnel in which the effects of air content upon inception sigma were studied. Consistent with other work, it was found that sigma was increased for higher air contents. Some theoretical justification based on the dynamics of individual bubbles is included.

13. National Engineering Laboratory, East Kilbride, Scotland (46 - 48, 61) and University of Durham.

While no air content work from the water tunnels at NEL have been reported to the writer's knowledge, some relatively basic work relating air content and nucleation under non-flowing conditions has been supported by NEL at King's College, University of Durham. Nucleation thresholds in static samples (water and organic liquids) under ultrasonic irradiation as a function of total air content, pressurization history (and other forms of pre-treatment such as centrifuging) were reported by Richardson, et al. (46 - 48, 61). For fixed total air content it was found that nucleation thresholds were strongly influenced by the distribution between entrained and dissolved portions, and nuclei diameters. Generally only the entrained portion was of importance. They developed a technique to measure the entrained gas spectra (46 - 48) based upon the attenuation of an ultrasonic beam caused by bubbles of a size resonant with the imposed frequency. This approach is similar to that used at the University of Minnesota (20, 21, e.g.), previously discussed. Iyengar and Richardson also experimented with a light-scattering instrument for the same purpose (61).

14. Miscellaneous Nucleation Studies for Non-Flowing Systems (49 - 57).

A. Galloway (49). Fig. 9 shows the strong increase in cavitation threshold (comparable to decrease in sigma in flowing test) observed by Galloway (49) for water and also benzine from a static test in an ultrasonic field, as air content is reduced. For this case of high-frequency excitation, substantial liquid tensions are found.

B. Hayward (50). Hayward (50) at NEL investigated the effects upon cavitation threshold of prepressurization with various liquids of various purities including water. He deduced from this work that water alone contained nuclei of the type postulated by Harvey (51), so that the conventional Harvey model (51) could not be a major cavitation nucleation mechanism. On the basis of the data obtained, this conclusion does not seem warranted to this writer.

C. Ward, Balakrishnan, and Cooper (52, 53). These authors theorize a much greater importance for dissolved (vs. entrained) gas than is usually supposed. However, their viewpoint is disputed by others in a discussion of their paper (53). The above paper, and others pertinent to the subject, appear in the very recent ASME Symposium Booklet, "The Role of Nucleation in Boiling and Cavitation" (54) and the accompanying Discussion Booklet (53). Ref. 55 by Holl in this Symposium Booklet is a particularly good survey of the nucleation state of art pertaining to cavitation.

D. Nystrom and Hammitt (56). Ultrasonic cavitation threshold tests in molten sodium by these authors (56) show the existance of large liquid tensions to nucleate cavitation under high-frequency irradiation (tension increasing with frequency), consistent with the previously discussed results of Galloway (49). The results in molten sodium are of interest (as compared with those in water and organic fluids used by Galloway) in that very little effect of dissolved gas is likely in liquid metals (because of very low gas solubilities).

E. New work on air content effects and "nuclei " measurements are reported from NSRDC in the US (80).

C. Major Basic Research Trends (Damage not Considered).

Since the overall objective of predicting in advance air content effects upon the cavitating behavior of various apparata has not yet been attained, many studies of empirical nature such as those reviewed in the preceding portion of this report have been necessary. To attain such a predicting capability more basic work dealing with the 3 issues which follow is required. The major trends of this work will then be discussed.

1) Measure (or compute) the nuclei spectrum upstream of the device

2) Compute nuclei trajectory and growth or collapse rates during their passage between the region where the spectrum is known and the region of cavitation. Since the flow is likely to be turbulent, 3 - dimensional, and biphasic, this is probably infeasible at present even for large computers. The applicability of adequately simplified models remains a question.

3) Compute the effect of the cavitating flow on the machine.

Though it remains infeasible to fully implement any of the above, many studies, as discussed below, have attempted to improve these capabilities.

1. Measurement of Entrained Gas Nuclei Spectra

Past progress and on-going developments exist in this area. Techniques include:

a) Utilization of effects of nuclei on sonic transmission, either by attenuation in frequency band of bubble resonance, or by reduction by bubbles of sonic velocity. Related work is reported from University of Minnesota (20 - 23), University of Durham (46 - 48), and from Russia (58).

b) Sampling technique using modified Coulter-Counter at University of Michigan (35, 43), previously discussed. A difficulty is the obtaining of a "true sample" from the tunnel in the measuring instrument.

Direct visual observation such as bubble microscope technique of SOGREAH (36, 37), previously discussed. The technique is relatively tedious and certainly limited to transparent fluids.

d) Use of light-scattering properties of gas nuclei (59, 61). Again transparent fluid is required and data reduction is relatively easy. However, the theory is somewhat uncertain so that full calibration is required.

2. Bubble and Fluid Flow Calculations.

a) Pennsylvania State University (Penn State) and California Institute of Technology (CIT).

Theoretical and experimental studies in these laboratories have considered both the behavior of bubble nuclei attached to a wall (16, 62, e.g., at CIT) and those growing in the flowing stream (Holl, et al, Penn State, 18, 19 e.g.). This latter theoretical work has been also applied successfully to the venturi sigma measurements at the University of Michigan (40, 42), previously discussed. However, important features such as turbulent effects upon gas diffusion have been largely neglected.

b) SOGREAH.

The overall problem of the behaviour of gas nuclei in a tunnel are presently being analysed at SOGREAH using a mathematical model hopefully including most pertinent effects. However, results are not yet available.

c) Individual Bubble Studies

Many individual bubble studies exist in the literature, too numerous to list here; many not pertinent to nucleation. One of the more comprehensive and applicable early studies is that of Gallant (63). Another of special interest,in that it involves overall bubble trajectories,is that by Johnson and Hsieh (64). This is one of the few which considers the effects of pressure and velocity gradients upon bubble trajectories.

D. Air Content Effects Upon Cavitation Damage

Studies of the effects of air content upon cavitation damage are far more limited than those upon cavitation inception and performance effects.

However, air content must have a substantial effect, at least in some cases, through the action of the following opposing mechanisms:

1) Higher air contents favor cavitation, providing an increased number of bubbles, the collapse of which may be damaging.

2) Higher air contents within individual bubbles reduces collapsing wall velocities and hence pressure radiation into the surrounding liquid (65, 66, e.g.). Field observations show that large quantities of free air in damage-prone regions reduces damage rates (24, e.g.).

More detailed consideration of these mechanisms indicates the strong probability that for very high gas contents (saturation and above), an increase in air will reduce damage through the "cushioning" effect on individual bubble collapse and perhaps through more rapid attenuation of shock waves in the surrounding liquid. On the other hand, for very low gas contents, sigma is substantially increased if gas content is further reduced (48, e.g.), so that the reduction in number of bubbles is more important than the increased collapse violence for individual bubbles. Thus cavitation damage is reduced if gas content is further reduced, and, in fact, in some cases cavitation may disappear entirely.

Beyond individual bubble collapse studies already discussed, there appear to be no theoretical studies of the effects of gas content upon cavitation damage*. A few isolated experimental results will be discussed next.

1. Venturi Tests at Holtwood Laboratory, Safe Harbor Water Power Corp., U.S.A., Mousson (67).

The earliest report of tests of air content effects upon cavitation damage is that by Mousson (67) in 1937 (see Fig. 10), from runs made in a special damage venturi. For substantial rates of air injection (range of 1 - 2%) damage was substantially reduced (air content itself was not measured). The proportionate air flow to reduce damage markedly increases with water velocity, so that injection power loss may become substantial at high water velocity.

2. Venturi Tests at Escher-Wyss, Vuskovic (11).

Vuskovic's air content damage tests (1940, Ref. 11) were made in a

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*However, such work is in progress by R.B. Mesler at University of Kansas, Lawrence, Kansas, USA (79).

venturi similar to that of Mousson (67), at a velocity of 60 m/s (lowest velocity of Mousson), and on copper (same material as Mousson). No actual weight loss measurements were made, but air content was measured. Consistent generally with Mousson's results, there was a steady reduction of damage as air content was increased from 0.3 to 1.7 of saturation at STP.

3. Rotating Disc and Venturi Tests, Rasmussen (68, 69, 78).

Rasmussen (1955) used both a rotating disc apparatus and a special damage venturi (Shal'nev-type). Air contents were measured. Fig. 11 and 12 show typical results for the rotating disc and the venturi, respectively. Again, damage decreased continuously and substantially as air content was increased from near zero to about 10% by volume (i.e., about 5 x saturation at STP), thus covering a range similar to that of Mousson (67) and Vuskovic (11). The proportionate decrease depends both on material and the type of test, being much greater for aluminum than for cast iron and greater for the venturi than for the rotating disc.

4. Non-Flowing, Vibratory Damage Tests - Hobbs (70, 71)*.

The first measurements of air content effects upon damage in a static vibratory-type test are apparently those of Hobbs (70, 71) in 1969. It is well known that damage rates maximize in a test of this sort for an intermediate temperature (24, 70 - 73), and the reduction at the low temperature end had been supposedly due to increased gas solubility at low temperature (and hence increased gas content since tests are normally conducted in an open beaker with free surface). His results show little effect on damage over the gas content range 0.1 - 1.0 x saturation at STP, tending to disprove this hypothesis. Hobbs does show a reduction in damage near the upper end of his gas content range (which is much lower than that used in the flowing tests), so that his results are not inconsistent with these tests. He also shows a reduction in damage at <u>low</u> gas content (which the flowing tests did not), presumably due to the lack of "nuclei" under this condition.

5. Cathodic Protection and Gas Content (74, 75).

Cathodic protection to suppress electro-chemical effects in cavitation

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*Related work has also been done in Russia by Sirotyuk (78).

was apparently first suggested by Petracchi (74) in 1944. Later work by Plesset (75) suggested that the damage reduction was actually due primarily to gas cushioning effects of the electrolytic hydrogen released at the wall. Thus the success of cathodic protection may be partially a gas content effect.

III CONCLUSIONS AND RECOMMENDATIONS

Although much remains to be done, it is possible at this point to formulate certain important recommendations and conclusions, as, e.g.:

1) In general, variation of air content has little practical effect upon the overall performance of machines operating well in the cavitating region. It does, however, often have an important effect upon inception sigma, in that an increase in air causes an increase in sigma. It can thus importantly affect the prediction of inception sigma for prototype machines from tests on models, if there are differences in water quality with respect to gas nuclei between model and prototype conditions.

2) Air content can importantly affect cavitation damage rates if, as in some cases, it establishes the existance and quantity of cavitation itself. Also large amounts of air, usually well in excess of saturation, will substantially reduce cavitation damage, probably because of the reduced violence of bubble collapse in a gassy liquid.

3) The importance of air content upon inception sigma depends upon the type of cavitation, i.e., bubble, laminar (steady cavity)., vortex cavitation, etc.; bubble cavitation being most sensitive. The type of cavitation found depends on geometry and other flow parameters.

4) Predictions of gas content effects upon cavitation are not possible if only total gas content is known. It is necessary to assure water of similar population and size spectra of "nuclei" as well as total gas content if gas content "scale effects" are to be avoided.

5) A general capability for a fully theoretical prediction of gas content effects upon cavitation is not within the present state of the art, since the flow is biphasic, multidimensional, and turbulent. None of these three factors can be feasibly handled in general alone. However, more limited mathematical

models are helpful to indicate at least trends to be expected. Much has been done and much remains.

6) Another essential capability for the prediction of gas content effects is the easy and practical measurement of the gas nuclei spectra in a flowing system. An alternative and complementary capability is the "calibration" of the liquid for "cavitatability" using a standard cavitating device.

In conclusion, it appears from all the foregoing that only rather vague guidelines can be drawn for the quantitative effects of gas content either upon inception sigma or damage rate for an untested condition. However, fairly firm qualitative results can be utilized, which are consistent both with the experimental and theoretical studies discussed, and with the pertinent physical laws. Fig. 13-a and b show such hypothetical curves for both inception sigma and damage rate. The curve for inception sigma (Fig. 25-a) is based upon the fact that for very small gas contents the tensile strength of the liquid is appreciable, and for very large gas contents, a large liquid pressure is required to prevent explosive growth of gas bubbles, i. e. "gaseous cavitation". The same concept leads to the damage curve (Fig. 25-b). No cavitation would occur for very low gas content due to insufficient nuclei. For somewhat higher gas content, the nuclei population would approach sufficiency, so that a further increase in gas content would not significantly increase the number of cavitation bubbles and hence damage. For very large gas contents, the cushioning effect upon bubble collapse would become predominent, and damage would decrease. The typical values shown in both curves (Fig. 13) are based upon the experimental results discussed in this report.

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LIST OF FIGURES

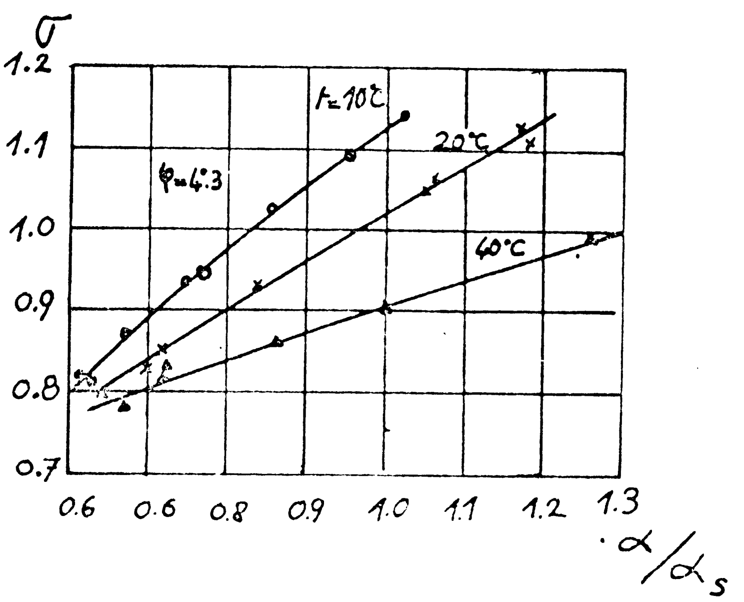

Fig. 1 Cavitation Inception Sigma for Flow Past Circular Section as Function of Relative Air Content Compared to Saturation at STP, Edstrand (8).

Le σ de début de cavitation dans un écoulement en veine circulaire en fonction de la teneur en air relative à saturation à N. T. P., Edstrand (8).

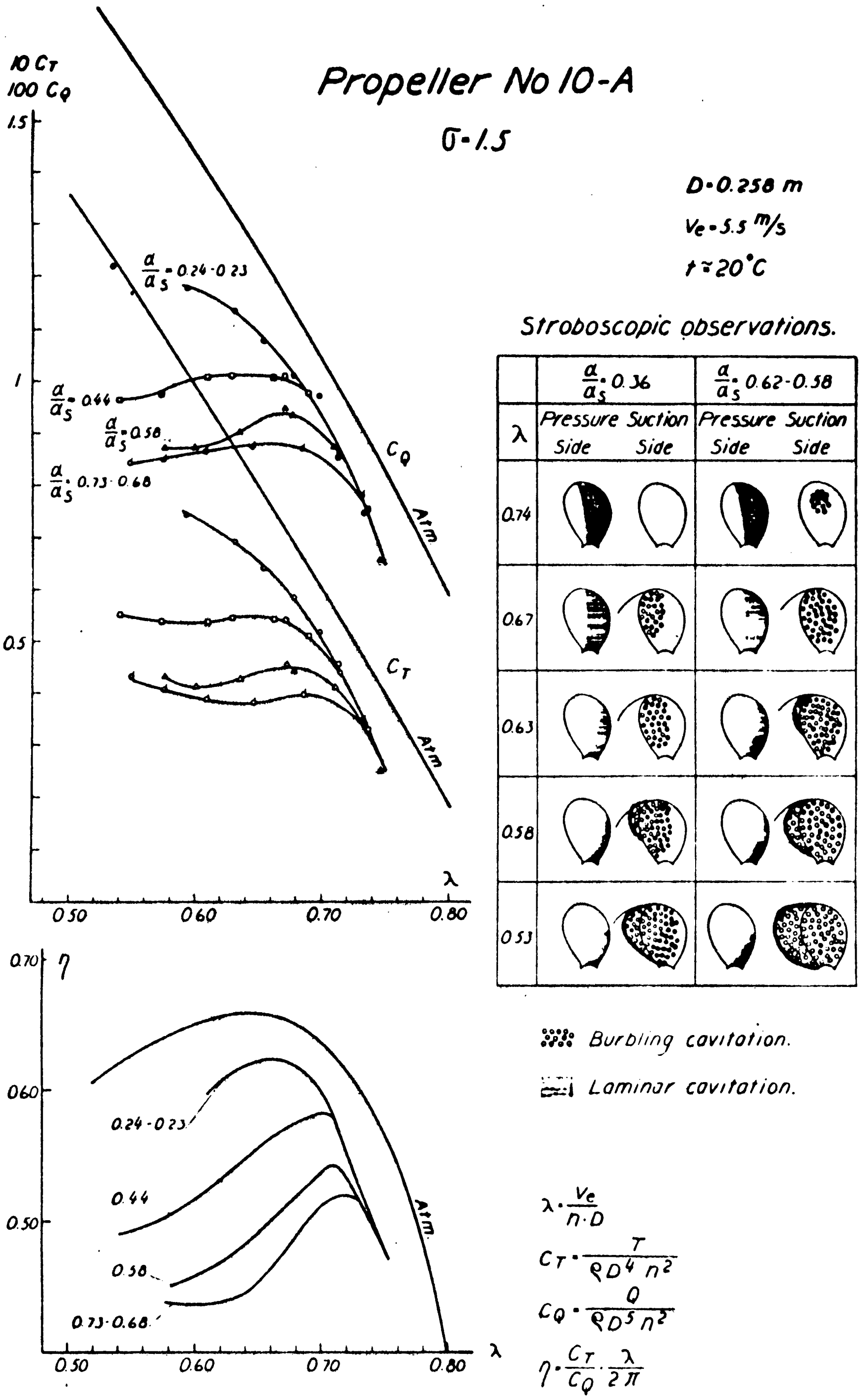

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Fig. 2 Propellor Cavitation Data for Different Relative Air Contents (Compared to STP, Edstrand (8).

Les effets de l'air pour les hélices cavitantes, Edstrand (8).

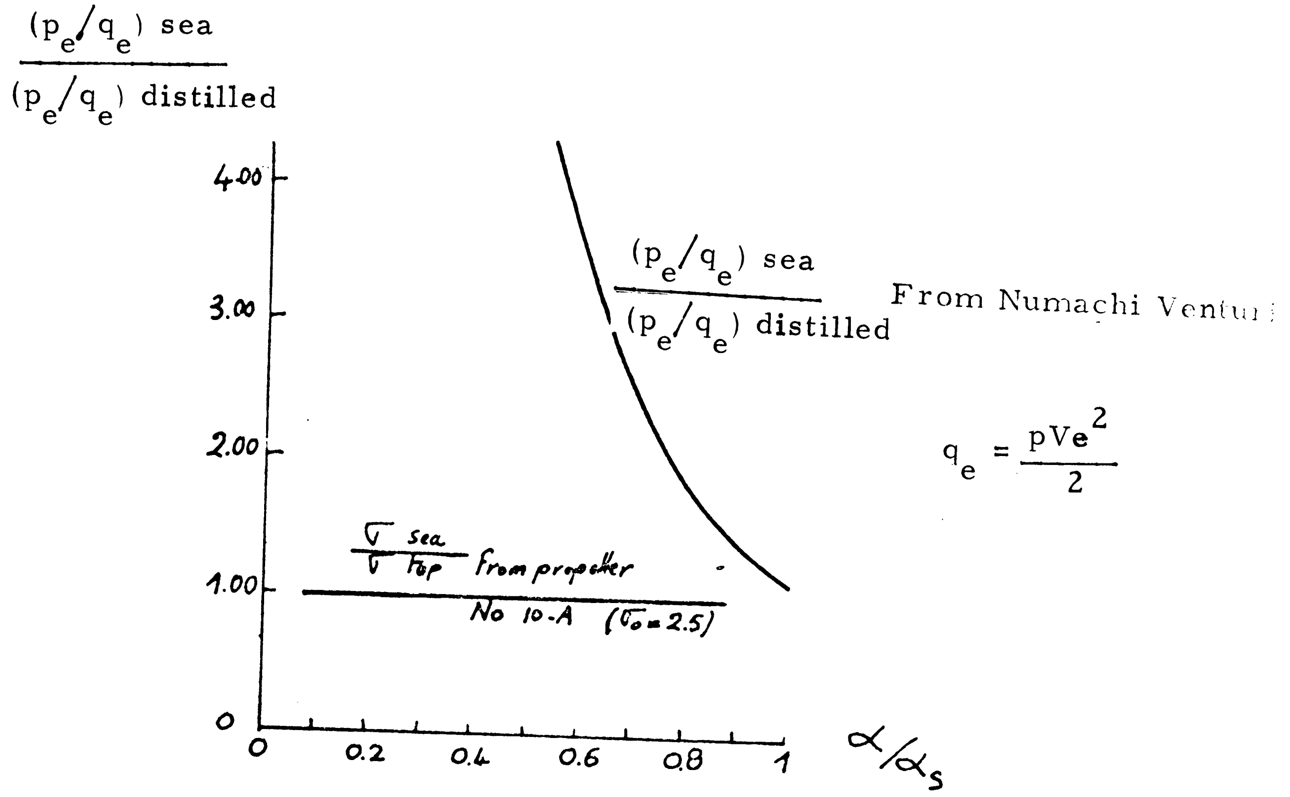
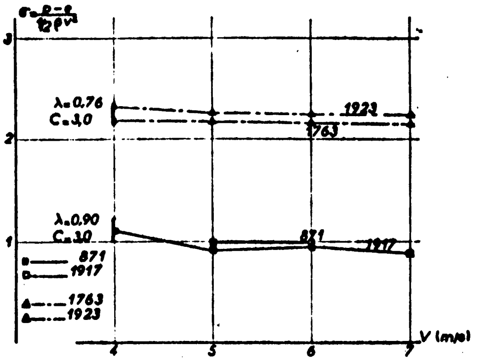
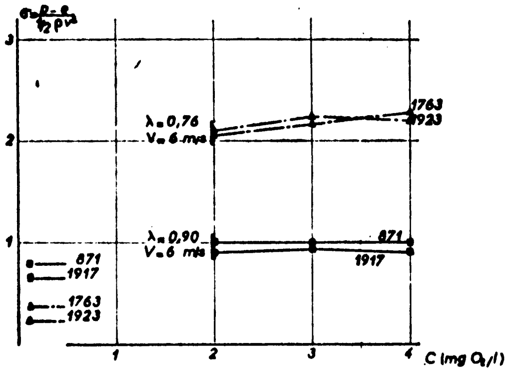


Fig. 3 Relative Air Content Effects in Sea Water vs. Fresh Water for Propellor and Numachi Venturi, Edstrand (9).

. Les effets de l'air dans l'eau de mer et dans l'eau douce pour les hélices et un venturi de Numachi, Edstrand (9).

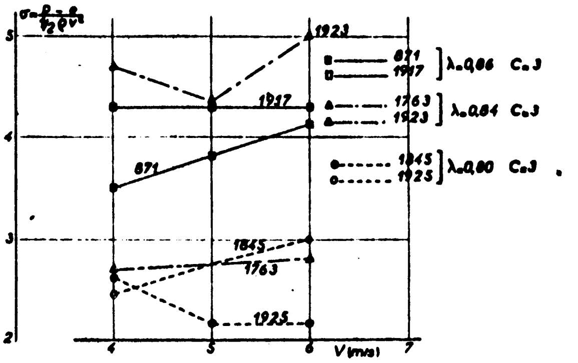


(a) CAVITATION par BULLES
INFLUENCE de la VITESSE

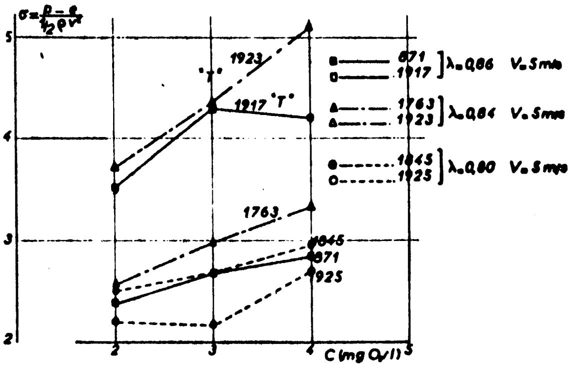


(b) CAVITATION par BULLES
INFLUENCE de la TENEUR en AIR

FIG. (*a* et *b*). — Hélices : Effet d'échelle.



(c) CAVITATION "cdt" TOURBILLON "T"
INFLUENCE de la VITESSE



(d) CAVITATION "cdt" ou TOURBILLON "T"
INFLUENCE de la TENEUR en AIR C

FIG. (*c* et *d*). — Hélices : Effet d'échelle.

Types de cavitation observés.

Fig. 4 Types of Cavitation Observed on Propellors and Effects of Oxygen Content and Velocity on Inception Sigma, Bindel and Riou (27).

Les types de cavitation observés pour les hélices, et les effets de la teneur en oxygène et la vitesse sur le σ de début, Bindel et Riou (27).

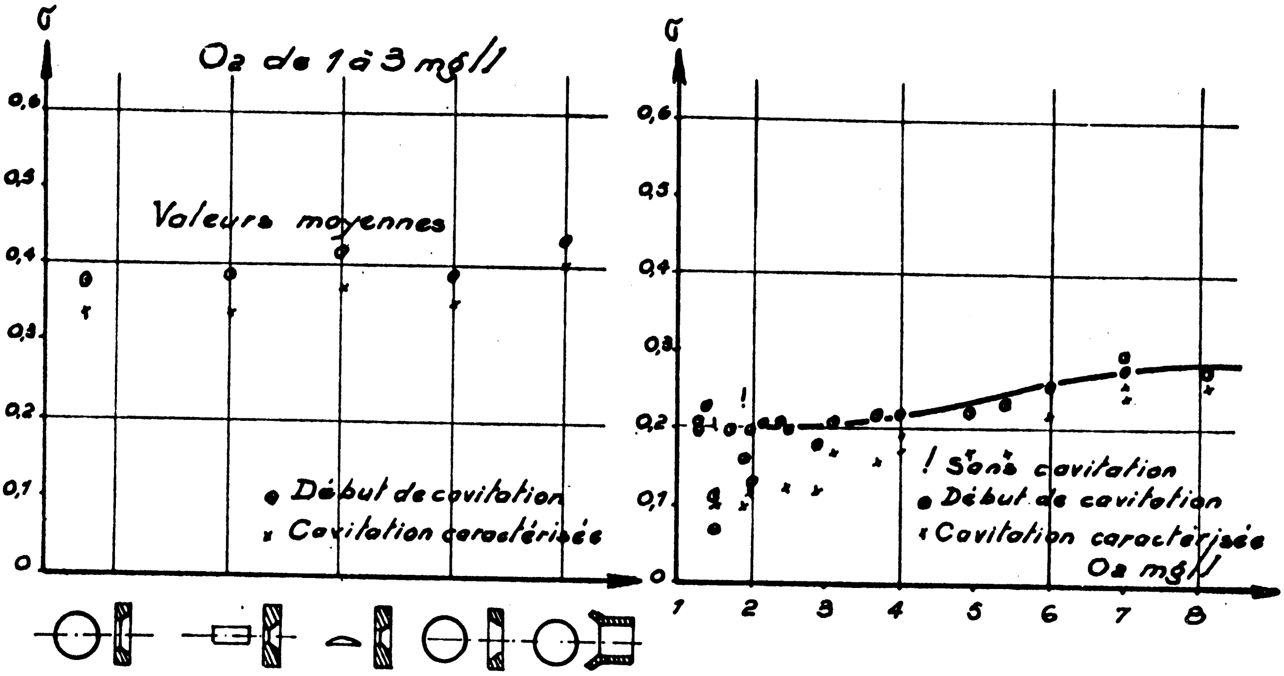


Fig. a — Influence de la forme de jet et de la buse.

Fig. c — Influence de O_2 (Veine de référence).

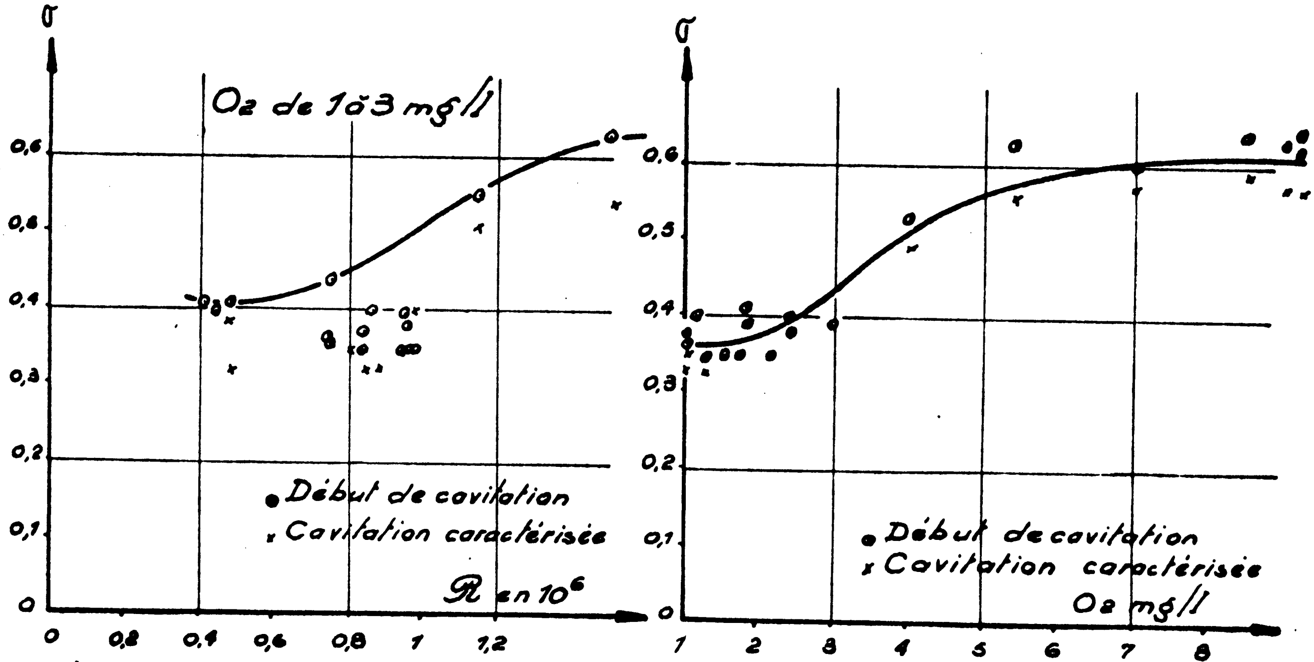


Fig. b — Influence du nombre de Reynolds (Diaphragme circulaire).

Fig. d — Influence de O_2 (Diaphragme circulaire).

Fig. 5 Influence of Oxygen Content and Reynolds Number for Various Orifice Shapes on Inception Sigma, Duport (34).

Les effets de la teneur en oxygène et le nombre de Reynolds sur le σ de début pour des types d'orifices différents, Duport (34).

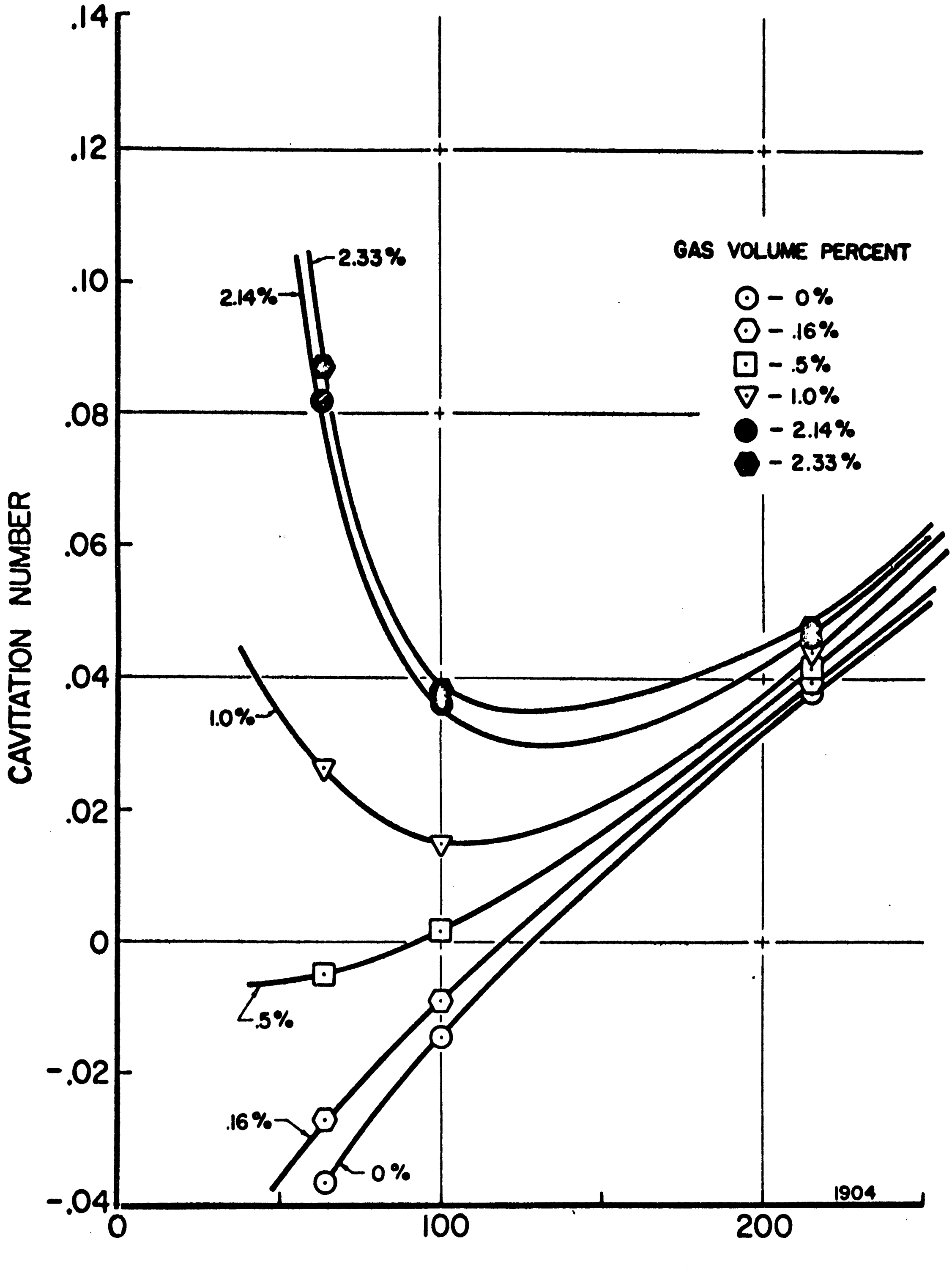


Fig. 6 Cavitation Inception Sigma vs. Throat Velocity - 1/2 inch Venturi, Hammitt, etal (42).

Le σ de début de cavitation en fonction de la vitesse au col d'un venturi de 1/2 pouce, Hammitt, etal (42).

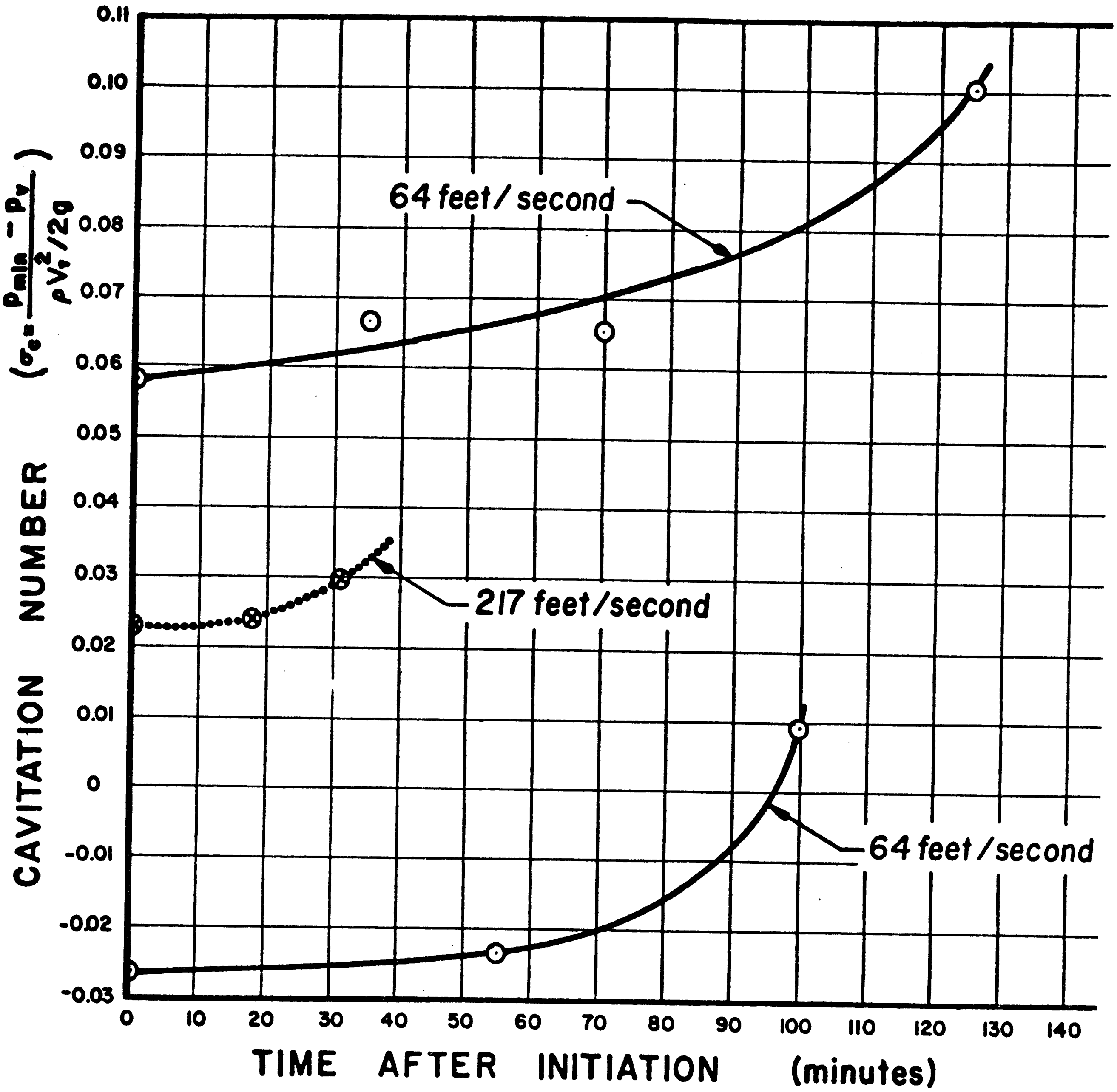


Fig. 7 Prepressurization Effects on Cavitation Sigma, 1/2 inch Venturi, Hammitt, etal (42).

Les effets de la pré-pression sur le σ de début de venturi de 1/2 pouce col, Hammitt, etal (42).

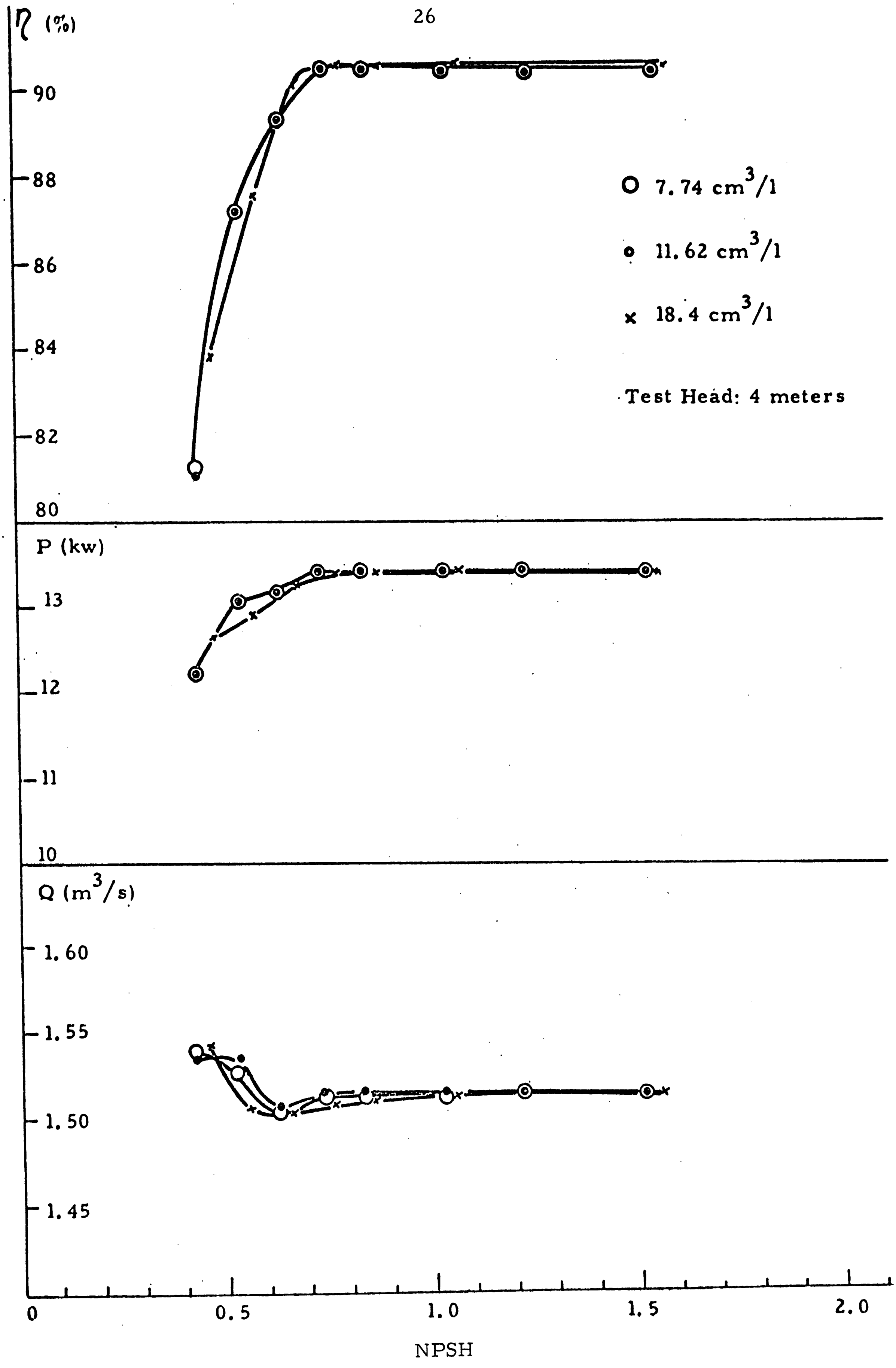


Fig. 8 **Air Content Effects on Kaplan Turbine, Fallström (45).**

Les effets de la teneur en air sur une turbine Kaplan, Fallström (45).

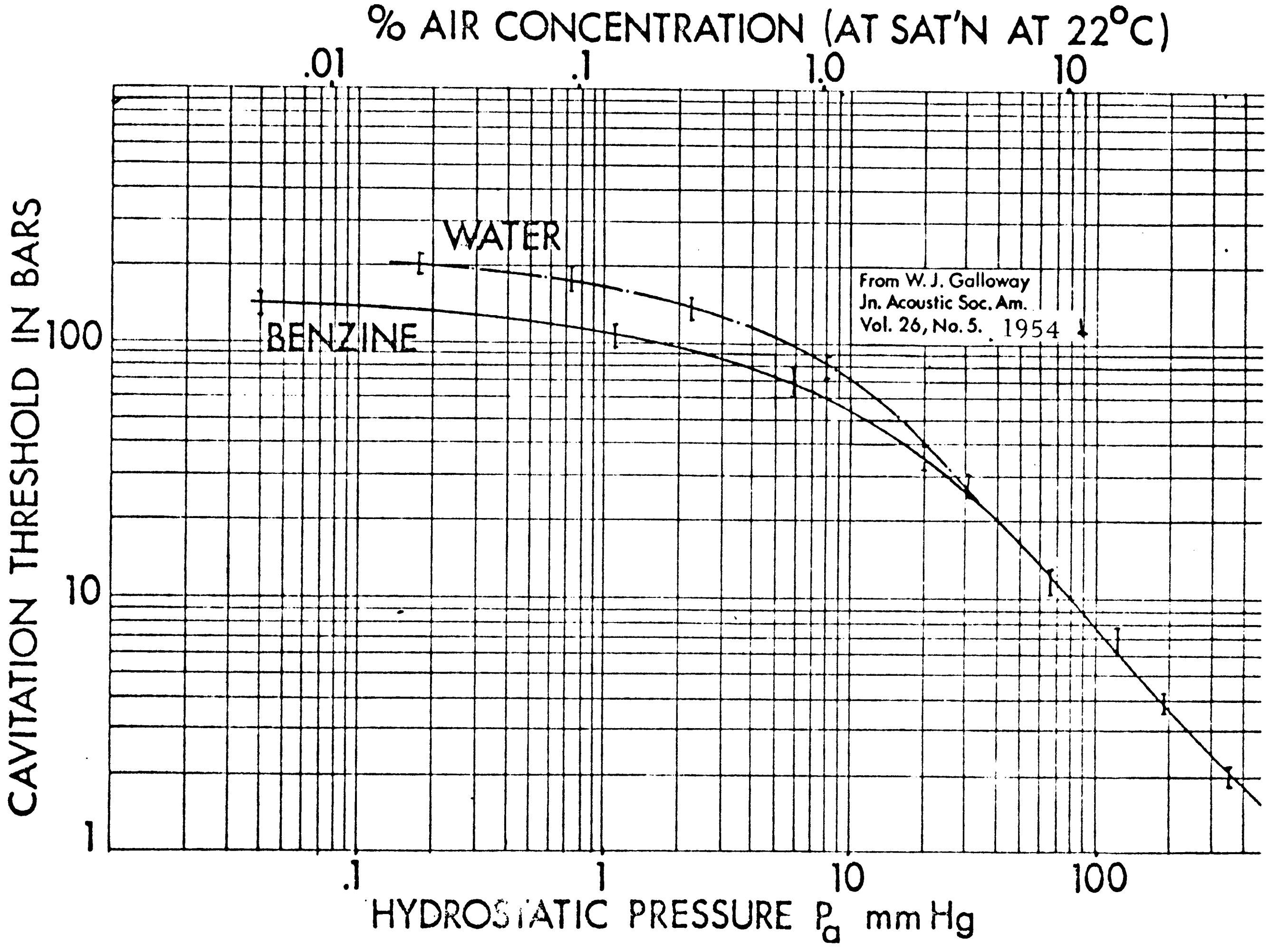


Fig. 9 Cavitation Threshold of Water and Benzine as Function of Relative Air Content (Compared to STP), Galloway (49).

Le seuil de cavitation de l'eau et de la benzine en fonction de la teneur en air, Galloway (49).

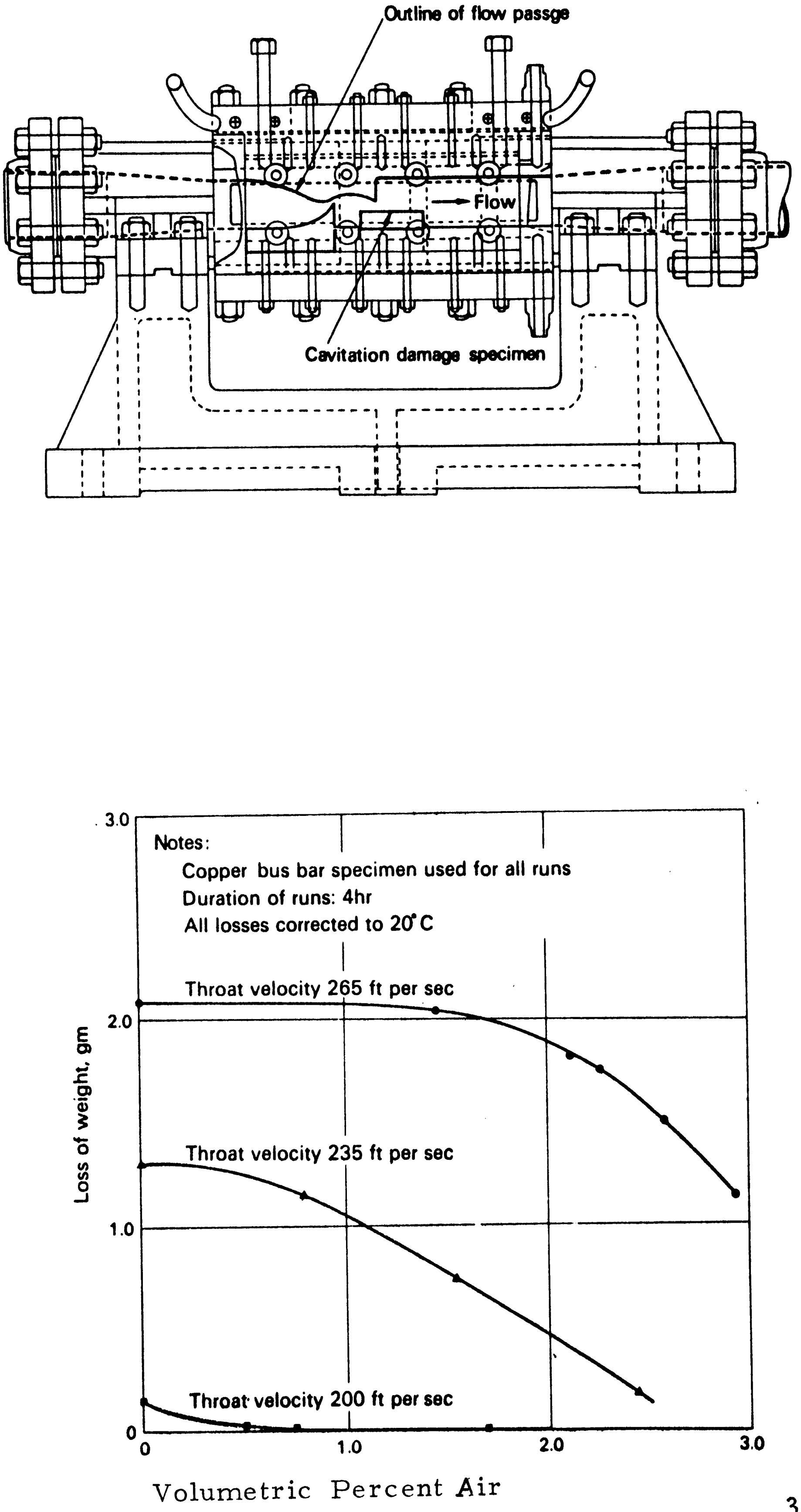


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Fig. 10 **Effects of Air Injection Upon Cavitation Damage in Venturi, Mousson (67).**

Les effets de l'injection de l'air sur l'érosion de cavitation en venturi, Mousson (67).

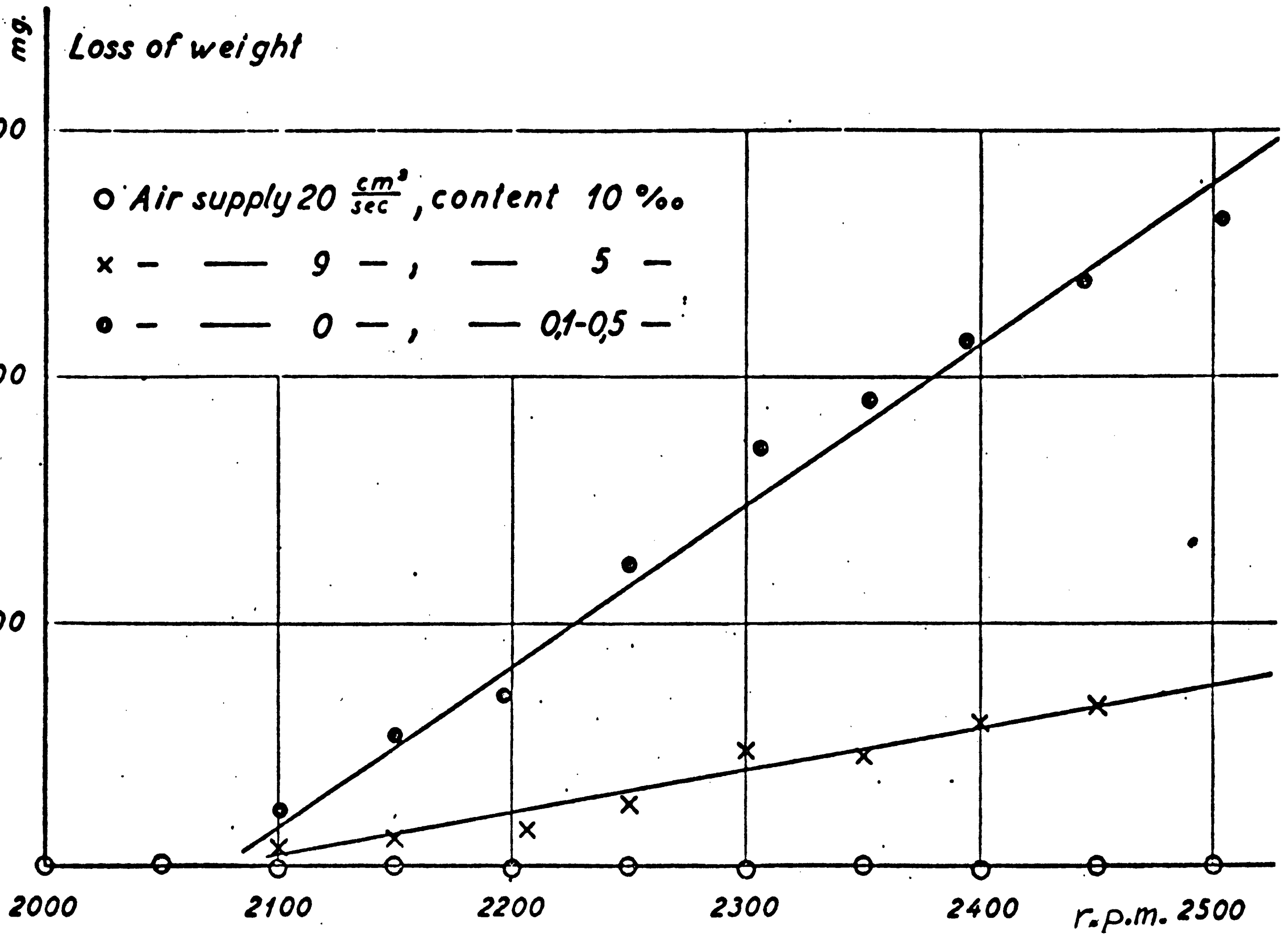


Fig. 11 Effects of Air Content Upon Cavitation Damage in Rotating Disc Apparatus, Rasmussen (68, 69), Aluminum Alloy

Les effets de la teneur en air sur l'érosion de cavitation en disque tournant, Rasmussen (68, 69).

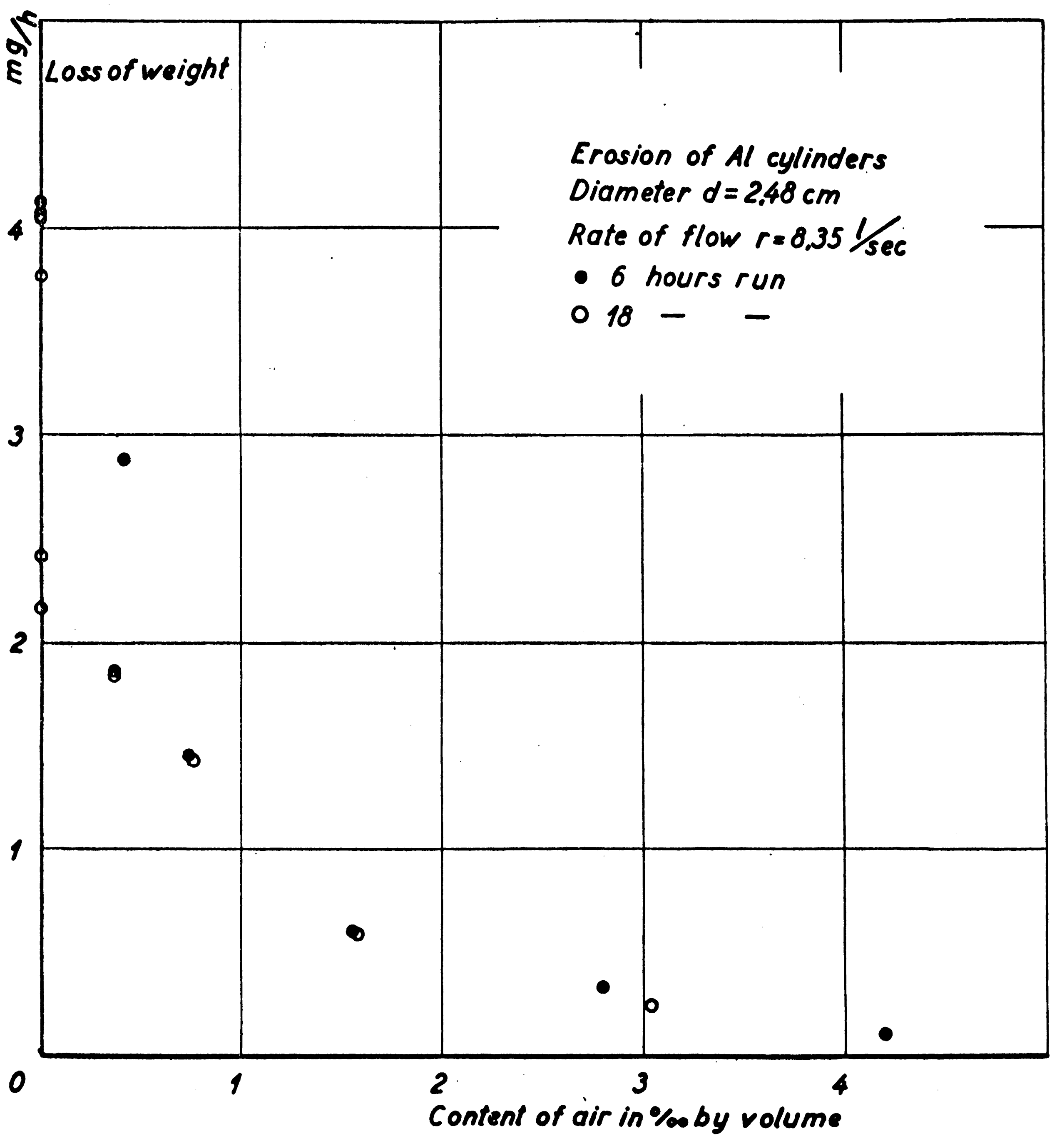
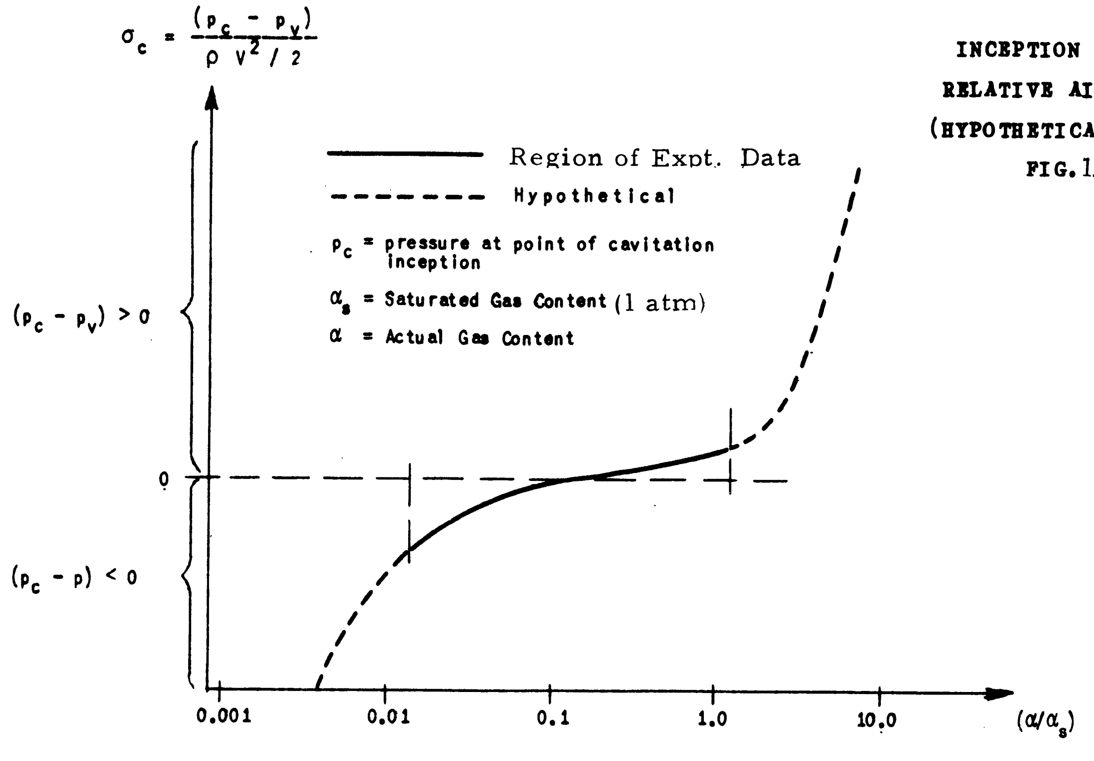
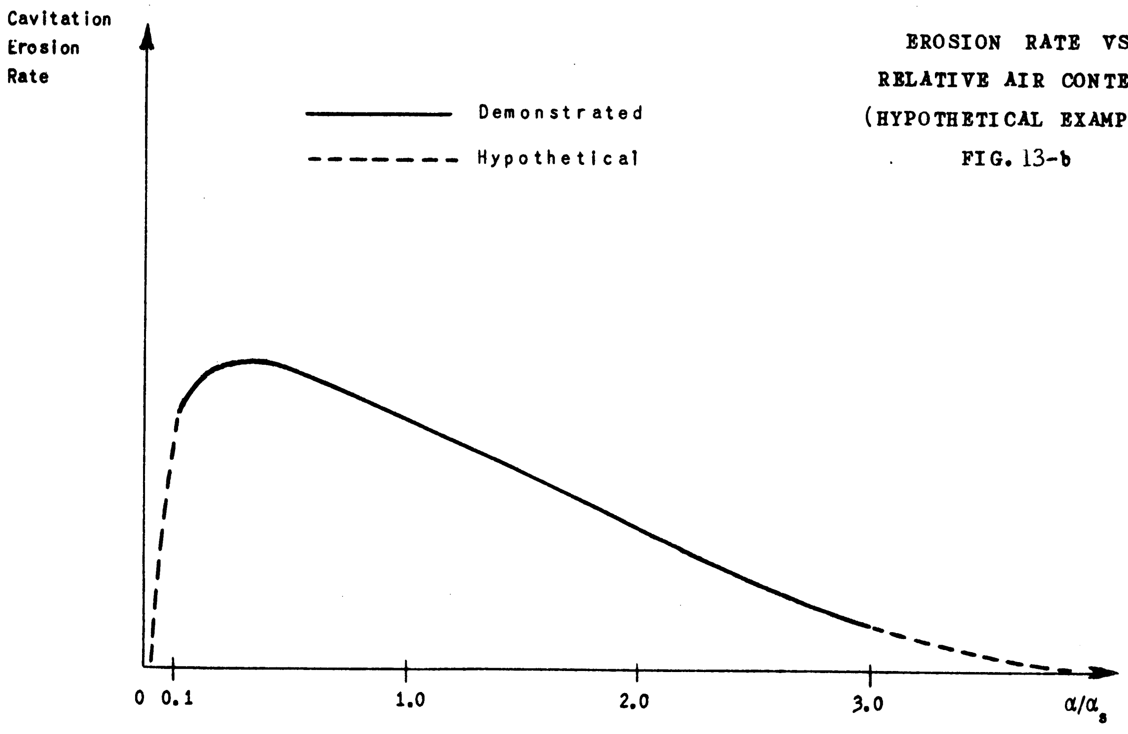


Fig. 12 Effects of Air Content Upon Cavitation Damage in Venturi Upon Aluminum Alloy, Rasmussen (68,69).

Les effets de la teneur en air sur l'érosion de cavitation en venturi sur un alliage d'aluminium, Rasmussen (68, 69).



INCEPTION SIGMA VS
RELATIVE AIR CONTENT
(HYPOTHETICAL EXAMPLE)
FIG. 13-a



EROSION RATE VS
RELATIVE AIR CONTENT
(HYPOTHETICAL EXAMPLE)
FIG. 13-b

Fig. 13 Hypothetical Overall Dependence of Inception Sigma and Erosion Rate on Relative Air Content

σ et taux d'érosion en fonction hypothétique de la teneur en air

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