A Peculiar Behavior of Cavitation-Nuclei-Size Distributions in Sample Water Under Vibratory Erosion Tests*

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In order to clarify the necessary conditions for cavitation-erosion tests with a vibratory apparatus, we carefully measure the cavitation-nuclei-size distributions and the relative air content rate of test water with respect to time by means of a Coulter counter and a van Slyke apparatus, respectively. It is found that the exponent of the distribution curve and the volume concentration of nuclei characterizing the nuclei-size distributions do not fluctuate with time during the equilibrium period, and that the relative air content rate first decreases monotonously with time and then reaches a definite equilibrium value after 40 min which is longer than the 15 min recommended by the ASTM.

Key Words: Cavitation, Erosion, Bubble, Cavitation Nuclei, Air Content, Vibratory Erosion Test, Coulter Counter

1. Introduction

With the rapid speeding-up of hydraulic machinery, the possibility of fatal cavitation erosion becomes increasingly higher. Much interest has therefore been focused on finding erosion resistant materials and looking for the most practical method of rapid erosion tests.

As is well known, there are several types of cavitation each with its own aspects, behavior and occurrence zones. Most of them are nonerosive, but some are highly erosive\(^{1(2)}\), and the types of cavitation are governed by cavitation-nuclei-size distributions. Since cavitation-erosion tests aim inherently to evaluate the lifetime of materials against erosion, it is necessary to secure steady occurrences of a prescribed type of cavitation and/or to secure uniform cavitation-nuclei-size distributions\(^{3(4)}\) in test water during a test period. According to the literature, vibratory acceleration methods have been widely used in such erosion tests\(^{5(6)}\), and a standard method has been proposed\(^{14(15)}\). A few studies have been carried out to observe the cavitation aspects\(^{16(17)}\) and indicating remarkable changes in the relative air content rate in test water\(^{18}\). However, no studies have been performed under conditions of the steady cavitation occurrence of prescribed types or under conditions of the steady existence of nuclei-size distributions. The authors\(^{19}\) found recently that the number and the size of nuclei increased tremendously near the occurrence zone of cavitation after some types of cavitation took place there. In the present stage of cavitation investigations, therefore, it is doubtful whether or not such distributions are kept uniform during the test period.

In this paper, for the first step of this series, we describe typical vibratory erosion tests, which conform to the ASTM Standard\(^{1(2)}\). The time dependence of nuclei-size distributions in test water is precisely monitored by a Coulter counter. It is shown that the distributions scarcely change with time when clean tap water is settled for 24 hours as test water.

2. Experimental Apparatus and Procedure

The experiments are carried out in an electros-
tractive vibratory apparatus conforming precisely to
the ASTM Standard\(^{[16]}\), as shown in Fig. 1. The driv-
ing frequency \( f \) of the vibratory generator is 19.5 kHz,
and the displacement amplitude "a" of the test speci-
men in water is set at 50 \( \mu \)m in the present exper-
iments. The driving power of the vibratory generator
is selected to be 1 200 W which is much larger than the
standard power of 500 W, for future studies on highly
erosion-resistant materials.

Since cavitation is said to be a typical stochastic
phenomenon, test water should have the same popula-
tion of nuclei. In the present experiments, therefore, it
is necessary that fresh tap water with uniform
nuclei-size distributions be supplied as test water
before each test run, and that the distributions and the
relative air content rate \( a/a_s \) be monitored and kept
uniform during the test period.

In order to keep the nuclei-size distributions as
uniform as possible before each test, fresh tap water
is poured into a large and sufficiently clean plastic tank,
0.04 m\(^3\) in volume, and then is settled for 24 hours in
atmosphere. For every test run, the test water is
carefully sampled from the tank, and is contained in a
standard commercial glass beaker standing in a lucite
water bath to maintain a constant temperature of 22
\( \pm 1\)°C, in which the water is exposed to the atmos-
phere. Immediately before every test run, the relative
air-content rate and the nuclei-size distributions are
measured.

Since the water temperature markedly affects the
degree of erosion\(^{[17]}\), it is automatically adjusted within
22\( \pm 1\)°C by means of heat conduction through the
wetted wall of the beaker. Then the beaker is made of
high heat-conductive glass.

In conformity with the ASTM Standard, a flat
disc-type test-specimen, 15.9 mm in diameter and 11
mm high, is used. It is well known that the dish-type
specimen and the groove-type one minimize data
scattering\(^{[17]}\).\(^{[18]}\). In the present experiments, however,
we stress adherence to the ASTM Standard and also
the easiness of surface finishing of very hard speci-
mens. All the specimens are made of 304 stainless
steel, a typical erosion-resistant stainless steel, and are
very smoothly polished with # 3000 emery paper.
The initial surface roughness \( R_{\text{max}} \), measured by a
profilometer, is 0.025 \( \mu \)m. To assure sampling from
the same population, all the specimens are cut from a
single large block of 304 stainless steel with uniform
chemical compositions conforming to the JIS
Standard.

The cavitation nuclei are measured by means of a
Coulter counter\(^{[19]}\). The Coulter tube was 0.2 mm in
orifice diameter, 0.15 mm in throat length, 1.3 m/s in
mean throat velocity and 10 mA in electric current
flow. The data shown later are the average values from
5 measurements in which each measuring time is
2 min. The measuring method is described in detail
elsewhere\(^{[19]}\).

The aspects of cavitation are always changing with
time very rapidly, so that they are photographed with
a Xenon flash lamp of 1 \( \mu \)s exposure time. The photos are simultaneously taken with the sinusoidal
wave signal from the vibratory generator. The rela-
tive air content rate \( a/a_s \) is measured by means of a
kind of van Slyke apparatus\(^{[20]}\) where \( a \) is the total air
content and \( a_s \) the saturation air content at the water
temperature \( T_w \).

3. Results

3.1 Characteristic change in relative air content
rate

In order to specify the state of test water during
the test period, first, the relative air content rate \( a/a_s \)
is carefully measured with changing time \( t \) after each
test run at the typical water temperature \( T_w = 22\)°C,
as shown in Fig. 2. In this figure, the data by Kerr\(^{[21]}\)
are also shown for comparison although his apparatus
does not necessarily conform to the ASTM Standard.
The slight difference between these data could be
attributed to the difference in the driving frequency,
the amplitude, and the test water temperature. Clear-
ly, the rate \( a/a_s \) at first decreases monotonously with

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Fig. 1 Schematic diagram of vibratory test apparatus
and test specimen

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Fig. 2 Relative air content rate \( a/a_s \) with test time \( t \)

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time; then it reaches a definite equilibrium constant. In the following, the first region will be called the "nonequilibrium region," the second region the "equilibrium region," and the time until entry into the equilibrium region, the "required equilibrium time \( t = t_e \)."

In the nonequilibrium region, the marked increase in the degassing is attributed to the rectified diffusion in which more gas is admitted into bubbles than the amount of gas leaving them. The definite equilibrium rate depends on the variation of both the temperature \( T_w \) and the applied pressure \( P_a \). Kapustina concluded, from his experimental and theoretical work on the degassing process of water in a sound field, that the equilibrium volume concentration was kept unchanged. He interpreted this result to mean that the work done by removing a certain amount of gas from water remained constant. The present degassing process also supports his conclusion.

It might be overhasty to conclude that the aforementioned marked degassing in the equilibrium region directly relates to the marked change in the nuclei-size distributions which are the most important factor of cavitation occurrence, since the undissolved air content, corresponding to the total volume of nuclei, must be much smaller than the dissolved air content. But it might be said that contained air in the test water is unstable, so that such a state of test water is not necessarily suitable for our erosion tests. For the same condition of test water temperature \( T_w \), atmospheric pressure \( P_a \), driving frequency \( f \), and amplitude \( "a" \), the ASTM recommends 15 min to stabilize the relative air content of test water. Notice here that the obtained equilibrium time, \( t_e = 40 \text{ min} \), is much longer than the ASTM-recommended time. Thus, the ASTM Standard is said to be insufficient.

### 3.2 Limited change in nuclei-size distributions with test time

Most readers will be interested in whether or not the nuclei-size distributions in test water rapidly and significantly change with an abrupt cavitation occurrence after test runs. So, the nuclei-size distributions in the test water at different test times \( t = 4 \sim 120 \text{ min} \) and before test runs \( t = 0 \text{ min} \) are measured by using the Coulter counter. Figure 3 illustrates the typical nuclei-size distributions, i.e., the relation between the number-density distribution-function \( N_{nn} \), the number of nuclei \( N \) versus the nuclei diameter \( d_n \), on the logarithmic scale. For comparison between the nuclei distributions after test runs shown by dotted lines and those of standing water shown by solid lines, both results are shown in the same figure.

In both the equilibrium and the nonequilibrium region, the nuclei distributions do not change much even though cavitation suddenly occurs, and they have almost the same trend before and after the test runs. This fact is worth noting. Therefore in the future, vibratory-erosion tests under ideal conditions where cavitation aspects remain sufficiently uniform during the tests will be sufficient, if the nuclei distributions can be uniformly adjusted before test runs.

Unexpectedly, the nuclei distributions shown by \( t = 0 \text{ min} \) in the figure vary somewhat for every test run of different test time. As described above, each run requires 20-30 min, so that entire experiment requires...
about ten days. During such a long period, the nuclei distributions vary somewhat with idealized erosion tests in the future, therefore, the erosion tests must solve one or more problem to keep the nuclei distributions sufficiently uniform throughout the experiment.

In order to specify the state of nuclei more precisely, the dominant parameter to characterize the nuclei distributions, i.e., the exponent number \( m \) and the volume concentration \( v_n \) of nuclei are calculated for the test water, changing with time before and after the test as shown in Fig. 4. The number \( N \) and the volume concentration \( v_n \) of nuclei can be given by

\[
N = C d_n^m
\]

\[
v_n = \frac{1}{6} \int_{(d_n)_{\text{min}}}^{(d_n)_{\text{max}}} N d^2 d(d_n)
\]

where "c" and "m" are constants which are determined by the least-square fitting for the \( N-d_n \) curves. \((d_n)_{\text{min}}\) and \((d_n)_{\text{max}}\) are the minimum and the maximum measured diameter of nuclei. To eliminate unfavorable effects due to the inevitable scattering in the nuclei distributions of the present test water, the relative exponent \( m = m/m_{10} \) is drawn, as shown in Fig. 4. In the nonequilibrium region where the relative air content rate considerably changes with time, both of \( m \) and \( v_n \) significantly fluctuate unstably with time, and the periods of fluctuations of \( m \) and \( v_n \) are quite different from each other, showing a marked unstable behavior of the nuclei. However, in the equilibrium region (note that the equilibrium time \( t=60 \text{ min} \) is fairly longer than the 40 min obtained from the \( a/a_0 \) data), \( m \) and \( v_n \) scarcely fluctuate with time so that the distributions must be stable. In short, the nonequilibrium region and the neighborhood (or transient region), where unfavorable and unstable behavior arises, is said to be unsuitable for erosion tests.

3.3 Cavitation Aspects

In order to clarify what types of cavitation correspond to these results, Fig. 5 shows the cavitation aspects for the three typical regions; namely, the nonequilibrium region, the equilibrium region, and the transient region between them. These photographs are taken perpendicular to the test surface through the mirror, which is set in the beaker at an angle of 45 degrees from the horizontal axis, by means of a Xenon flash lamp. They are taken simultaneously at three positions marked by (1), (2) and (3) on the time-displacement diagram. Bubbles may rebound or begin to grow at the position (1), and are densely populated on the surface at the position (2), while at position (3), they are in a state of collapse.

It is clearly observed from these photographs that the size of cavitation bubbles in the nonequilibrium region \((t \approx 5 \text{ min})\) is somewhat smaller than those in others, while the cavitation aspects in the transient region \((t \approx 45 \text{ min})\) and the equilibrium one \((t \approx 115 \text{ min})\) are almost the same. Therefore, the cavitation aspects change with \( a/a_0 \) or the nuclei.

4. Conclusions

In order to establish the necessary conditions for such cavitation erosion experiments in a vibratory test apparatus, the cavitation-nuclei-size distributions and the relative air content rate \( a/a_0 \) in the test water are carefully measured with respect to test time \( t \). The results are summarized as follows:

Fig. 4 Relative exponent \( m \) and volume concentration of nuclei \( v_n \) versus test time \( t \)

![Fig. 4](image)

Fig. 5 Cavitation aspects for the three typical regions (1, 2, and 3 correspond to the instant time of 5, 10 and 40 \( \mu \text{s} \))

![Fig. 5](image)
(1) The rate \( a/\alpha_w \) at first decreases with time \( t \) monotonously, then it reaches a definite equilibrium constant. The required equilibrium time \( t_e \) is approximately 40 min, which is longer than the 15 min recommended by ASTM, so that the ASTM Standard is said to be insufficient.

(2) In both the equilibrium and the nonequilibrium region, the nuclei distributions do not change much even though cavitation suddenly occurs, and they have almost the same trend before and after the test runs.

(3) The relative exponent \( m \) and the volume concentration \( \nu_\alpha \), which characterize the nuclei distributions with respect to time (\( t = 4 \sim 120 \) min), can be divided into three regions, i.e., the equilibrium, the nonequilibrium and the transient region. The required equilibrium time is 60 min. In the equilibrium region \( m \) and \( \nu_\alpha \) scarcely fluctuate with time, suggesting that the nuclei are stable here. In short, the nonequilibrium region and the transient one where unfavorably unstable behavior arises on the cavitation aspects are said to be unsuitable for erosion tests.

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