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SUMMARY

Measured damping forces on fuel sloshing baffles of varying thickness are presented from tests conducted with water in a two-dimensional tank and a cylindrical tank. The results show that baffle thickness decreases baffle effectiveness by as much as 50 percent at moderate amplitudes of oscillation.

Ink-trace experiments conducted in the two-dimensional tank show baffle thickness effects on flow similarity. These results are used to show the mechanism by which baffle thickness affects damping. A table of critical thickness for flow similarity is given to serve as a guide to designers and experimenters.

INTRODUCTION

The design of baffles to damp liquid propellants in rocket vehicles usually depends upon results of experiments conducted in small-scale tanks. This procedure is followed because no satisfactory theoretical methods are available to account for the complex turbulent motion of the fluid, and full-scale tests are usually impractical during development stages of the rocket vehicle. Because of the wide gap in size between small-scale experiments and full-scale vehicles, the designer must determine whether or not certain results from small-scale experiments are applicable to full-scale vehicles. To help in this determination, experiments have been conducted on one problem area of small scale experiments, the baffle thickness.

Geometric similarity should be maintained between model and full-scale, and the thickness of the baffle is sometimes an important geometric parameter. Since, in true scale, most small scale models require exceedingly thin materials for baffles, there is a tendency to make the model baffle thicker to simplify construction. Unfortunately, in a great portion of the literature the thickness factor has been ignored to the extent that thickness of plates used is not even specified. Some limited effects of thickness were presented in reference 1 in which it was pointed out that moderate baffle thickness could reduce baffle effectiveness by as much as 50 percent. In the present report the effects of thickness are considered in more detail to allow designers to judge the applicability of various experiments and also to serve as a guide to experimenters.

Another scaling parameter for similarity is, of course, Reynolds number. However, it was pointed out by Miles in reference 2 that drag coefficient of plates reported in reference 3, was uncorrelated with Reynolds number over a range from 5×10^3 to 14×10^3. He also noted "a less reliable criterion is the critical Reynolds number above which the flow is fully turbulent and C_D constant in steady flow" ($\overline{Re} = 1000$). Because of this insensitiveness of drag coefficients to Reynolds number, a considerable number of experiments have been conducted in small tanks with water as a working fluid without regard for Reynolds number. To reduce the uncertain effects of critical Reynolds number as applied to oscillatory flow, the present experiments were conducted at mean Reynolds numbers of 3000 and greater.

In the present report, results of effects of baffle thickness on the damping effectiveness are presented from forced-oscillation measurements in a two-dimensional tank and free oscillations in a cylindrical tank. Ink patterns are also shown in order to demonstrate the mechanism of the flow and to indicate the limitations of application of model results.

NOTATION

A double amplitude of motion at the baffle edge

$\overline{A}$ mean double amplitude of motion at baffle edge in cylindrical tank

$\overline{V}$ mean absolute velocity of baffle edge, ft/sec

a cylindrical tank radius

a_1 amplitude of fundamental-frequency baffle force in phase with velocity for a thick plate

a_o amplitude of fundamental-frequency baffle force in phase with velocity for a thin plate

d depth of baffle measured from quiescent liquid surface to baffle center line

h depth of fluid

$\overline{Re}$ baffle Reynolds numbers defined in text for two-dimensional and cylindrical tank fluid oscillations

t baffle thickness

w baffle width measured along perpendicular line from wall to edge of baffle

y_s amplitude of liquid surface motion at tank wall in fundamental sloshing mode

ν kinematic viscosity for water at 78° F, 1.08×10^{-5} ft²/sec

ζ damping ratio

ζ_o damping ratio of tank without baffle

MEASURED DAMPING FORCES WITH VARIOUS THICKNESS RATIOS

Two types of damping measurements were used to vary baffle effectiveness with thickness: forced oscillation of plates in a two-dimensional tank and free oscillation in a cylindrical tank. In the forced-oscillation technique, the baffles were driven in sinusoidal motion in a rectangular tank with the baffles spanning the width of the tank. Thus, the flow was two-dimensional. The damping force was obtained by Fourier analysis of the amplitude and force measurements. In the free-oscillation technique, a cylindrical tank with ring baffles was placed in sinusoidal motion with a hydraulic drive system, and was then released. The damping effectiveness was obtained by taking the logarithmic decrement of the wave height measurements in free motion. The test equipment and reduction of data are described in reference 1.

Forced-Oscillation Data

The forced-oscillation measurements are shown on table I which gives the period of the oscillation and the Reynolds number which is defined as follows

$$\overline{Re} = \frac{2\overline{V}w}{\nu}$$

The Reynolds numbers in these tests are comparable to Reynolds numbers to be expected in full-scale tanks and are considerably above critical Reynolds numbers of 1 to 5×10^3 previously mentioned. The force measurements on the plate at three amplitude-to-width ratios (A/w) are shown over a range of frequencies. Finally, the effectiveness of the baffle relative to a plate 1/16 inch thick is shown as a_1/a_o. It may be seen that at amplitude-to-width ratios of 0.5 the thick plate is only half as effective as the thin plate. (It should be noted that the precision of these results is about 10 percent as stated in reference 1.)

Free-Oscillation Data

The free-oscillation damping ratios, obtained from the logarithmic decrement of wave height in a 3-foot-diameter cylindrical tank, are shown on figure 1 for various baffle thicknesses and for the baffle placed at various depths. The "zero thickness" baffle was obtained by grinding the outer edge of the $t/w = 0.04$ baffle to a sharp edge. The baffle was not made thinner because it was desired to maintain its rigidity so that results would not be confused with flexibility effects reported in reference 4. The amplitude-to-width range varies from about 0.5 to 1.1 for these tests based on the mean amplitude of the baffle around the ring

$$\bar{A} = \frac{4}{\pi} y_s e^{-1.84d/a}$$

Mean Reynolds numbers here are 3×10^3 and greater defined as follows:

$$\overline{Re} = \frac{4}{\pi^2} 1.425\times10^6 \, a^{3/2} \frac{w}{a} e^{-1.84d/a} \frac{y_s}{a}$$

where dimensions are in feet. This Reynolds number is based on the mean absolute velocity of the baffle edge averaged around the ring, the baffle width, and a kinematic viscosity of water of 1.08×10^{-5} ft^2/sec. This Reynolds number becomes equivalent to the one used in reference 2 with the approximation

$$\alpha = \frac{w}{a}\left(2 - \frac{w}{a}\right) \approx 2\frac{w}{a}$$

It may be seen from the results that increasing thickness tends to reduce baffle effectiveness (with the exception of a reverse trend from 0 to 0.04). In view of the fact that the zero thickness was obtained by sharpening the outer edge and, hence, that geometric similarity was violated, it is not known whether the reverse trend is due to thickness or to the geometric change.

Effect of Amplitude

The data from the previous sections are shown plotted on figure 2 versus amplitude-to-width ratio and approximate fairings have been shown so that thickness effects can be estimated. The data from figure 1 were referenced to the 0.04 baffle and data on table I are referenced to a baffle with a thickness ratio of 0.01. Also the damping ratio without baffles (ζ_o) was subtracted before taking the ratio so that the true effect of the baffle on the damping would be obtained. It should be noted that the data are quite consistent within ±15 percent which is the precision to be expected when extracting damping values from slow time-varying exponential decays. The solid lines are approximate curves to indicate trends within this precision. It is interesting that the thick baffles have effectiveness approaching that of the thin plate at large amplitudes.

As previously noted, the effect of small geometric changes, such as sharpening the baffle edge, has not been determined. In the free-oscillation tests, the baffles had sharp corners as compared to the slightly rounded baffle edge for the forced-oscillation tests (table I). In view of the consistency of the data on figure 2, it appears that the effect of this geometric change is small compared to the overall thickness effect. The data on figure 2 may also be compared with the free-oscillation data referenced to the zero-thickness baffle without substantially changing the comparison. Hence, it appears that the effect of these small geometric changes is secondary and falls within the precision of the data.

Ink-Trace Experiments[1]

Because of the large difference in the measured forces on thick and thin baffles, some ink-trace experiments were conducted in order to gain an insight into the flow mechanism. Baffles 3 inches wide with various thickness-to-width ratios were installed on the side wall in the two-dimensional tank of reference 1. A depth of five times the baffle width was used so that surface effects would be negligible. The water in the tank was oscillated by a hand paddle to give amplitude-to-width ratios from 0.33 to 2.5 which correspond to Reynolds numbers from 5×10^3 to 40×10^3. During the oscillations a thinned mixture of India ink was introduced at the baffle edge, and the motion was photographed with a 16 mm movie camera.

Several frames of ink patterns are shown on figure 3. The background grid is in 1-inch squares and the curved line shown is the theoretical streamline for the tank without a baffle as given in reference 5. At a constant amplitude of oscillation, a distinct change in the flow pattern occurs as the baffle becomes thicker. At an amplitude-to-width ratio of 0.6, baffles up to $t/w = 0.1$ shed a single strong vortex as shown on figure 3(a). Baffles of $t/w = 0.23$ and thicker, on the other hand, shed multiple small vortices which traveled inward along the surface of the baffle (fig. 3(b)).

The paths for upper and lower vortices were traced and are drawn on figure 4. The paths for the $t/w = 0.02$, 0.04, and 0.10 baffles were clearly defined. For the 0.23 baffle and thicker, a single strong vortex did not form, and hence, the lines indicate only the average direction of ink flow. The beginning of the change in the vortex pattern is apparent on the trace for the 0.10 t/w baffle.

Similar studies were conducted at other amplitudes and the results are given in table II. The flow conditions for which a single vortex formed and followed a path away from the baffle are indicated by plus signs. Conditions where no clear vortex formed and the flow was along the baffle are marked with a minus sign. Since there is a clear lack of flow similarity between the plus and minus regions, experiments conducted in one region should not be applicable to the other.

Table II indicates where major changes in flow configuration occur, but it does not show smaller degrees of change in detail. For example, in figure 4 it may be seen that the vortex path for the $t/w = 0.1$ baffle differs somewhat from that of the thinner baffles. In the presence of the boundaries, the upper vortex will tend to move downward and outward. This is counteracted by the upward motion of the fluid until the downward half of the cycle begins. At this time the lower vortex forms with opposite rotation and the two vortices then move outward away from the baffle.

Since the oscillatory fluid motion is held constant, the strength of the vortex determines the path. Hence, changes of vortex strength can be detected by studying the vortex path. In figure 4, it may be seen that both the upper

[1]Acknowledgment is given to William E. Moritz for developing and conducting the ink-trace experiments.

and the lower vortices of the 0.1 baffle deviate from the path of the vortices shed by the thinner baffles. The direction of the deviation indicates that the vortices are becoming weaker and that the 0.1 thick baffle is less effective than the thinner ones. When a thickness of 0.23 is reached, the vortices are so weak that they travel inward instead of outward.

Application of Results

Table II and figure 2 may be used to evaluate thickness effects over a range of Reynolds numbers from 3,000 to 170,000. Table II indicates the boundary of complete breakdown in flow similarity across which experimental results obtained in one region would not be valid in the other region. The loss of effectiveness due to thickness can be estimated from figure 2 within the precision indicated and over the Reynolds number range indicated. These results would not be expected to apply for Reynolds numbers lower than 3,000 since the critical Reynolds number should be higher for thick plates than for thin ones.

These new experimental results may have a large effect on the interpretation of model test results. For example, in figure 12 of reference 4, data obtained with a moderately thick baffle ($t/w = 0.22$) are compared at amplitude-to-width ratios of 0.2 to 1.5 with Miles' equation which is based on data from relatively thin baffles ($t/w = 0.07$). On the basis of the comparison, it is concluded that the "trends and magnitudes agree closely with the equation." In the present report it is shown that the vortex flow differs widely for the above baffle thicknesses at the amplitude-to-width ratios of the test. The agreement, then, can only be considered fortuitous because the numerical values of damping are meaningless unless flow similarity is established.

The results of reference 4 may be interpreted in the light of reference 6 in which Miles' equation is compared with measured damping of baffles of comparable thickness in a 3-foot-diameter tank. Reasonably good agreement is obtained when the tare damping (ζ_o) is added to the equation. If this is accepted as the correct procedure, then it would appear that the agreement in reference 4 is due to the compensating effect of the tare damping and the baffle thickness. The addition of the tare damping to Miles' equation is reasonable because no provision was made in the equation for this effect. The question of the tare damping becomes especially critical in small tanks at low amplitudes of oscillation where the tare damping is a significant part of the total damping measurement.

Throughout the literature, many other experiments are described in which baffle thickness is not specified. Unless flow similarity is established for these experiments, agreement with theory may be only fortuitous as in the example above, and application of the results to large-scale tanks will be questionable.

CONCLUSIONS

The damping of oscillating plates of varying thickness has been measured with water in a two-dimensional tank and in a cylindrical tank over a range of amplitudes and frequencies at Reynolds numbers from 3,000 to 170,000. Ink-trace experiments were also conducted to study details of the vortex patterns. On the basis of these results the following conclusions have been reached.

1. The effectiveness of fuel-sloshing baffles depends on the thickness of the baffle and the amplitude of oscillation, and these effects should be taken into account in applying model results to full-scale designs and in comparing results of experiments.

2. Baffle effectiveness is closely related to the vortex path; the thickness effect is apparent on ink-trace patterns.

3. In comparison of theory and experiment in small-scale tests, results are not reliable unless actual similarity of flow is established.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., April 15, 1966

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TABLE I.- FORCE MEASUREMENTS ON OSCILLATING PLATE WITH THICKNESS RATIO OF 0.2

Run	Period, sec	$\overline{Re} \times 10^{-3}$	a_1, lb	A/w	a_1/a_0
259	1.21	122	12.4	1.54	0.92
260	1.01	146	17.8	1.54	.96
261	.87	170	26.4	1.54	1.05
262	1.20	83	6.2	1.03	.85
263	1.01	98	8.6	1.03	.80
264	.90	111	11.5	1.03	.81
265	.76	130	14.0	1.03	.82
266	1.01	48	2.2	.5	.55
267	.76	64	3.4	.5	.51
268	.63	77	4.7	.5	.52
269	.51	94	5.5	.5	.46

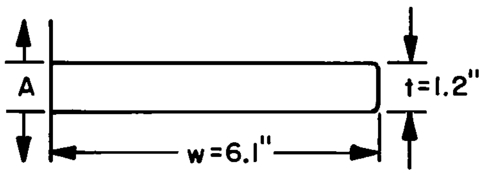


TABLE II.- SUMMARY OF VORTEX SHEDDING OBSERVATIONS

A/w	0.33	0.6	0.99	1.56	2.46
$\overline{Re} \times 10^{-3}$ / t/w	5.4	9.7	16.3	25.8	40.7
0.02	+	+	+	+	+
.04	+	+	+	+	+
.10	+	+	+	+	+
.23	–	–	+	+	+
.42	–	–	–	–	–
.49	–	–	–	–	–

\+ Clear vortex formation
\- Vortex undeveloped

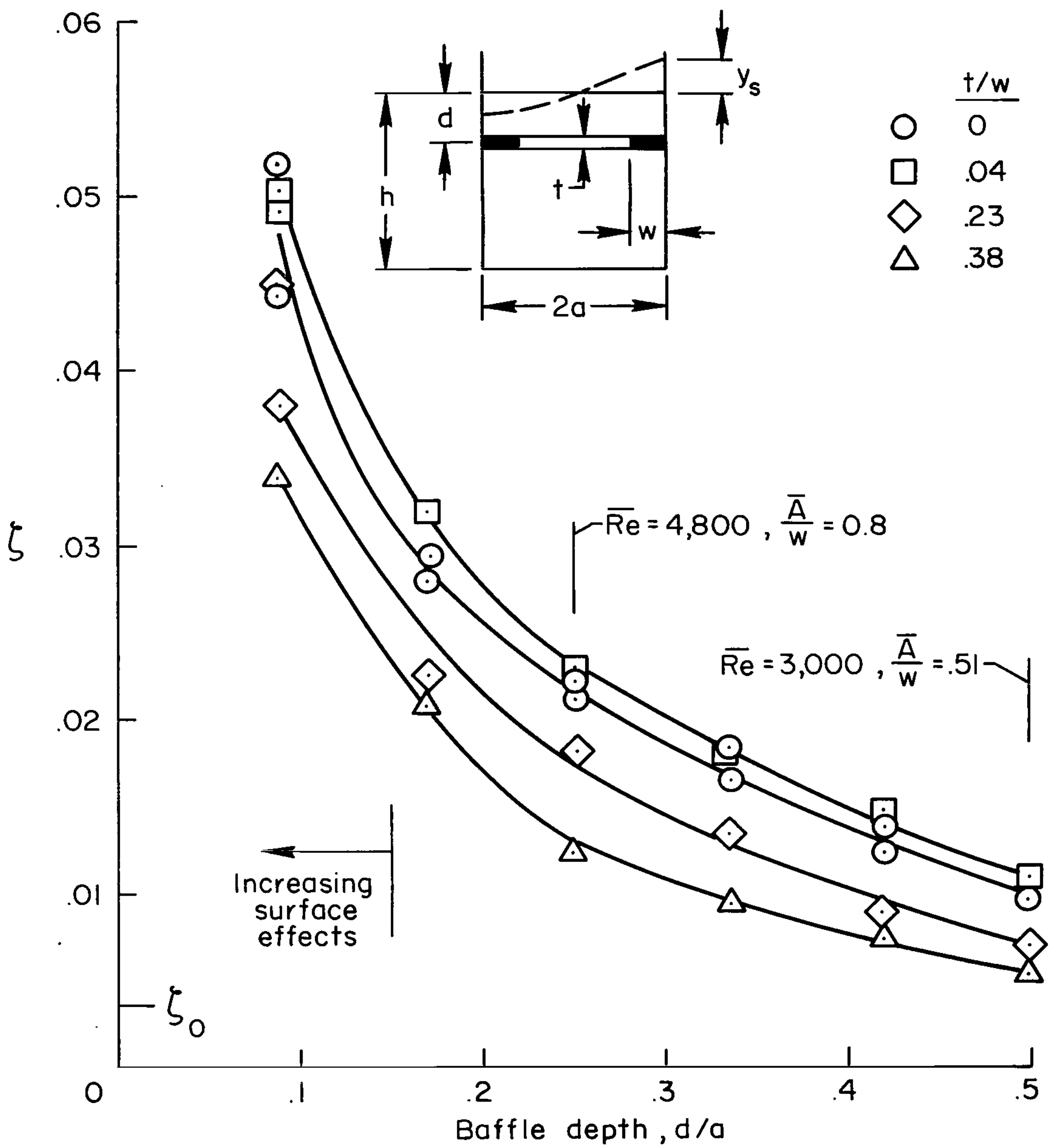


Figure 1.- Measured damping in a 3-foot-diameter tank with baffles of various thicknesses ($w/a = 0.084$, $h/a = 2$, $y_s/a = 0.084$).

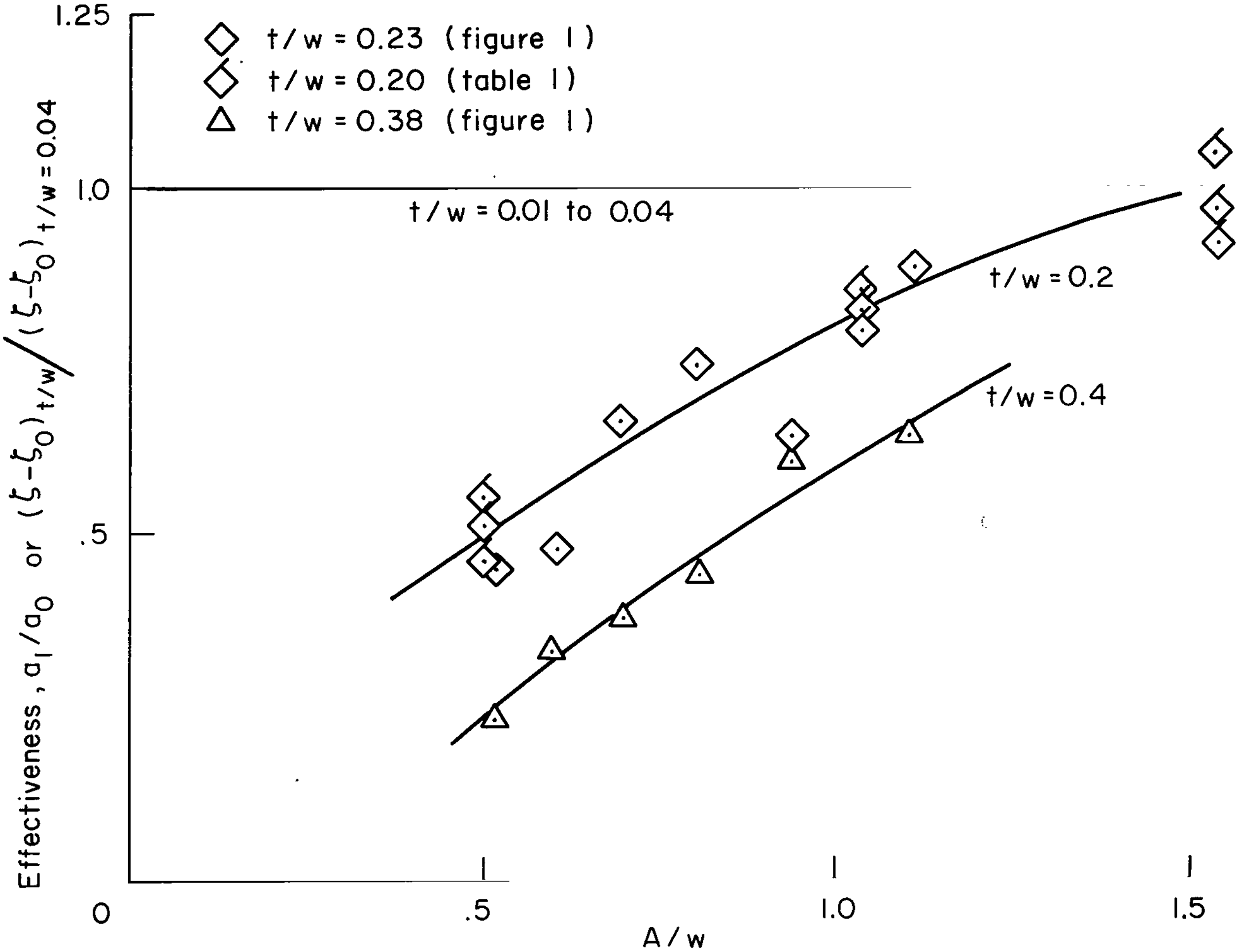
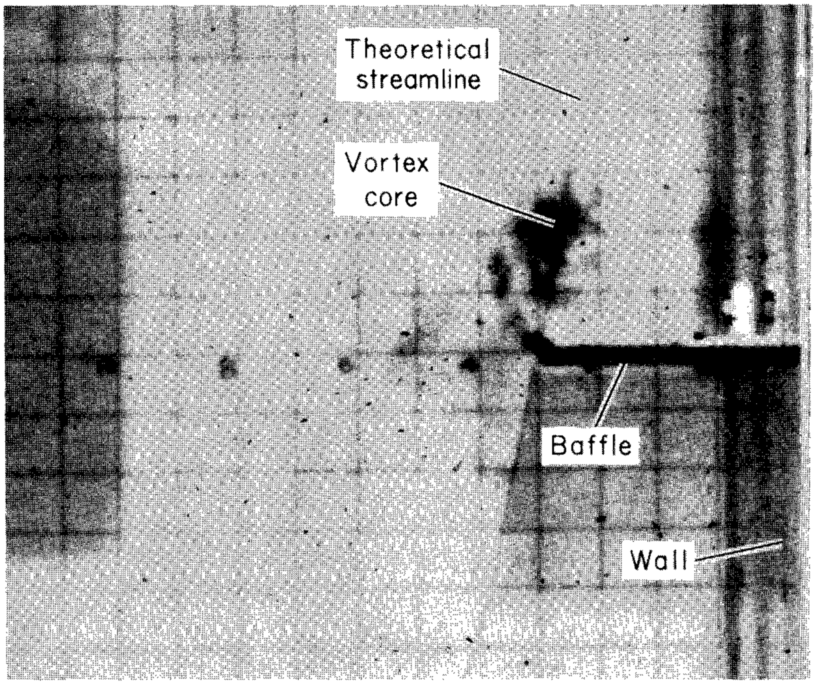
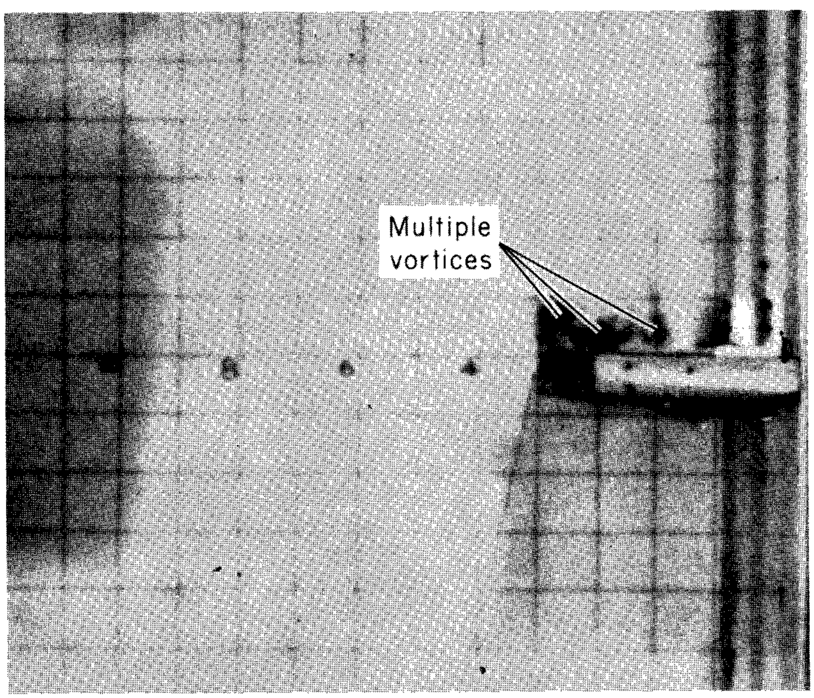


Figure 2.- Variation of baffle thickness effect with amplitude to width ratio.



(a) t/w = 0.1, A/w = 0.6



(b) t/w = 0.23, A/w = 0.6

Figure 3.- Example ink trace patterns shown at the same amplitude.

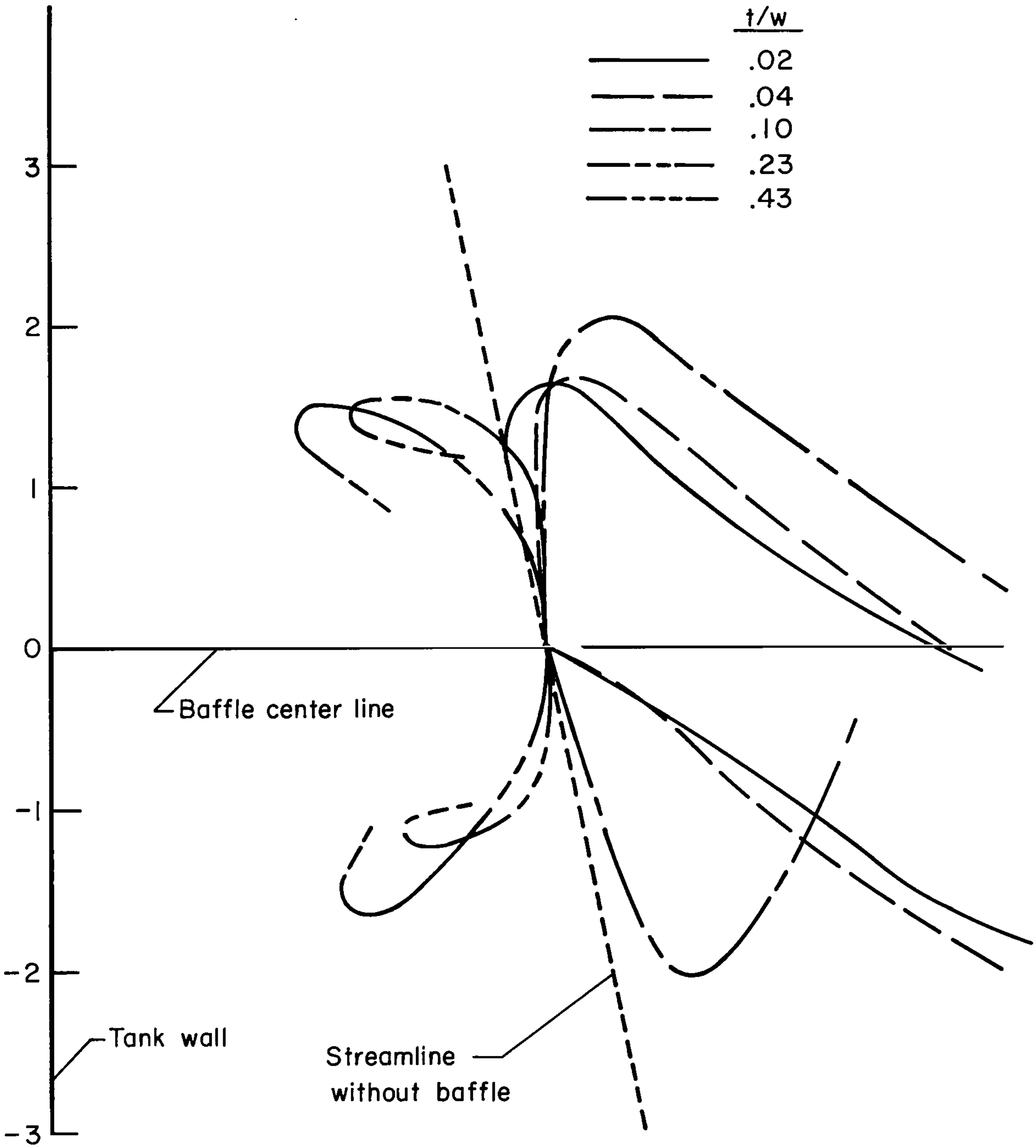


Figure 4.- Vortex paths for baffles of various thicknesses ($A/w = 0.6$, $Re = 10 \times 10^3$).

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