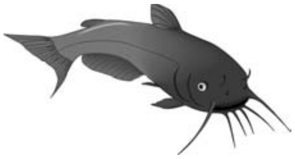
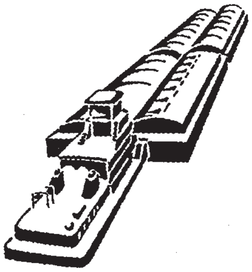
ENV Report 23

Interim Report For The Upper Mississippi River - Illinois Waterway System Navigation Study



Concentric Cylinder Experiments of Shear Mortality of Eggs and Larval Fish



January 2000

Rock Island District
St. Louis District
St. Paul District

US Army Corps
of Engineers

Upper Mississippi River - Illinois Waterway
System Navigation Study

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Concentric Cylinder Experiments of Shear Mortality of Eggs and Larval Fish

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Contents

Preface

The work reported herein was conducted as part of the Upper Mississippi River-Illinois Waterway (UMR-IWW) System Navigation Study. The information generated for this interim effort will be considered as part of the plan formulation process for the System Navigation Study.

The UMR-IWW System Navigation Study is being conducted by the U.S. Army Engineer Districts, Rock Island, St. Louis, and St. Paul, under the authority of Section 216, Flood Control Act of 1970. Commercial navigation traffic is increasing and, in consideration of existing system lock constraints, will result in traffic delays that will continue to grow into the future. The system navigation study scope is to examine the feasibility of navigation improvements to the Upper Mississippi River and Illinois Waterway to reduce delays to commercial navigation traffic. The study will determine the location and appropriate sequencing of potential navigation improvements on the system, prioritizing the improvements for the 50-year planning horizon from 2000 through 2050. The final product of the System Navigation Study is a Feasibility Report, which is the decision document for processing to Congress.

The work was performed by members of the staff of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), during 1997-1998. The study was under the direction of Dr. James R. Houston, Director, CHL; and Mr. C. E. Chatham, Jr., Chief, Navigation and Harbors Division (NHD), CHL. The study was conducted by Dr. S. T. Maynord, Navigation Branch, NHD.

At the time of publication of this report, Acting Director of ERDC was Dr. Lewis E. Link. Commander was COL Robin R. Cababa, EN.

1 Introduction

Background

The Upper Mississippi River-Illinois Waterway System (UMR-IWWS) Navigation (Feasibility) Study will evaluate the justification of providing additional lockage capacity at sites on the UMR-IWWS while maintaining the social and environmental qualities of the river system. The system navigation feasibility study will be accomplished by executing the Initial Project Management Plan (IPMP) outlined by the U.S. Army Engineer Districts (USAED), St. Paul, Rock Island, and St. Louis (USAED 1994). The IPMP outlines Engineering, Economic, Environmental, and Public Involvement Plans.

The Environmental Plan identifies the significant environmental resources on the UMR-IWWS and probable impacts in terms of threatened and endangered species; water quality; recreational resources; fisheries; mussels and other macro invertebrates; waterfowl; aquatic and terrestrial macrophytes; and historic properties. It considers system-wide impacts of navigation capacity increases, while also assessing in preliminary fashion potential construction effects of improvement projects.

One element of the Environmental Plan addresses the impacts of navigation on larval and adult fish. One element of the fish study addressed in another part of the UMR-IWWS study is the mortality of early life stages of fish that pass through the propeller jets of commercial tows. The part of the fish study addressed herein evaluates the impact of early life stages of fish passing near the hull of the vessel where they could be exposed to shear stress that could lead to mortality. The various elements of the hull shear mortality study are the waterway zone passing adjacent to the hull, the distribution of larval fish in the hull passage zone, the quantity of water passing through the zone having lethal values of shear stress, and the mortality of larval fish subjected to shear stress.

Objective

The objective of this study is to evaluate the experiments by Morgan et al. (1976) who used concentric cylinders to determine the mortality of larval fish subjected to shear stress.

2 Mortality Tests (Morgan et al. 1976)

Details of Experiments

Morgan et al. (1976) conducted mortality experiments using concentric cylinders to subject larval fish and eggs to shear stress. Details of the experiments can be found in Morgan et al. (1973). The outer cylinder (30.5-cm-diam) was stationary, while the inner cylinder (25.4-cm-diam) rotated. The experimental region between the cylinders was filled with water and larval fish or eggs. Morgan et al. (1976) reported LS_{50} (lethal shear) values which is the shear required to kill 50 percent of a specified life stage within a given time interval. The Morgan et al. (1976) results for long-term exposure are shown in Table 1.

Table 1
Mortality Results for Long-Term Exposure to Shear Stress (Morgan et al. 1976)

Species and Life Stage	Exposure, days	LS_{50}, dynes/sq cm
White perch eggs	3	56.5
White perch larvae	3	87.5
Striped bass eggs	2	70.3

The Morgan et al. (1976) LS_{50} for long-term shear mortality can be compared with the shear stress that occurs during normal river flows. Bed shear stress can be approximately determined from

$$\tau = \gamma h S \qquad (1)$$

where

τ = bed shear stress

γ = unit weight of water

h = local flow depth

S = slope

The slope of the Upper Mississippi river is about 0.000095, and the main channel depth at normal flows is about 6.1 m. The resulting bed shear stress is about 57 dynes/sq cm. The bed shear stress is zero at the water surface, and a linear variation between bed and water surface is a fair approximation. As a general rule, the shear stress will be higher in bends and at higher flows and lower away from the main channel and at lower flows. This ambient value of about 57 dynes/sq cm at the bed can be compared to the results for long durations given in Table 1 (Morgan et al. 1976). If the Morgan et al. (1976) long-duration LS_{50} values are correct, ambient flows expose these three species to near lethal values of shear when they are near the bed of the river. It seems unlikely that normal ambient flows are damaging significant numbers of larvae and eggs. This suggests that it will require more shear than Morgan et al. (1976) estimated to cause the reported mortality levels, at least for long-duration exposure.

The Morgan et al. (1976) results for short-term exposure are shown in Table 2.

Table 2
Mortality Results for Short-Term Exposure to Shear Stress (Morgan et al. 1976)

Species and Life Stage	Exposure, min	LS_{50}, dynes/sq cm
Striped bass eggs	1 2 4	542 255 190
Striped bass larvae	1 2 4	785 510 300
White perch eggs	1 2 5 10 20	425 415 175 165 120
White perch Larvae	1 2 4	415 340 125

Based on a review by Garcia (1996) attached as Appendix A, two questions must be answered before the Morgan et al. (1976) results can be adopted for application to the UMRS. These questions are:

a. Is the shear in a concentric cylinder similar to the shear in the boundary layer along the hull of a vessel?

b. Are torque measurements available in the range of Reynolds number R used by Morgan et al. (1976) so that the empirical results of Wendt (1933) (see Donnelly and Simon 1959) do not have to be extrapolated?

These questions are answered in the following paragraphs.

Similarity of Shear in a Concentric Cylinder and in the Boundary Layer Along the Hull of a Vessel

Based on the findings of Lathrop, Fineberg, and Swinney (1992), flow in a concentric cylinder having R > 1.3 × 10^4 behaves like a wall-bounded shear flow (such as pipe flow, duct flow, and flow over a flat plate). Lathrop, Fineberg, and Swinney (1992) based their conclusions on similarity of the mean zero crossing times and conformity to a Prandtl-von Karman-type skin friction law. Reynolds number is defined as

$$R = \frac{\Omega\, R_1 \left(R_2 - R_1\right)}{\nu} \tag{2}$$

where

R_1 and R_2 = radius of the inner and outer cylinders

Ω = angular rotation in rad/sec

ν = kinematic viscosity of water

Reynolds number in the Morgan et al. (1976) experiments ranged from 1.0 × 10^5 to 4.0 × 10^5 which is larger than the minimum found by Lathrop, Fineberg, and Swinney (1992).

Torque Measurements at Large Reynolds Number to Validate Wendt (1933) Equation

Morgan et al. (1976) used the Wendt (1933) equation to define the relationship between shear stress and rotation speed of the inner cylinder. Wendt (1933), as presented in Donnelly and Simon (1959), determined the friction coefficient C_{fi} on the inner cylinder as

$$C_{fi} = 0.073 \left[\frac{\left(R_2 - R_1\right) R_2}{R_1^2} \right]^{0.25} R^{-0.3} \tag{3}$$

and

$$C_{fi} = \frac{\tau_i}{1/2\, \rho\, \Omega^2\, R_1^2} \tag{4}$$

where

τ_i =shear stress on the inner cylinder

ρ = water density

From Donnelly and Simon (1959), Wendt's equation (3) is valid above R = 1 × 10^4, but data used in the development of this empirical relation were limited to R = 1 × 10^5. Wendt's (1933) equation was based on data having R_1/R_2 = 0.935, 0.850, and 0.680. The Morgan et al. (1976) test cylinder had R_1/R_2 = 0.833. Lathrop, Fineberg, and Swinney (1992) conducted torque measurements for R from 8 × 10^2 to 1 × 10^6 in a cylinder having R_1/R_2 = 0.725. For Reynold's number in the Morgan et al. (1976) experiments from 1 × 10^5 to 4 × 10^5, the Lathrop, Fineberg, and Swinney (1992) torque data having R_1/R_2 = 0.725 varied from the Wendt (1933) Equations 3 and 4 by less than 10 percent based on Figure 10 of the Lathrop, Fineberg, and Swinney (1992) report. Therefore, the Wendt equation is valid for the range of Reynold's number used in the Morgan et al. (1976) experiments.

Evaluation of Morgan et al. (1976) Shear Values

The Morgan et al. (1976) report was not clear on how the LS_{50} values were determined from the inner cylinder speed of rotation other than referencing Donnelly and Simon (1959). In addition, the LS_{50} values from the Morgan et al. (1973) report were significantly less than the values in the Morgan et al. (1976) report. A telephone conversation with R. E. Ulanowicz (Co-author of Morgan et al. 1973 and 1976) resulted in his recollection of some problem with the 1973 LS_{50} values that were corrected in the 1976 report. Rotation speeds for the inner cylinder were not given in the 1973 nor the 1976 report. Morgan et al. (1973) used the following relationship between average shear and RPM.

$$\tau = 0.00288\,(RPM) \tag{5}$$

The Morgan et al. (1973) LS_{50} values were incorrect because Equation 5 is not applicable to R from 1 × 10^5 to 4 × 10^5. Table 3 provides the Morgan et al. (1973) LS_{50} values and the derived speed of the inner cylinder based on the 1973 LS_{50} values and Equation 5. This is not exactly a correct transformation because the LS_{50} values do not represent an actual experiment but are the result of numerous experiments at ranges of both duration and shear stress. The error in using the LS_{50} values to determine the rotation speed that produces a 50-percent mortality should not be large. Combining the Wendt (1933) Equations 3 and 4 and substituting ρ = 1 gram/cm^3, ν = 0.01 cm^2/sec, and the geometry of the Morgan el al. (1976) experimental cylinders results in

$$\tau_i = 0.365\,\Omega^{1.7} \tag{6}$$

or

$$\tau_i = 0.00788\,RPM^{1.7} \tag{7}$$

Table 3
Mortality Results for Short-Term Exposure to Shear Stress and Computed Shear Using Equation 7 (after Wendt (1933)) and Equations 8 Through 11 (after Lathrop, Fineberg, and Swinney (1992)) Using the Derived Speed of Rotation of the Inner Cylinder (after Morgan et al. 1976 and 1973)

Species and Life Stage	Exposure, min	LS_{50}, dynes/sq cm (Morgan et al. 1976)	LS_{50}, dynes/sq cm (Morgan et al. 1973)	Derived Speed of Inner Cylinder, RPM (from Eq 5 and 1973 LS_{50})	LS_{50}, dynes/sq cm (from Eq 7 and Derived RPM)	LS_{50}, dynes/sq cm (from Eq. 8-11 and Derived RPM)
Striped bass eggs	1	542	2.1	729	579	470
	2	255	1.16	403	212	164
	4	190	1.04	361	175	135
Striped bass larvae	1	785	3.4	1,181	1,316	1,113
	2	510	2.1	729	579	470
	4	300	1.25	434	240	187
White perch eggs	1	425	1.7	590	405	323
	2	415	1.6	556	365	291
	5	175	0.88	306	132	101
White perch larvae	1	415	1.63	566	377	300
	2	340	1.38	479	284	223
	4	125	0.9	313	138	105

Equations 6 and 7 can be used with reasonable accuracy over the range of Reynolds Number used in the Morgan et al. (1976) tests. Table 3 shows the shear stress computed using the derived RPM and Equation 7. Also shown in Table 3 is the shear stress using the Lathrop, Fineberg, and Swinney (1992) model as described by Lewis (1996) using the derived speed of rotation of the inner cylinder. The Lathrop model assumes two logarithmic velocity profiles that match at the middle of the gap which results in

$$\frac{R}{\sqrt{G}} = N \; Log_{10} \sqrt{G} + M \tag{8}$$

where G is the dimensionless torque and

$$N = \frac{\left(1-\eta^2\right)Ln10}{\eta\kappa\sqrt{2\pi}} \tag{9}$$

where

η = inner cylinder radius/outer cylinder radius

κ = von Karman constant = 0.4 and

$$M = \frac{N}{Ln10}\left\{ Ln\left[\frac{1-\eta}{(1+\eta)y_0^+\sqrt{2\pi}}\right] + \kappa y_0^+ \right\} \tag{10}$$

and

$$\tau = \frac{\rho G \nu^2}{2\pi R_2^2} \tag{11}$$

where ρ is the water density.

Lewis (1996) found that the parameter $y_0^+ = 3$ provided a good fit of the data having $R_1/R_2 = 0.725$ and was used in the Table 3 calculations. The Lathrop, Fineberg, and Swinney (1992) model produces computed shear stress that averages 79 percent of the Morgan et al. (1976) values. Some of this difference is due to Wendt (1933) using the inner cylinder radius to compute shear stress whereas Lathrop, Fineberg, and Swinney (1992) use the outer cylinder radius.

Comparison of Hull Shear and Mortality Results (after Morgan et al. 1976)

Typical boat speeds and lengths on the UMRS suggest durations of exposure to the shear stress for 1 to 2 min, depending on vessel speed and length. Based on the results from Keevin et al. (in preparation), a high-speed (4-m/sec), five-barge-long, loaded tow, operating in shallow water of 3.7 m with 2.7-m draft, has a shear stress of greater than 250 dynes/sq cm in only 5 percent of the region beneath the tow. The same tow has shear stress greater than 225 dynes/sq cm and 135 dynes/sq cm in 10 percent and 50 percent of the region beneath the tow, respectively. For the same tow and channel depth, a typical tow speed (2.9 m/sec) results in shear stress greater than 142, 129, and 87 dynes/sq cm in 5, 10, and 50 percent of the region beneath the tow, respectively. For high-speed tows, the duration of shear exposure is about 1 min, whereas typical tow speeds result in duration of exposure of about 2 min. The Morgan et al. (1976) values of LS_{50} for a duration of 1 or 2 minutes ranges from 255 to 785 dynes/sq cm as shown in Table 3. While the LS_{50} values are greater than the representative shears from Keevin et al. (in preparation) for both fast and typical tow speeds, some level of mortality is expected. Morgan et al. (1976) presents regression equations for each species/life stage and duration tested that allows determination of percent mortality as a function of shear stress in dynes/sq cm. Using representative shear stresses of 225 dynes/sq cm (10 percent of zone, fast tow speed), 135 dynes/sq cm (50 percent of zone, fast tow speed), and 87 dynes/sq cm (50 percent of zone, typical tow speed), the percent mortality is shown in Table 4. For typical vessel speed (2.9 m/sec) and a representative shear (87 dynes/sq cm) that is exceeded/not exceeded in 50 percent of the zone beneath the tow, the average mortality for the four species/life stages is about 9 percent.

Table 4
Percent Mortality for Representative Shear Stresses of 225, 135, and 87 dynes/sq cm

Species/Life Stage	Coefficients A,B for 1-min Duration Applicable to Fast Tow Speed	Percent Mortality for Shear = 225 dynes/sq cm for 1-min Duration	Percent Mortality for Shear = 135 dynes/sq cm for 1-min Duration	Coefficients A,B for 2-min Duration Applicable to Typical Tow Speed	Percent Mortality for Shear = 87 dynes/sq cm for 2-min Duration
Striped bass eggs	-0.278,0.723	26	18	-0.721,1.006	17
Striped bass larvae	-4.361,2.094	4	1	-2.008,1.370	4
White perch eggs	-1.806,1.333	21	11	-1.430,1.194	8
White perch larvae	-2.681,1.675	18	8	-2.277,1.571	6

Note: Regression equation is Log Y = A+B Log X, where Y is the percent mortality and X is the shear stress in dynes/sq cm. Coefficients A and B from Morgan et al. (1976).

3 Discussion of Results and Conclusions

Results show that the Morgan et al. (1976) mortality tests are representative of shear along the hull of a vessel, and the shear stress computed in that publication is validated by recent measurements. The computed shear along the hull of UMR-IWWS tows is below the levels required to produce mortality of 50 percent of the fish eggs and larval tested. For typical vessel speed (2.9 m/sec) and a representative shear (87 dynes/sq cm) that is exceeded/not exceeded in 50 percent of the zone beneath the tow, the average mortality for the four species/life stages is 9 percent. The Morgan et al. (1976) results do not provide information about the sensitivity of most species of fish in the UMR-IWWS. Some of these species may be more sensitive to shear than the striped bass and white bass tested by Morgan et al. (1976).

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Appendix A

A Review of the Technique Used by Morgan et al. (1976) to Estimate Shear-Induced Larval Fish and Eggs Mortality

Appendix A A Review of the Technique Used by Morgan et al. A1

A REVIEW OF THE TECHNIQUE USED BY MORGAN *ET AL.* (1976) TO ESTIMATE SHEAR-INDUCED LARVAL FISH AND EGGS MORTALITY

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REVIEW AND ANALYSIS

Shear stresses generated by navigation traffic can kill fish eggs and larvae by causing rotation and deformation. Morgan *et al.* (1976) estimated shear-induced mortality rates with the help of a Couette cell. Such apparatus consisted of two concentric cylinders, one of 20.3 cm diameter and one of 30.5 cm diameter mounted in a constant temperature bath. A 25.4 cm diameter cylinder was placed between the 20.3 cm and the 30.5 cm cylinders such that the 25.4 cm cylinder could be rotated in a concentric path with the help of a pulley system attached to fixed-speed gear motors. The shear stress experienced by a fish egg or larva in such experimental apparatus is a function of the speed of rotation of the middle cylinder.

Couette cells such as the one used by Morgan *et* al. (1976), have been used extensively to generate well-controlled shear-stress conditions (e.g. Latz *et al.,* 1994; Mead and Denny, 1995). However, particular care must be exercised when designing and building such apparatus, because for certain conditions the flow between the cylinders might become unstable. This would render theoretically determined values of shear-stress, and thus the associated mortality rates, useless.

Unfortunately, the configuration chosen by Morgan *et* al. (1976) to determine mortality rates, was one that promoted the formation of Taylor vortices. They concentrated their observations in the outer annulus, where the gap between the outer and the middle rotating cylinder is equal to: $d = (30.5 - 25.4)/2 = 2.55$ cm. When such gap is divided by the radius of the middle rotating cylinder, R, = 25.4/2, d/R, = 0.20. Such value places the Couette flow apparatus used by Morgan *et al.* (1976) in the category of those having a so-called “wide gap” (Donnelly and Simon, 1959). The parameter used to determine the conditions for which vortices will develop is known as the Taylor number, and for the wide-gap case takes the form (Walowit *et al.,* 1964)

$$T = \frac{2\,\Omega^2 R_1^2 d^3}{\nu^2 (R_1 + R_2)} \tag{1}$$

where Ω is the angular velocity of the rotating cylinder in rad/sec, d is the gap between the outer and the rotating cylinder, R_1 and R_2 are the radius of the rotating and the outer cylinder, respectively, and ν is the kinematic viscosity of the fluid between the cylinders. There is a critical value of the Taylor number $T_c \cong 1800$, above which Taylor vortices are bound to appear. For the geometry used by Morgan *et al.* (1976), the critical angular velocity associated with the above mentioned critical Taylor number would be $\Omega_c = 1.40$ rad/sec. Herein $\nu = 0.01$ cm²/s was used, which corresponds to a water temperature of 20°C and seems to be the value used by Morgan *et al.* (1976) in their experiments. Such critical angular velocity corresponds to $(1.40 \times 60)/2\pi = 13.37$ rpm. Since the Dayton fixed-speed gear motors have rpm's of 14, 61, 158, and 231, respectively, the above computations indicate that practically in all the tests conducted by Morgan *et al.*, flow instabilities were most likely present.

While in their paper Morgan *et al.* (1976) recognized the fact that the shear stresses corresponding to the flow in the outer annulus could not be estimated theoretically, an inspection of the original report on which the paper is based (Morgan *et al*, 1973) suggests that Morgan and his co-workers where convinced at the time they conducted the experiments, that a theoretical prediction of the shear stresses induced in the Couette apparatus was possible. In fact, Morgan *et al.* (1976) acknowledged one of the reviewers for bringing up the Taylor instability problem to their attention.

It is not clear how Morgan *et al.* (1976) ended up estimating the shear stress values that appear in their paper. They used Figure 4 in Donnelly and Simon (1959) as an example of how to estimate the magnitude of the shear stress for the lowest rpm value employed by them, but they do not explain how the values for the other rpm values where obtained. If the values in Table 1 of their report (Morgan *et al.*, 1973) are compared with those in Table 3 of their paper (Morgan *et al.*, 1976) the differences are quite large. For example, for white perch eggs under a 1 minute exposure, the report gives a shear stress of 1.70 dynes/cm^2 for a 50% mortality rate, while the paper gives a value of 425 dynes/cm^2 for the same mortality rate! Notice that the value in the paper is 250 times larger than the one in the report. Such large discrepancies can also be observed for the rest of the fish eggs and larvae tested by Morgan *et al.*

ESTIMATION OF SHEAR STRESSES

In what follows an attempt is made to estimate the magnitude of the shear stresses that were most likely produced by the Couette flow apparatus used by Morgan *et al.* (1973, 1976).

In page 7 of their report, Morgan *et al.* (1973) show the relation that they used to estimate average shear stresses as a function of rotational speeds:

$$\bar{\tau} = 0.00288 \times \text{rpm} \qquad \textbf{(2)}$$

where $\bar{\tau}$ is in dynes/cm^2. Such relation can be used to back calculate the rpm values corresponding to the average shear stress quoted in the report.

Once the rpm values are known, they can be converted into angular speeds or Ω values. Donnelly and Simon (1959, p. 413) give an empirical relationship (eqtn 24b) that was obtained for the observations made by Wendt (1933) using a wide-gap Couette apparatus having a d/R$_1$ ratio of 0.18 and a gap d = 2.2 cm both quite similar to the ones associated with the Morgan *et al.* apparatus. Such equation is:

$$\lambda = 0.073 \left[\frac{(R_2 - R_1) R_2}{R_1^2} \right]^{1/4} R_e^{-0.3} \qquad \textbf{(3)}$$

where:

$$\lambda = \frac{\tau_i}{\frac{1}{2}\,\Omega^2 R_1^{\,2}} \qquad \textbf{(4)}$$

and

$$R_e = \frac{\Omega R_1 (R_2 - R_1)}{\nu} \qquad \textbf{(5)}$$

Equation (3), which is valid for Reynolds numbers R_e larger than 10^4, can be used to estimate shear stress τ_i at the surface of the rotating cylinder. Such computations were done for the low intensity, long-term exposure experiments (TABLE A) as well as for the high intensity, short-term exposure experiments (TABLE B). Tables A and B correspond to Tables 1 and 3 in Morgan *et al.* (1976), respectively.

In general the magnitude of the computed shear stresses (τ_i values) is found to be similar to that of the 50% mortality rate values (LS_{50}) estimated by Morgan *et al.* (1976). The only values that are quite different, are those for white perch larvae in Table A and striped bass larvae for 1 minute exposure in Table B. Such discrepancies could be explained by looking at the figures in Morgan *et al.* (1973) report, which shows that in both instances it is necessary to extrapolate outside the range of observations in order to estimate the shear stresses corresponding to 50% mortality rates.

One point that is important to mention relates to the fact that equation 3 is only valid for values of the Reynolds number R_e up to 40,000. Such limits, which can be observed in Figure 10 (i.e. log (40,000) = 4.6) of Donnelly and Simon (1959), corresponds to an angular speed of 12.35 rad/sec or 118 rpm. An inspection of Tables A and B, indicates that in all the tests conducted by Morgan *et al*, $\Omega > 12.35$ rad/sec. This fact suggests that the shear stresses given by Morgan *et al.* as well as those estimated in this report, are beyond the limit for which direct measurements are available, (e.g. Wendt, 1933) and therefore it is not possible to know whether they are correct or not. They can only provide approximate estimates.

A recent paper by Lathrop *et al.* (1992), indicates that the shear-driven turbulence in a Couette-Taylor flow, corresponds well with observations made in wall-bounded shear flows such as pipe flow and flow over a flat plate. Thus, Lathrop *et al.* findings support the idea that a closed system such as a Couette cell, can be used effectively to reproduce shear stresses and flow characteristics akin to those observed along the hull of barges.

It was also found that the fit to the data of Wendt *et al*,. i.e. eqtn (3), can reproduce both the torque and shear stress measurements made by Lathrop *et al.* (1992).

The Morgan *et al.* set-up differs from those of Wendt *et al.* and Lathrop *et al.*, since the Couette cell of the former had a free surface and the water could go in and out of the cell through the bottom. These end effects suggest that the "true" shear stresses experienced by the fish eggs and larvae in the Morgan *et al.* experiments were most likely lower than those estimated with the help of the Wendt *et al.* fit. It is, however, almost impossible to determine how much lower they actually were.

CONCLUSIONS

Several conclusions can be drawn from the analysis above:

1. Based on the Lathrop *et al.* (1992) observations, the apparatus used by Morgan *et al.* (1976) produced a turbulent shear flow which is similar to the one that larval fish and eggs encounter during tow boat passages.

2. The magnitude of the shear stresses produced by the Couette cell used by Morgan *et al.* could be estimated only with the help of an empirical relationship (eqtn. 3) obtained by Wendt *et al.* (1933)

which is valid for Reynolds numbers smaller than the ones present in the experiments. Therefore, such estimates of shear stress can only be considered as approximate values keeping in mind that they can only be used to make an educated estimate of the order of magnitude of the shear stresses responsible for the observed mortality rates.

3. The estimates of shear stress for high-intensity, short-term exposure conditions are much larger than values commonly expected in large rivers. However, without the benefit of direct measurements, it is difficult to assess the magnitude of the shear stresses along the hull of tow barges and how they might compare with those used by Morgan *et al.* to estimate mortality rates.

RECOMMENDATIONS FOR FUTURE WORK

While the Morgan *et al.* (1976) study can be used to have a rough idea about mortality rates, in order to assess the effect of shear stresses induced by navigation on fish eggs and larvae, it would be necessary to use an apparatus where the flow conditions are well controlled. At this point, it would seem that a Couette cell with the same characteristics as those of the one used by Lathrop *et al.* (1992) would be the most appropriate set-up, since advantage could be taken of the extensive set of measurements that those researchers have done to characterize the flow structure and associated shear stresses. Another interesting device could be the one proposed by Edwards, *et al.* (1989), which combines a Couette cell with a cone and plate viscometer to assess shear effects on suspended microbial cultures.

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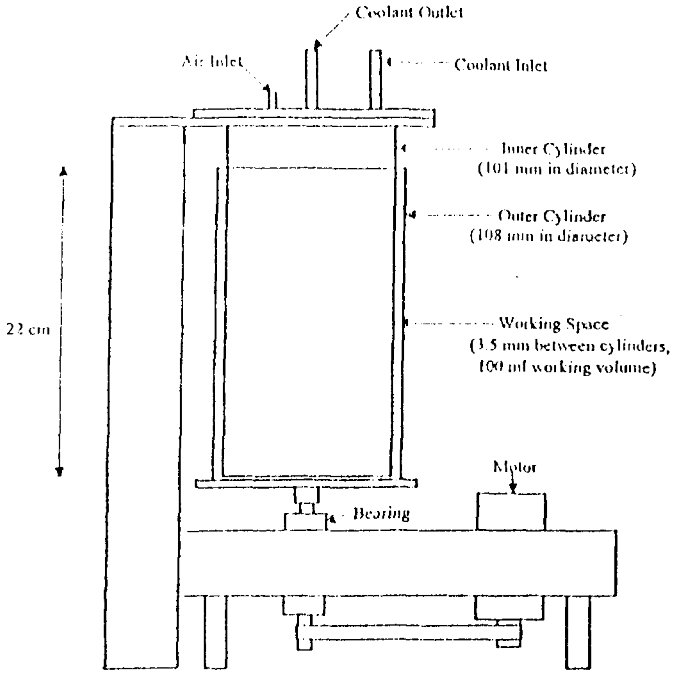

Fig. 1 Couette cell with narrow gap (Mead and Denny, 1995).

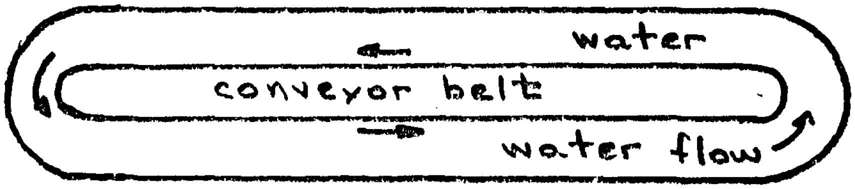

Fig. 2 Couette flow apparatus to reproduce flow conditions along a barge hull.

TABLE A: Low intensity and long-term exposure experiments.

Life Stage	LS_{50} (dynes/cm^2) (Morgan et al., 1976)	Ω (rad /s)	τ_i (dynes/cm^2)
White Perch Eggs	58.5	11.6	23.5
White Perch Larvae	87.5	38.9	184.2*
Striped Bass Eggs	70.3	25.1	87.5

*computed by extrapolation in Fig. 3 of Morgan et al. (1973).

TABLE B: High intensity and short-term exposure experiments.

Life Stage	Exposure (Min)	RPM	Ω (rad/s)	LS_{50} (dynes/cm^2) (Morgan et al., 1976)	τ_i (dyn/cm^2)
Striped Bass Eggs	1	729	76.3	542	579
	2	403	42.2	255	212
	4	361	37.8	190	175
Striped Bass Larvae	1	1,181	123.7	785	1,316*
	2	729	76.3	510	579
	4	434	45.4	300	240
White Perch Eggs	1	590	61.8	425	405
	2	556	58.2	415	365
	5	306	32.0	175	132
	10	--	--	165	--
	20	--	--	120	--
White Perch Larvae	1	566	59.3	415	377
	2	479	50.2	340	284
	4	313	32.8	125	138

*computed by extrapolation in Fig. 8 of Morgan et al. (1973).