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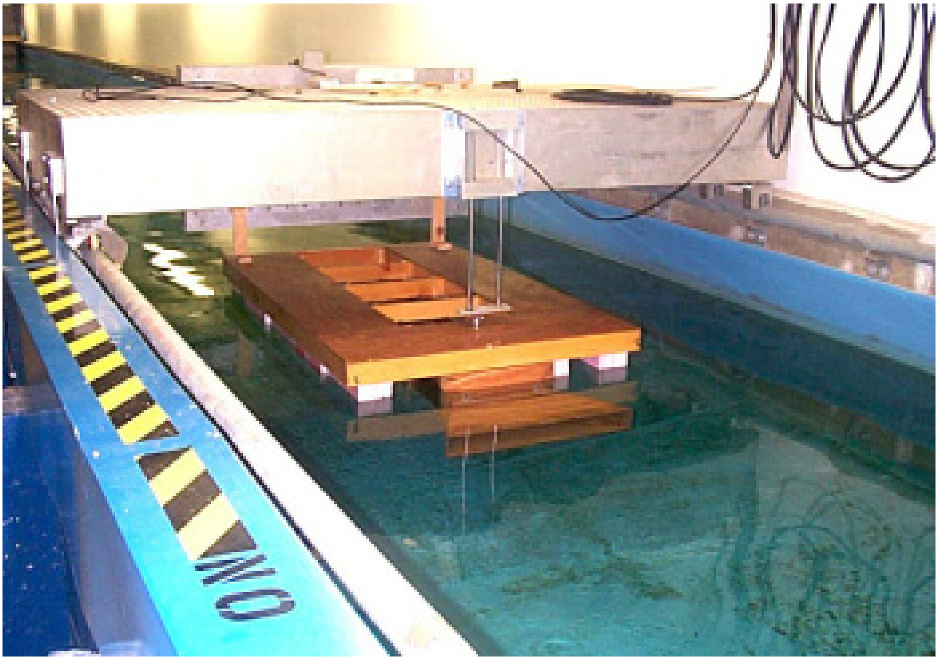

Tow Tank Scale Modeling in the Design of Tidal Upwellers

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INTRODUCTION

In February 1999 an ad hoc committee of representatives of Maine's shellfish aquaculture industry, The University of Maine, and the Maine Sea Grant College Program met to discuss priorities for research to improve the performance of tidally powered shellfish upwellers. Information from this meeting was incorporated into a proposal submitted later in the year to the Maine Aquaculture Innovation Center. The project was funded and work began in January 2000. The project involved engineering analysis, field measurements of shellfish seed properties, and scale-model testing conducted in the university wave/towing tank with the overall goal of optimizing the design of a tidal upweller used for nursery production of oyster and hard clam seed. This report describes the model-testing component.

BACKGROUND

Tray culture of shellfish, particularly oysters, has been used for many years, with the trays either floating on the surface or fixed to wooden frames. At some point in the early 1900s it was discovered that the shellfish grew faster if the water flow was vertical, passing through rather than over the bed within the tray. Over the past 30 years there has been a steady development in the technology of upwellers, both in the USA and Europe (Spencer and Hepper 1981). They have become common in hatcheries, with water pumped upward through the bed of shellfish and the flow either driven by a pump or by tidal currents. The main advantage of the latter type is that there is no dependence on electrical power, allowing them to be located in more remote locations. This advantage together with the presence of very strong tidal action has aroused the interest of shellfish growers in Maine.

The design for a tidal upweller in Maine was proposed by Mook (1986) based on earlier work in Britain and on shore-based systems, and a guide to construction was published (Mook 1988). The capital cost and operating costs of this upweller were lower than for a land-based system. Since that time the original design has been modified and used in Maine, Massachusetts, and South Carolina. Several publications are available describing construction details and operating procedures (Hadley et al. 1999; Karney and Blake 2000). These designs have generally evolved through an iterative process based on trial and error. Operators of systems in Maine have been concerned about the unevenness of flow through the upweller, the effect of varying tidal current velocities, and other design considerations. This project was initiated to investigate the underlying hydrodynamic characteristics of tidally powered upwellers with the goal of optimizing the design in terms of efficiency and overall performance, using scale models and engineering analysis.

A shellfish upweller of the Mook type (see Figure 1) consists of a flotation-supported raft approximately 20 ft long by 10 ft wide. Beneath the raft, a plywood tank 3 ft wide and 3 ft deep extends the length of the raft. One end of the tank is closed and the other is fitted with a diverging scoop or horn. The raft uses a single point mooring so that the scoop is always facing into the tidal current. Water entering the tank is forced upwards through an array of screened trays in boxes or "silos" suspended from the raft and containing shellfish seed. After the water has passed through the beds of seed, it exits via a hole back into the ocean. Since the tidal current provides the energy for inducing the flow of water upwards through the shellfish, optimization of the design for an upweller driven by tidal currents requires an understanding of the underlying hydrodynamics of the system. Growth rates of the shellfish in the upweller depend largely on the volumetric flow rate through the system. Predicting this flow rate is not a straightforward matter. Even in a powered upweller with a pump providing the flow, the system is dynamic, with the shellfish seed size and bed depth changing continuously as the animals grow. With a tidally powered system the situation is further complicated by the continuous varia-

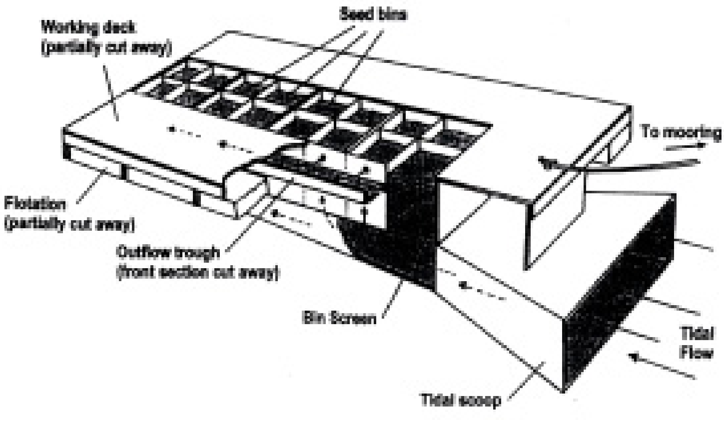

Figure 1. Diagrammatic representation of the tidal-powered upwelling system (from Hadley et al. 1999).

tion in current speed. The problem of studying different designs and modifications of upwellers lends itself to scale modeling and The University of Maine wave/tow tank provided a suitable facility for such tests.

THEORY

Physical modeling has been used extensively in the study of fluid flow problems for hundreds of years (Murphy 1950). Models are used to optimize the design of offshore structures and for the design and analysis of ship hulls (Randall 1997). The theory of fluid flow modelling is quite complex and will only briefly be discussed.

The basic requirement for modeling is that there is *geometric* similarity between model and prototype, i.e., a consistent scale where all length ratios are the same. If we are modelling an upweller that is, for example, 25 ft long, 10 ft wide and 5 ft deep and wish to use a scale, n, of 1/5, then the model must be 5 ft x 2 ft x 1 ft. For modeling that involves time (e.g., velocity, flow rate) we need *kinematic* similarity. It can be shown that this requirement is satisfied if the Froude numbers (see Appendix A) are equal; to attain this, the ratio of velocities of the model and prototype must be equal to $\sqrt{n}$. For example, if the current speed for the prototype is 2 knots, then the model current speed must be $2 \times \sqrt{1/5} = 0.89$ knots. For tests involving length, time, and force, we need *dynamic* similarity. This requires that the Reynolds numbers (see Appendix A) be equal. This term includes the viscosity of the fluids, and it can be shown that the ratio of kinematic viscosities of model and prototype be equal to $n^{3/2}$. With water as the fluid in the prototype, for a scale of $n = 1/5$, we would need a model fluid velocity of 0.09 times that of water. No such fluid exists with the required kinematic viscosity, so any modeling involving viscous forces is “distorted.” There are procedures to deal with this distortion, but for this study no predictions were made, from model to prototype, of forces resulting from resistance of the fluid as measured by viscosity. In these cases only the performance of one model with another was compared; here the length scale is unity and the dynamic similarity requirement is met.

MATERIALS AND METHODS

The University of Maine wave/towing tank is 120 ft long, 8 ft wide, and 4 ft deep with a lexan underwater viewing window at the midpoint. It contains 25,000 gallons of freshwater continuously filtered and ozonated to prevent any biological growth. An aluminum carriage

8 ft wide and 4 ft long rides on tracks running the length of the tank and driven through a stainless steel tape drive by a 7.5-hp three-phase motor digitally controlled by a programmable inverter. The system can provide a maximum speed through the water of approximately 5 knots. Maximum design drag force is 121 lbf and is measured by strain gauge load cells between carriage and model, with the signal transmitted to the control room by a festooned instrumentation cable carried on a track on the ceiling. In the control room a wide range strain indicator and continuous chart recorder provide data acquisition. Flow velocity is measured with a Nixon Streamflo Probe (Novonic Instruments, Gloucester, England) with the signal carried in the instrumentation cable to an indicator in the control room. The system also has wavemaking capabilities, but these were not used in this study.

Plywood models were fabricated to a length scale of 1/5. The first model was based on the original Mook upweller from plans first published in 1988 (Mook 1988). Modifications to this design have been made since that time, but it was felt important to begin here and try to understand the reasons for these modifications. A schematic diagram of the upweller is shown in Figure 1, and the model is shown in Figures 2 and 3. The powered carriage on the wave/tow tank was used to tow the upweller through the water at speeds simulating currents of up to 5 knots. Figure 4 shows the upweller in the tank. Several weeks were spent observing the behavior of the model without any measurements of flow rates through the individual bins as the researchers were unable to locate a flow meter small enough and with a low enough range. Flow rates through the collection trough, however, were measurable. Later in the project a suitable flow meter was made available. As a result of our observations several modifications were made to the original, and two further models were constructed to evaluate various suggested concepts. For example, scoops of different size and geometry were made, and the size and shape of the outlet holes from the bins was made variable. These are discussed later.

RESULTS

Stability and Variation of Flow Rates

It was immediately clear that only a fraction of the current flow was actually translated into flow through the upweller bins and out into the collection trough. It was also interesting to note that as current speed increased, the bow of the upweller dropped and the exit holes from the bins at the stern became elevated to the point where there was no flow through these bins. With less than 2 inches of total

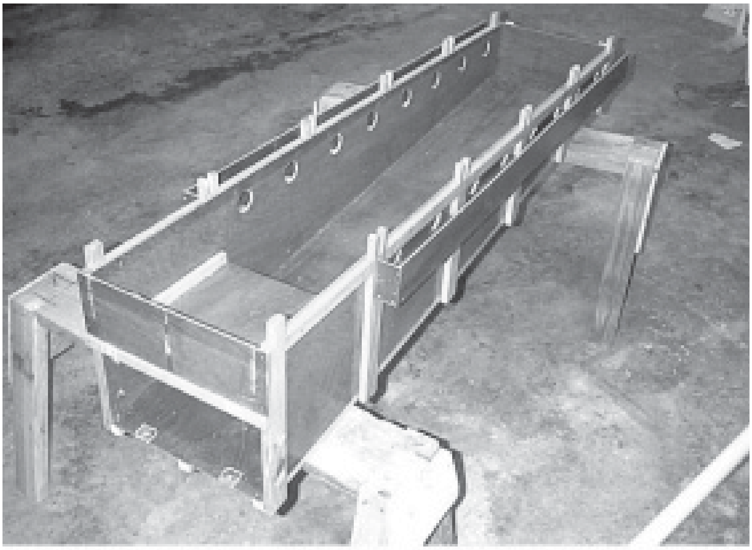

Figure 2. Model of original design of upweller tank.

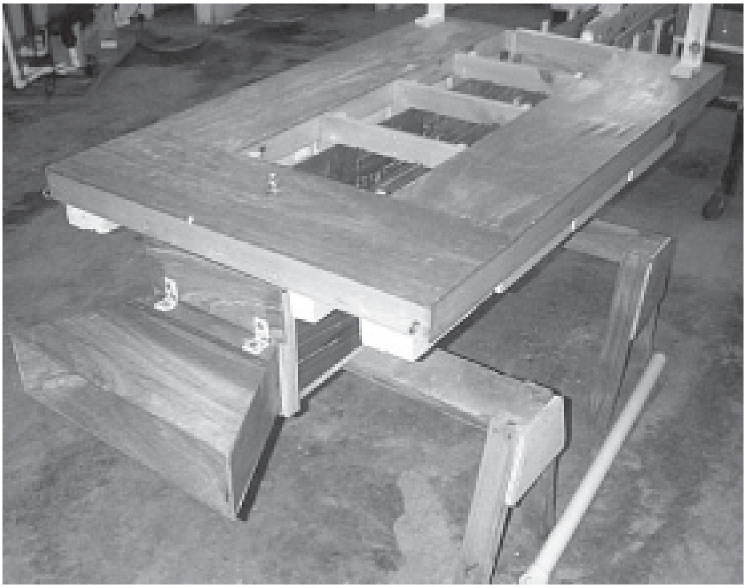

Figure 3. Model of complete upweller.

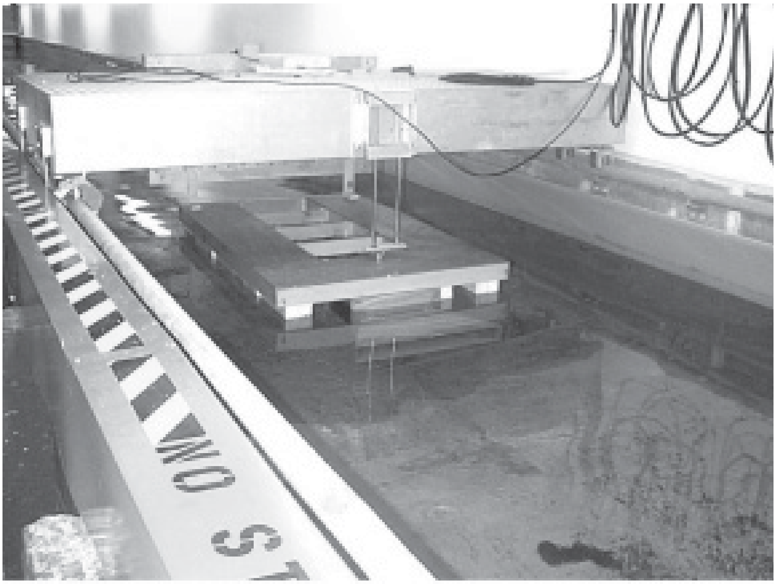

Figure 4. Model of upweller in tow tank.

head available (at a 2-knot current), the flow could not overcome the static head caused by this elevation and flow through these rear bins was reduced. Operators of some upwellers have reported greater growth in the front bins, so the importance of keeping the upweller horizontal is clear (Simmons 2000). Other researchers have not noticed this uneven growth but it is likely that in those situations current speeds were relatively low (<2 knots) and that the problem only occurs at higher current speeds such as those that occur in Maine. When ballasted with strategically placed bricks on the deck, the model remained relatively level at an arbitrary current speed, and flow through the bins was observed to be more uniform. This was confirmed when a suitable flow meter was obtained. However, it was necessary to move the ballast for every current speed to ensure a level deck, and this is obviously not a practical solution.

An attempt was made to reduce the diving of the front of the upweller by installing angled planes at the bow. Several different sized planes, at several angles of attack were tried with no success and it was concluded that if planes were to be successful even at these relatively low speeds they would have to be extremely large hydrofoils.

Scoop Size

If the cross-sectional area of the tank and the opening presented to the tidal current flow is increased, then the volume flow through the upweller will increase. However, there is no increase in velocity and therefore no increase in potential head. Use of a converging mouth or scoop on the front of the tank increases both flow rate and velocity, and therefore has the potential to develop greater head. However, this increase is not linear and is greatly affected by the geometry of the scoop. Unless the flow contraction is well streamlined, there can be a significant energy loss. Analytical prediction of these energy losses is not possible, but a series of experiments by Gibson (1952) indicated that minimum energy loss occurred when the angle of the contraction was approximately 7 degrees. This presents a practical problem since a scoop designed to increase the area presented to the current flow from 6 ft wide to 8 ft wide with a 7-degree angle of contraction would need to be 16 ft long. In addition, the energy losses are affected by the profile of the forward edge of the scoop. A well-rounded edge produces less energy loss than a square edge (Pao 1961). Since most scoops we have encountered have a convergence well above the 7-degree figure and have square edges, there is a significant energy loss. The model tests with three different sized scoops gave interesting results.

The three scoops, designated small, medium, and large, are shown in Figure 5. Actual dimensions are shown in Appendix B. The upweller was fitted with each scoop in turn and towed through the tank at various speeds. The rear of the tank was removed and the flow through the upweller measured in the center of the tank. One run was conducted with no scoop. Results are shown in Figure 6. It is interesting to note that the increase in flow at a given current speed with the increasing size of scoop is by no means linear and is actually quite small. The biggest scoop, with a large angle of contraction in fact produced less flow than the medium scoop. This is in agreement with the theory as explained by Gibson (1952).

The project also sought to minimize mooring line and anchoring forces. As flow through the upweller increases, the hydrodynamic drag force increases exponentially. In addition there is a force on the rear wall of the tank resulting from the horizontal flow being directed vertically. Both of these forces affect the load on the mooring line and anchor. It has been suggested that flow rate could be increased and mooring forces reduced by installing curved vanes to direct the water flow upwards from the tank. However, by the Law of Conservation of Momentum as the flow makes a 90-degree turn from horizontal to vertical there will always be a horizontal force on the back wall of the tank, and it will be proportional to the horizontal flow velocity. The

Figure 5. Three different scop sizes used on models.

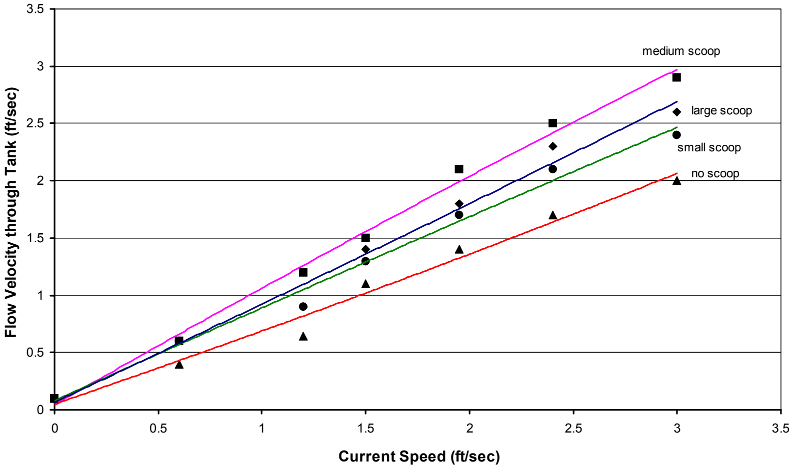

Figure 6. Flow relationships for different scoop sizes.

horizontal force would not change with the installation of curved vanes and would be transferred from the vanes to the body of the upweller and then to the mooring line and anchor.

Another suggestion for a way to reduce drag forces and mooring loads at high current speeds was to use the rear wall of the tank as a "relief valve." One of the models was fitted with this wall hinged at the top but otherwise unrestrained. With varying sizes of weight attached to the bottom of this flap, the model spilled water progressively as current speed increased. With a weight of 5 lbs attached, the model flap did not begin to open measurably until a (model) current speed of 1 ft/sec was reached. With a length scale of 1/5 and volume as an indicator of weight, the same result would be expected with a weight of $5 \times 5^3 =$ 625 lbs.

Outlet Sizing

The theory indicated that frictional losses through the upweller should be reduced as much as is practical. Karney and Blake (2000) reported a large increase in production capability relative to a Mook upweller with the outlet holes removed to reduce constriction, but it is difficult to attribute all of this increase to this effect as there were many other modifications made. In our testing, the original model used 1-inch PVC pipe for bin outlets. This was removed leaving an outlet size of 1.5 inches diameter. The second model used a rectangular outlet 3 inches x 1.5 inches. Tests were conducted with the two models at two different current speeds. While flow velocity slowed through the larger outlet, there was almost a doubling of volume flow through the bins indicating the importance of outlet size. See Figure 7.

CONCLUSIONS AND RECOMMENDATIONS

Maintaining the raft in a horizontal position with all bin outlet holes submerged will ensure even growth in all bins. There was no noticeable variation in flow through different bins if the raft was kept level. If the upweller has a tendency to dig in at the bow at high current speeds or if anchoring considerations are critical, the hinged flap described earlier offers a solution.

The addition of a scoop at the front of the tank will increase velocity and therefore flow rate through the upweller, but bigger is not necessarily better. For example, a modest increase of 50% in the area presented to the current, with a scoop length equal to its width, results in an angle of convergence of 26 degrees, well above the 7-degree ideal. Larger scoops with very high angles of convergence result in turbulence at the mouth, with very little or even no increase in flow and also

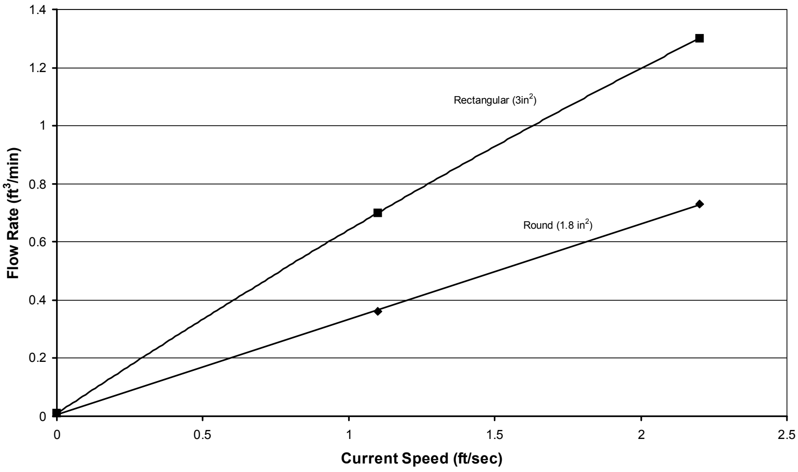

Figure 7. Effect of outlet size on flow rate through a single outlet.

increase the drag on the upweller generating higher mooring forces. The 45-degree angle of contraction used in the original Mook design should be reduced as much as possible, but due to the resulting increase in the length of the scoop, an angle of 30 degrees may be the best compromise.

Our results showed that the outlets from the seed bins should be as large as is practical. The 4-inch PVC pipe commonly used should be increased to 6 inches diameter if practical. With the extremely small head developed by tidal current velocities any restriction to flow will have a significant effect. There have been reports suggesting modifying the outlets in various ways to achieve a venturi effect (Karney and Blake 2000). Unfortunately the theory of venturis does not support this idea since the flow velocity outside the venturi is in fact lower than the velocity inside. The increased flow measured was probably due to the large diameter of pipe used (12-inch diameter).

The most important overall conclusion is that the original Mook design was well thought out and that there is no reason to abandon this concept. Modifications made to this design by others have been relatively minor; some were successful, others less so. Construction methods have been streamlined and alternative materials tried, but there have been no statistically supported significant breakthroughs in efficiency. This current study did not produce a radical new design, but does help explain why certain modifications work and others do not.

ACKNOWLEDGMENTS

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APPENDIX A

Reynolds Number = $VD\rho/\mu$ where:

V = Characteristic flow velocity
D = Characteristic linear dimension
ρ = Density of the fluid
μ = Viscosity of the fluid

Froude Number = V^2/LG where:

V = Characteristic flow velocity
L = Characteristic linear dimension
G = Gravitational constant

APPENDIX B—DIMENSIONS FOR DIFFERENT SCOOPS