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Performance evaluation of four different methods for circulating water in commercial-scale, split-pond aquaculture systems

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ABSTRACT

Split-pond aquaculture systems are being implemented by United States (US) catfish farmers as a way to improve production performance. The split-pond consists of a fish-culture basin that is connected to a waste-treatment lagoon by two water conveyance structures. Water is circulated between the two basins with high-volume pumps (water circulators) and many different units are being used on commercial farms. In this study circulator performance was evaluated with four different circulating systems. Rotational speeds ranged from 0.5 to 3.5 rpm for a twin, slow rotating paddlewheel; 12.5 to 56.5 rpm for a paddlewheel aerator; 60 to 240 rpm for a high-speed screw pump; and 150 to 600 rpm for an axial-flow pump. Water flow rates ranged from 8.6 to 77.6 m^3/min and increased with increasing rotational speed. Power input varied directly with flow rate and ranged from 0.24 to 13.43 kW for all four circulators. Water discharge per unit power input (i.e., efficiency) ranged from 3.5 to 70.9 $m^3\ min^{-1}\ kW^{-1}$ for the circulators tested. In general, efficiency decreased as water flow rate increased. Initial investment cost for each circulator and complete circulating system ranged from US $5850 to $22,900, and $15,335 to $78,660, respectively. The least expensive circulator to operate was the twin, slow-rotating paddlewheel, followed by the paddlewheel aerator, high-speed screw pump, and axial-flow pump. Our results show that four different circulating systems can be effectively installed and used to circulate water in split-ponds. However, water flow rate, rotational speed, required power input, efficiency, initial investment cost, and operational expense varied greatly among the systems tested. Long term studies are underway to better define the relationship between water flow rate and fish production in split-ponds. That information will help identify the water circulating system most appropriate for split-pond aquaculture.

1. Introduction

In an effort to remain competitive in the face of adverse economic conditions, some catfish farmers in the United States (US) have started using intensive, outdoor culture systems called split-pond aquaculture systems. Split-ponds are constructed by dividing an existing catfish pond with an earthen levee into two unequal basins. The smaller of the two basins (usually about 10–20% of total water area) is where fish are cultured and the larger basin (called the 'waste-treatment lagoon') treats fish waste and produces oxygen during daytime photosynthesis. The two basins are connected by conveyance structures that are screened to prevent fish escape from the fish-culture area. Water is circulated between the two basins using high-volume pumps (water circulators). Water flow rate estimates are based on the assumption that fish oxygen requirements are met during daylight and early evening by oxygen in water flowing into the fish-culture area from the algal basin. A simple mass balance is used to calculate flow rate (volume/time) by dividing estimated fish respiratory rate (oxygen mass/time) by the minimum desired dissolved oxygen concentration (oxygen mass/volume). Required water flow varies with time as fish grow and water temperature changes, while aerators in the fish-confinement area provide required dissolved oxygen at night.

In the original split-pond design (Tucker and Kingsbury, 2010; Brown and Tucker, 2013) water was circulated with a large, slow-rotating paddlewheel, but systems on commercial farms have been built using high-speed screw pumps, high-speed axial-flow pumps, or high-speed paddlewheels to recirculate water (Brown and Tucker, 2014; Park et al., 2014). Net annual catfish production (based on the total water area) in experimental and

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commercial split-ponds typically ranges from ∼13,450 to 24,660 kg/ha (∼12,000–22,000 pounds/acre; Tucker and Kingsbury, 2010; Brown and Tucker, 2013). This is 2–4 times the annual production typically achieved in traditional ponds (Hargreaves and Tucker, 2003). These high production rates stimulated rapid commercial adoption of split-ponds, with close to 700 ha (∼1730 acres) of ponds presently in use in Mississippi, Arkansas, and Alabama.

Three studies have been conducted to evaluate water circulator performance in split-ponds. One study (Brown and Tucker, 2013) evaluated performance characteristics for the slow-rotating paddlewheel used in the initial split-pond design. Relationships were developed among power input, rotational speed (circular tip velocity), water velocity, and water flow rate. Rotational speeds of 1–4 rpm were evaluated in open channels and in channels with fish barriers. Measured power input ranged from ∼0.08 to 1.34 kW (0.11–1.80 hp). Water flow rate ranged from ∼17 m^3/min to 73 m^3/min (4548–19,330 gal/min) and water discharge per unit power input (a measure of efficiency) decreased dramatically as rotational speed increased. Installation of fish barriers decreased channel open area and the resulting frictional losses reduced water flow rates.

The second study (Brown and Tucker, 2014) evaluated paddlewheel aerators as an alternative to slow-rotating paddlewheels as circulators for split-ponds. Circulator performance was evaluated at rotational speeds of 25–66 rpm and paddle submergence depths of ∼10, 17, and 24 cm (4.00, 6.75, and 9.50 in.). Water flow rates ranged from ∼31 m^3/min to 95 m^3/min (8200–25,100 gal/min). Flows increased with increasing rotational speed and paddle submergence depth. Power input varied directly with flow rate and ranged from ∼0.81 to 6.18 kW (1.08–8.28 hp). Water discharge per unit power input ranged from ∼15 to 55 $m^3\ min^{-1}\ kW^{-1}$ (3026–10,824 $gal\ min^{-1}\ hp^{-1}$). At all paddle depths, efficiency decreased as rotational speed increased. The second study by Brown and Tucker (2014) showed that commercial paddlewheel aerators can be modified, operated, and positioned to provide water flow rates needed in commercial-sized split ponds. Although more expensive to operate than slow-rotating paddlewheels that are specifically designed as water circulators, paddlewheel aerators offer the advantages of lower investment cost, availability, and easy maintenance.

The most recent study (Park et al., 2014) evaluated the performance and accuracy of engineering models for paddlewheel circulators in Arkansas used to move water through culverts in split-ponds on commercial catfish farms. Under field conditions, rotational speeds of the circulators ranged between 5.5–8.0 rpm at water depths of 0.94–1.42 m. Power requirements ranged from 2.91 to 7.85 kW (∼3.90–10.52 hp) at water flow rates of 41.1–87.1 m^3/min (∼10,857–23,009 gal/min). The models derived from this study determined that increasing the wetted surface area of paddles would be more energy efficient than increasing the rotational speed and also minimize mechanical failure. However, the required power input would also be expected to increase as wetted surface area increased.

The research conducted to date has focused on different types of paddlewheel circulators used in split-ponds. However, most fish culturists using split-ponds to raise catfish in the US do not use paddlewheels to circulate water in these systems. In total, about 82% of commercial split-ponds – 96% in Mississippi – have a high-speed screw pump or axial-flow pump instead of paddlewheels. There are several reasons for commercial adoption of these circulator types. First, it is much more economical to use small conduit structures, and circulators can be less expensive for these systems. This also simplifies and reduces installation costs. Since paddlewheels operate against low head and produce high volume water flows, they cannot effectively operate with conveyance structures that have a reduced cross sectional area as compared to open channel sluiceways or large culverts. High-speed screw pumps and axial-flow pumps can operate against greater head requirements, thus making them better suited than paddlewheels when used with smaller diameter conduits. Finally, fish culturists prefer to have access to all levees with equipment such as fish transport trucks, grass-mowing equipment, tractor-powered aerators, and feed trucks. Open-channel sluiceways or large culverts are needed when paddlewheels are used in split-ponds, and these conduits are more difficult to install and may require hardened structures to make vehicle and equipment passage possible. Screw pumps and axial-flow pumps can be operated with relatively small diameter, buried culverts that are less expensive, easier to install, and allow vehicle and equipment passage.

The objectives of this study were to evaluate four water circulating systems either in common use or currently considered for use in commercial-scale split-ponds and to develop performance models that can be used by scientists and industry personnel producing fish with this technology. An important aspect of split-pond operation is costs associated with the circulators, conveyance structures, and installation of both. Thus, we summarized the initial investment costs of the four circulating systems that were evaluated in this study. In addition, the cost of circulating water between the fish-culture basin and waste-treatment lagoon can be expensive depending on the system used. Therefore, we also calculated the operational expense of four different circulators used in split-ponds over a simulated production season to provide a baseline economic indicator of electrical energy use and potential profitability.

2. Materials and methods

2.1. System design

This study was conducted at the Thad Cochran National Warmwater Aquaculture Center, Stoneville, Mississippi. Four split-pond aquaculture systems were constructed and used to perform circulator performance tests; each consisted of a fish-culture basin (∼0.60 ha, 1.85 m average water depth), waste-treatment lagoon (∼2.24 ha, 1.32 m average water depth), two conveyance structures connecting the two basins, and a circulator (one type for each split-pond; Fig. 1). Circulator types and conveyance structures were selected based on current commercial use (screw and axial-flow pumps) or alternatives considered potentially applicable to commercial conditions (slow-rotating paddlewheels or paddlewheel aerators). An earthen baffle levee extended perpendicular to the dividing levee and parallel to the side levees of the waste-treatment lagoon (Fig. 1). The baffle levee directed water flow through the waste-treatment lagoon and prevented short-circuited flow in each split-pond. No fish were present in these systems during this study.

2.1.1. Split-pond with twin, slow-rotating paddlewheel

Two slow-rotating paddlewheels were used in this design and both worked in unison as one large circulator. Each slow-rotating paddlewheel was constructed from six sections of mild-steel plate (2.74 m long × 1.29 m wide × 0.4 cm thick) used as the blades, which were evenly distributed and bolted to circular struts connected to a central shaft. The central shaft (8.9 cm diameter) was fabricated from cold-rolled steel and supported on double-row, tapered roller bearings (Model 037611, Dodge by Baldor Electric Company, St. Louis, Missouri). The central shaft was welded to struts (1.2 m diameter mild-steel plate sections; 0.4 cm thick) in between paddles every 0.91 m. Each paddlewheel and supports had an overall diameter of 2.69 m and weighed approximately 1.2 mt (Fig. 2). Clearance between the bottom of the channel and the outermost part (tip) of the paddles and the outer channel wall and sides