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 m³/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 m³·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\$5,850 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 between 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.

Keywords: Circulators; pumps; split-ponds; water flow; efficiency

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 commercial split-ponds typically ranges from ~13,450 to 24,660 kg/ha (~12,000 to 22,000 pounds/acre; Tucker and Kingsbury, 2010; Brown and Tucker, 2013). This is 2 to 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 (~1,730 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, 2, 3, and 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 to 1.80 hp). Water flow rate ranged from ~17 m³/min to 73 m³/min (4,548 to 19,330 gallons/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 to 66 rpm and paddle submergence depths of ~10, 17, and 24 cm (4.00, 6.75, and 9.50 inches). Water flow rates ranged from ~31 m³/min to 95 m³/min (8,200 to 25,100 gallons/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 to 8.28 hp). Water discharge per unit power input ranged from ~15 to 55 m³·min⁻¹·kW⁻¹ (3,026 to 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 to 1.42 m. Power requirements ranged from 2.91 to 7.85 kW (~3.90 to 10.52 hp) at water flow rates of 41.1 to 87.1 m³/min (~10,857 to 23,009 gallons/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 x 1.29 m wide x 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 of the paddles of each slow-rotating paddlewheel were 12.7 cm and 4.5 cm, respectively.

Each slow-rotating paddlewheel was powered by a 2.2-kW, three-phase electric motor (Model WWHT3-18-182TC, Worldwide Electric Corporation, Rochester, New York) that had a

rated rotational speed of 1,770 rpm. The motor was attached to an enclosed gear drive (Model 305 L4 446 NPC N140TC, Bonfiglioli, Hebron, Kentucky) that directly reduced shaft speed by a factor of 446:1. A coupling attached the output of the gear drive to the shaft of the slow-rotating paddlewheel. The combination of the motor and gear drive produced a paddle-wheel rotational speed of approximately 4.0 rpm at 60 Hz. A variable-frequency drive (Model FRN003C1S4U, Fuji Electric Corporation of America, Edison, New Jersey) was wired to the electric motor to allow control of paddlewheel speed. Each slow rotating paddlewheel with drive assembly was fitted to a permanent modular frame where it could be crane lifted into position (Fig. 2).

Two structures were used to convey water between the fish-culture basin and waste-treatment lagoon. First, three box culvert channels (each 3.34 m² x 12 m in length) were installed through the levee (Fig. 3) and fitted with the two slow-rotating paddlewheels located on a concrete foundation. Poured concrete wing walls were used at the entrance of the slow-rotating paddlewheels and at the exit end of the box culverts (water outflow from the fish-culture basin). Second, for the return flow, three corrugated galvanized metal culverts (1.22 m inside diameter x 21 m in length, 7.62 cm pitch x 2.54 cm rise, and spiral corrugation) were installed through the levee and used as the inflow to the fish-culture basin (Fig. 3).

2.1.2. Split-pond with paddlewheel aerator

A commercial electric paddlewheel aerator was purchased from Peaster Enterprises, Brooksville, Mississippi (Fig. 4). The aerator had a 0.2-m-diameter x 3.7-m-long hub with short, 5.0-cm-diameter shafts at each end. Paddles were 13 cm wide x 38 cm long and triangular (133°) in cross section. There were five paddles per row (90° apart), and each of the five lines of paddles were semispiraled, with 20 paddles along the length of the hub (100 paddles total). The paddlewheel was supported by double-bored, water-lubricated bearing blocks mounted on a

metal frame. The frame was attached at each end to 2.4-m-long x 0.6-m-diameter aluminum tanks for flotation. The frame was attached to tanks with threaded rods through holes that allowed for adjustment of frame height and paddle submergence depth. The deepest paddle submergence depth (15.9 cm) was used for all performance tests based on Brown and Tucker (2014) who found that paddlewheel aerators used as circulators should be modified to increase paddle submergence depth to increase efficiency. This allows the same water volume to be circulated at lower rotational speeds and lower power input relative to shallower paddle submergence depths.

The paddlewheel aerator was powered by a 7.5-kW, three-phase, 230/460-V electric motor (Model 0104SDSR42A-P, Toshiba Electric, Houston, Texas) with a rated rotational speed of 1,760 rpm. The motor was mounted directly to the frame and was attached to an enclosed gear drive (Model CHHJS-6165Y-21, Sumitoma Drive Technologies, Chesapeake, Virginia) that reduced the shaft speed by a factor of 21:1. The gear drive was attached to the 5.0-cm-diameter shaft of the paddlewheel rotor. This combination produced a paddlewheel rotational speed of approximately 84 rpm at 60 Hz. A variable-frequency drive (Model N700E-110HF/150HFP, Hyundai by Worldwide Electric Corporation, Rochester, New York) was installed to allow control of the paddlewheel rotational speed.

Two corrugated galvanized metal culverts (1.52 m inside diameter, 7.62 cm pitch x 2.54 cm rise, and spiral corrugation) were installed through a levee dividing each pond into two sections. Both culverts were 18 m in length and the first was attached to the paddlewheel aerator with a rectangular funnel (Fig. 4) while the other culvert was used to return water flow.

2.1.3. *Split-pond with high-speed screw pump*

A commercial electric high-speed screw pump was purchased from Geddie's Machine and Repair Shop, Hollandale, Mississippi (Fig. 5). The screw pump consisted of a 30-m-long x 60-cm-diameter steel helical surface surrounding a central cylindrical steel shaft (5 cm diameter) inside a hollow steel pipe (64 cm inside diameter). The intake of the pipe was orientated 45° from the water surface (0.9 meters in length) toward the bottom of the pond. A 1.2 m section of pipe was welded to the 45° of the intake side and was then welded perpendicular to a 1.49-m² flange (0.6-cm thick plate steel). The central shaft was supported by a rubber and brass cased bushing on the intake side for under water operation and tapered roller bearings (Model 203010, Dodge by Baldor Electric Company, St. Louis, Missouri) on the other end of the shaft that operated out of the water. A frame (20.3 cm x 5.0 cm steel channel) was welded to the intake pipe and flange to serve as a support.

The high-speed screw pump was powered by a 7.5-kW, three-phase, 230/460-V electric motor (Model PEWWE 10-12-256T, Worldwide Electric Corporation, Rochester, New York) with a rated rotational speed of 1,185 rpm. The motor was mounted directly to the frame and output from the motor was attached to a taper-lock sprocket (11.4-cm diameter). A taper-lock sprocket (57.2 cm diameter) was attached to the shaft of the screw drive and the two sprockets were connected with a reinforced neoprene rubber belt (Model 2200 GLD 8-35 HTRC Tracker, Dodge by Baldor Electric Company, St. Louis, Missouri). The combination of the motor, two taper-lock sprockets, and belt produced a screw rotational speed of approximately 240 rpm at 60 Hz. A variable-frequency drive (Model N700E-110HF/150HFP, Hyundai by Worldwide Electric Corporation, Rochester, New York) was installed to allow control of the high-speed screw pump rotational speed.

Two circular pipes (both 21 m in length) were installed through the levee of the split-pond. The high-speed screw pump was attached with a flange to the first pipe (0.76 m inside diameter, smooth walled steel pipe, 0.8 cm wall thickness) which pushed water horizontally into the fish-culture basin from the waste-treatment lagoon. The second pipe was used for the return flow from the fish-culture basin to the waste-treatment lagoon and was corrugated (0.91-m inside diameter) high density polyethylene culvert that was double-walled with a smooth surface on in the inside.

2.1.4. Split-pond with axial-flow pump

A commercial direct drive electric fluid mixer (Model PP 4660, Flygt by Xylem, Rye Brook, New York) was purchased from Gulf States Engineering, Jackson, Mississippi (Fig. 6). The mixer was modified into an axial-flow pump by changing the pitch and size of the three-blade propeller (11 degrees and 57.8 cm diameter, respectively), attaching an anti-vortexing shield, and welding a flange (1.49-m² and 0.6-cm thick steel plate) to the frame of the mixer.

The axial-flow pump was powered by a 11.2-kW, three phase, 460-V submersible electric motor with rated rotational speed of 600 rpm at 60 Hz. The motor was encased in a stainless steel housing and mounted to the frame of the pump. A variable-frequency drive (Model N700E-150HF/185HFP, Hyundai by Worldwide Electric Corporation, Rochester, New York) was installed to allow control of the axial-flow pump rotational speed.

Two circular pipes (both 21 m in length) were installed through the levee of the split-pond. The axial-flow pump was attached to the first pipe (0.76 m inside diameter, smooth walled steel pipe, 0.8 cm wall thickness) with a flange and pushed water horizontally to the fish-culture basin from the waste-treatment lagoon. The second pipe was used for the return flow from the fish-culture basin to the waste-treatment lagoon and was corrugated (0.91 m inside

diameter) high density polyethylene culvert that was double-walled with a smooth surface on the inside.

2.2. Data collection

Field data was collected from four split-ponds in 2014 and 2015. Water level in each system was maintained at $> 95\%$ of maximum volume with pumped well water during all data collection events for each split-pond. The average wind speed was ≤ 10 kilometers per hour during all field tests. All water velocity measurements were made without obstructions between conveyance structures (i.e., no screens or other fish barriers were in the system).

2.2.1. Water flow measurement, rotational speed, and power consumption

Water velocity was measured with a current velocity meter (Model FH950, Hach Company, Loveland, Colorado). All water velocity measurements ($n = 17,250$) were made in the return channel flow opposite the location of each circulator to reduce the effect of turbulence on flow measurements (Brown and Tucker, 2014). A 15 to 20-cm diameter hole was drilled on the top of the outflow culvert(s) at a distance of three times the diameter of the pipe from the exit and a 1.5 m long metal or plastic standpipe was installed vertically through the ground to assist with water velocity measurements (Park et al., 2014). Water velocity was measured at 60% of total water depth from the surface of the water along the pipes centerline as described by Park et al. (2014). Water flow rate was calculated by multiplying the average water velocity by the open area of the outflow pipe for each rotational speed and each circulator tested.

Rotational speeds for the twin, slow-rotating paddlewheel and the paddlewheel aerator were verified using a stopwatch while rotational speeds for the high-speed screw pump and axial-flow pump were estimated by monitoring the frequency (Hz) of operation of each electric motor during tests as the maximum rotational speed of each circulator at 60 Hz was known. For

example, the high-speed screw pump would have an estimated rotational speed of approximately 140 rpm at 35 Hz $[(35/60) \times 240]$ since the pump had a maximum rotational speed of approximately 240 rpm at 60 Hz. Rotational speeds of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 were tested with the twin, slow-rotating paddlewheel; 12.5, 25.0, 37.5, 50.0, and 56.5 for the paddlewheel aerator; 60, 120, 180, and 240 for the high-speed screw pump; and 150, 300, 450, and 600 for the axial-flow pump. The actual power supplied to the electric motor of each unit was obtained directly from the variable frequency drive (Brown and Tucker, 2013; Brown and Tucker, 2014).

Regression equations between variables (water flow rate, rotational speed, power input, and water discharge per unit power input) were developed using Microsoft Excel 2013 (Microsoft Corporation, Redmond, Washington) and the highest R-squared values were chosen as representative models; equations were forced through the origin when appropriate (e.g., zero water flow rate at zero rotational speed) as recommended by Brown and Tucker (2014).

3. Results and discussion

3.1. Measured water flow rates, rotational speed, and power requirements

3.1.1. Split-ponds with twin, slow-rotating paddlewheel and paddlewheel aerator

The twin, slow-rotating paddlewheel produced water flow rates that ranged from 11.7 to 77.6 m³/min. The paddlewheel aerator produced slightly lower maximum flow with a range of 15.2 to 55.7 m³/min. Flow rate increased with increasing rotational speed for both units (Fig. 7). Increasing the rotational speed increases paddle tip velocity, which in turn induces higher water velocities and flow rates (Drapcho, 1993; Brown and Tucker, 2013; Brown and Tucker, 2014; Park et al., 2014).

The measured power input requirement increased with increasing rotational speed for both units (Fig. 8). As examples, the required power for the twin, slow-rotating paddlewheel increased from 0.24 to 1.96 kW as rotational speed increased from 0.5 to 3.5 rpm and the power requirement for the paddle-wheel aerator increased from 0.50 to 6.91 kW as rotational speed increased from 12.5 to 56.5 rpm. An increase in the power requirement with increasing rotational speed was also observed with a slow-rotating paddlewheel (Brown and Tucker, 2013), paddlewheel aerator (Brown and Tucker, 2014), and paddlewheel circulator (Park et al., 2014). Brown and Tucker (2013) found that increasing the rotational speed of a slow-rotational paddlewheel from 1.0 to 2.0 rpm slightly increased the power requirement from 0.08 to 0.26 kW, respectively, but when the rotational speed was increased from 1 to 3 rpm and 1 to 4 rpm, there was excessive power required by the motor, 0.72 and 1.34 kW, respectively. Brown and Tucker (2014) observed a dramatic increase in power required from ~0.7 kW to 4.5 kW (<1 hp to > 6 hp) by a paddlewheel aerator as rotational speed was increased from 33 to 66 rpm at a paddle submergence depth of 10.2 cm (4.0 inches). Park et al. (2014) estimated that power expended by a paddlewheel circulator would be 2.70 to 7.19 kW at rotational speeds of 5.5 to 8.0 rpm and measured values were found to be close at 2.91 to 7.85 kW, respectively.

As in the case with all pumps (circulators), the twin, slow-rotating paddlewheel and paddlewheel aerator required more power to induce higher water flow rates (Fig. 9). The power requirement increased from 0.24 to 1.96 kW as the water flow rate increased from 11.7 to 77.6 m³/min for the twin, slow-rotating paddlewheel while the paddlewheel aerator required 0.5 to 6.91 kW as water flow rate increased from 15.2 to 55.7 m³/min. Note that a water flow rate ranging from approximately 15 to 55 m³/min could be achieved with either unit (Fig. 7 and 9). Power requirements for both circulators were similar at very low flow rates (10-20 m³/min) but

at high flow rates ($>30 \text{ m}^3/\text{min}$) much more power was required to induce the same flow when using the paddlewheel aerator. Brune et al. (2012) found that slow-speed paddlewheels required excessive power input at higher water velocities ($\geq 0.15 \text{ m/s}$) in large open channels.

Water discharge per unit power input ranged from 39.5 to $70.9 \text{ m}^3 \cdot \text{min}^{-1} \cdot \text{kW}^{-1}$ to 8.1 to $30.5 \text{ m}^3 \cdot \text{min}^{-1} \cdot \text{kW}^{-1}$ for the twin, slow-rotating paddlewheel and paddlewheel aerator, respectively (Fig. 10). The greatest efficiency ($70.9 \text{ m}^3 \cdot \text{min}^{-1} \cdot \text{kW}^{-1}$) was observed at a water flow rate of $36.2 \text{ m}^3/\text{min}$ (1.5 rpm) for the twin, slow-rotating paddlewheel. However, a slight decrease in efficiency was observed at lower flow rates (Fig. 10) and rotational speeds. At very low flows there may not have been enough induced flow to prevent or minimize backflow. There potentially also could have been associated mechanical inefficiency. Overheating of the electric motors could have contributed to these results due to the lower than normal rotational speed and resulting ineffective cooling of the motor by its fan. For example, at a rotational speed of 0.5 rpm (slow-rotating paddlewheel), the electric motor speed was only 220 rpm at 7.5 Hz. Most variable frequency drive manufacturers recommend a minimum speed of 30 percent of their rated speed (18 Hz) for standard motors, to prevent motor overheating due to inadequate air flow, although, inverter duty motors can operate below 20 percent (12 Hz) of rated motor speed (Tredinnick, 2006). As with all circulators, there are thresholds of operating efficiently and non-efficiently and if designed incorrectly, they can be the most unforgiving component of the system. Efficiency also decreased as water flow rate increased for the paddlewheel aerator we tested (Fig. 10). The same relationship was observed with a paddlewheel circulator by Park et al. (2014); as rotational speed was increased from 5.5 to 8.0 rpm circulator efficiency decreased from 18.1 to $9.8 \text{ m}^3 \cdot \text{min}^{-1} \cdot \text{kW}^{-1}$. Brown and Tucker (2014) also observed similar results with a paddlewheel aerator moving water through open sluiceways.

3.1.2. Split-ponds with high-speed screw pump and axial-flow pump

The high-speed screw pump and axial-flow pump produced water flow rates that ranged from 8.6 to 34.6 m³/min and 12.3 to 47.2 m³/min, respectively, and flow rate increased with increased rotational speed (Fig. 11). Howerton et al. (1994) observed a maximum discharge rate of 63 m³/min with four six-blade impellers operating at 144 rpm using a horizontal, axial-flow water circulator which was the maximum rotational speed tested with that impellor arrangement. In addition, Howerton et al. (1994) found that a two three-blade impellor configuration had the highest discharge rate (53 m³/min) at 180 rpm. In all cases, water flow rate increased as rotational speed increased.

The measured power input requirement also increased with increasing rotational speed for both pump types (Fig. 12). For example, the required power for the high-speed screw pump increased from 0.73 to 5.03 kW as rotational speed increased from 60 to 240 rpm. Additionally, as rotational speed of the axial-flow pump increased from 150 to 600 rpm, the required power also increased from 3.14 to 13.43 kW. In general, increasing the rotational speed of water circulators used in pond aquaculture increases the power requirement as seen with slow-rotating paddlewheels (Brown and Tucker, 2013), paddlewheel aerators (Brown and Tucker, 2014), paddlewheel circulators (Park et al., 2014), and horizontal, axial-flow water circulators (Howerton et al. 1994).

As seen with most pumps, the high-speed screw pump and axial-flow pump required more power to induce higher water flow rates (Fig. 13). The power requirement of the high-speed screw pump increased from 0.73 to 5.03 kW as water flow rate increased from 8.6 to 34.6 m³/min as compared to the axial-flow pump that had a power requirement of 3.14 to 13.43 kW at

water flow rates of 12.3 to 47.2 m³/min. Howerton et al. (1994) also observed a greater power requirement to induce higher water flow rates with a horizontal, axial-flow water circulator.

Water discharge per unit power input ranged from 6.9 to 11.7 m³·min⁻¹·kW⁻¹ for the high-speed screw pump and 3.5 to 4.0 m³·min⁻¹·kW⁻¹ for the axial-flow pump (Fig.14) and in general, increasing discharge rates decreased circulator efficiency. The highest efficiency for the high-speed screw pump was at a water flow rate of 8.6 m³/min (60 rpm). Highest efficiency for the axial-flow pump water flow rate was at 23.7 m³/min (300 rpm). The axial-flow pump had an efficiency range that was much narrower than the other three circulators tested. A maximum efficiency (91.4 m³·min⁻¹·kW⁻¹) of a horizontal, axial-flow water circulator was achieved using a three-blade impellor configuration (one to four fans) operating at 90 rpm and producing water flow rates that ranged from 22 to 32 m³/min (Howerton et al., 1994). In addition, a decrease in efficiency was observed by Howerton et al. (1994) with increased discharge rates.

3.2. Initial investment costs of each pump and pumping system

The twin, slow-rotating paddlewheel was large, required special fabrication and components, and was the most expensive (US\$22,900) of the four circulators compared in this study (Table 1). For example, each slow-rotating paddlewheel had to be crane lifted into position while the other circulators were installed with a boom truck indicating the massive size and weight of this particular circulator. The axial-flow pump was the second most expensive circulator (\$16,720), but, the manufacturer claims that it will operate for decades with minimal repairs and maintenance. It was also the lightest of the four units and easiest to install. The high-speed screw pump was the third most expensive circulator (\$7,500) and most widely used in the catfish farming industry. It's also fabricated by a local machine shop which is convenient to farmers for initial purchase and installation. Easily acquired parts for repairs and maintenance

issues is also an advantage, although it displayed the lowest water flow rate of the four circulators tested. The lowest priced circulator was the paddlewheel aerator (\$5,850).

Paddlewheel aerators have been used in aquaculture for decades and offer the advantage of lower investment cost and greater availability. In addition, catfish farmers are proficient at the repair and maintenance of these devices, and replacement parts are readily available. However, paddlewheel aerators have higher operational costs than slow-rotating paddlewheels because of increased power requirements (Brown and Tucker, 2014).

Total costs with existing cross levee of the various systems include costs other than just the circulator, and vary widely. Both paddlewheel-type circulating systems were the most expensive in this study, and especially the twin, slow-rotating paddlewheel (\$78,660 or \$27,697 per ha). That system required concrete box culverts, a concrete pad, concrete wing walls, and three galvanized corrugated culverts with small wing walls for return flow, which adds considerably to the cost of system installation. However, this system was built for research and many features were over designed. Commercial circulating systems using slow-rotating paddlewheels can be built and installed at significantly reduced cost. The paddlewheel aerator circulating system (\$33,000 or \$11,620 per ha) also required large, expensive components which increased the cost of the conveyance structures. Unfortunately, both of these units must operate against low hydraulic head, which makes it impossible to significantly reduce the cross-sectional area of the water-conveyance structures without restricting water flow to the point where efficiency drops dramatically. However, repairs and maintenance costs appear to be low with slow-rotating paddlewheels and longevity and useful life could offset the large initial investment cost over time.

The axial-flow pump circulating system was the third least expensive design (\$24,555 or \$8,646 per ha) and high-speed screw pump circulating system the least expensive (\$15,335 or \$5,400 per ha). One of the main reasons most farmers in the catfish industry are using high speed pumps as circulators is the reduced initial investment cost and ease of installation as compared to slow-rotating paddlewheels and paddlewheel aerator circulating systems. The relatively small-diameter water-conveyance structures are identical for both pump types (high-speed screw and axial-flow) and interchangeable. For instance, it's easy to switch from using a high-speed screw pump to an axial-flow pump because the flanges are the same and you can lift each circulator in or out of the pond with small equipment (e.g., a backhoe, boom truck, or frontend loader). Although not a problem in this study, repair and maintenance issues have been reported by some commercial catfish producers using high-speed screw pumps and axial-flow pumps in split-ponds. Several producers have reported belt and bearing mechanical failure with high-speed screw pumps and some have reported impeller damage with axial-flow pumps when large, solid objects (sticks, branches, or even turtles) are entrained in the water flow and pulled into the pump housing.

4. Conclusions

The split-pond aquaculture system was derived from the partitioned aquaculture system (PAS; Brune et al., 2012), which used slow-turning paddlewheels to circulate water throughout the system. Slow-turning paddlewheels were used in the PAS because circulators operated continuously, thereby putting a premium on efficiency and low maintenance requirements. However, slow-turning paddlewheels are expensive and require specialized design and fabrication as compared to paddlewheel aerators which are widely available and relatively

inexpensive (Brown and Tucker, 2014). Unfortunately, compared to slow-turning paddlewheels, paddlewheel aerators are more expensive to operate as circulators. Both paddlewheel-type circulators require large water-conveyance structures and overall system costs are expensive. High-speed screw pumps and axial-flow pumps are more expensive to operate than paddlewheel-type circulators, but are easier and less expensive to install. Of the units tested, the axial-flow pump was the most expensive to operate. As examples, assuming a desired water flow rate of 30 m³/min, an operational period of 12 hours per day over 210 days, and an electrical cost of \$0.14 per kilowatt-hour, the total operating cost would be approximately \$150 for the twin, slow-rotating paddlewheel, \$450 for the paddlewheel aerator, \$1,350 for the high-speed screw pump, and \$2,800 for the axial-flow pump (Fig. 15).

Although water flow requirements have not been defined for split-ponds, commercial-scale split-ponds are normally 2-4 ha (5-10 acres) and use pumps that are capable of circulating approximately 38 to more than 75 m³/min (Brune et al., 2012). If water flow rates on the higher end are desired (>50 m³/min), the twin, slow-rotating paddlewheel and paddlewheel aerator are the only circulators tested capable of providing that water flow. One solution to achieving higher water flows with screw- or axial-flow pumps would be to use two or more in a split-pond or use larger high-speed pumps and conveyance structures. However, initial investment cost would double or triple and operational cost would increase. A last resort would be to construct smaller sized split-ponds, but this would more than likely increase construction cost even more.

The selection of a water circulator system in a commercial split-pond environment requires a compromise among flow efficiency, initial investment cost, and reliability (Brown and Tucker, 2014). The results from this study demonstrated that four different systems can be installed and effectively used to circulate water in split-ponds, although, water flow rate,

rotational speed, required power input, and water discharge per unit power input vary greatly for each unit. Initial investment cost of each system also varies greatly and is likely a contributing factor in the decision of most farmers for using the least expense circulating systems in split-ponds for catfish culture. Energy requirements and operational costs also vary greatly. Although operational costs are not currently as important as upfront capital costs in economic decisions regarding split-pond design, they may be a larger concern in the future as energy costs increase. Long-term studies are underway to better define the relationship between water flow rate and fish production in split-ponds and to determine the useful life of each circulating system. Useful life of each circulating system will be used as a gauge to estimate depreciation for future economic analysis of split-ponds. This information will help identify the water circulator system most appropriate for split-pond aquaculture.

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Figure Captions

Figure 1. Two 7.0-acre split-pond aquaculture systems with fish-culture basins (foreground), dividing levees with water-conveyance structures and circulators, and waste-treatment lagoons and earthen baffle levees (background). The split-ponds are next to a traditional catfish pond (right-hand side) and intensively aerated catfish ponds can be seen to the far left. Aerial photograph courtesy of Danny Oberle.

Figure 2. A twin, slow-rotating paddlewheel installed in a split-pond aquaculture system.

Figure 3. Conveyance structures for a split-pond aquaculture system prior to the installation of the twin, slow-rotating paddlewheel with box culverts (a) for water outflow and three corrugated galvanized metal culverts (b) for return flow (water inflow).

Figure 4. A commercially available paddlewheel aerator (a) that was attached to a rectangular funnel (b) to circulate water in a split-pond aquaculture system.

Figure 5. A high-speed screw pump flange-connected to a steel inflow (to the fish-culture basin) pipe in a split-pond aquaculture system. Arrows indicate water flow direction.

Figure 6. An axial-flow pump before (a) and after (b) installation in a split-pond aquaculture system. The pump was horizontally attached by flange-connection to a steel inflow (to the fish-culture basin) pipe. The arrow indicates water flow direction.

Figure 7. Relationships between water flow rate and rotational speed of a twin, slow-rotating paddlewheel and paddlewheel aerator used to circulate water in split-pond aquaculture systems.

Figure 8. Relationships between power input requirement and rotational speed of a twin, slow-rotating paddlewheel and paddlewheel aerator used to circulate water in split-pond aquaculture systems.

Figure 9. Relationships between power input requirement and water flow rate of a twin, slow-rotating paddlewheel and paddlewheel aerator used to circulate water in split-pond aquaculture systems.

Figure 10. Relationships between water discharge per unit power input and water flow rate of a twin, slow-rotating paddlewheel and paddlewheel aerator used to circulate water in split-pond aquaculture systems.

Figure 11. Relationships between water flow rate and rotational speed of a high-speed screw pump and axial-flow pump used to circulate water in split-pond aquaculture systems.

Figure 12. Relationships between power input requirement and rotational speed of a high-speed screw pump and axial-flow pump used to circulate water in split-pond aquaculture systems.

Figure 13. Relationships between power input requirement and water flow rate of a high-speed screw pump and axial-flow pump used to circulate water in split-pond aquaculture systems.

Figure 14. Relationships between water discharge per unit power input and water flow rate of a high-speed screw pump and axial-flow pump used to circulate water in split-pond aquaculture systems.

Figure 15. Operational costs (\$US) of a twin, slow-rotating paddlewheel, paddlewheel aerator, high-speed screw pump, and axial-flow pump used to circulate water (12 hours per day) in a split-pond aquaculture system over a 210-day culture period at mutable water flow rates.

Electrical energy cost was assumed to be \$0.14 per kilowatt-hour—the standard electrical rate in west Mississippi.

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Table 1. Initial investment costs (US\$) for the components and installation of four units used to circulate water in split-pond aquaculture systems. Fish barriers (screens or gates) for fish culture were not included in the costs of each circulating system. Each split-pond had a total water area of approximately 2.84 ha.

Circulator type	Circulator Cost (\$)	Conveyance		Total cost (\$)	Per ha cost (\$)
		structure cost (\$)	Installation cost (\$)		
Twin, slow rotating paddlewheel	22,900	48,655	7,105	78,660	27,697
Paddlewheel aerator	5,850	23,910	3,240	33,000	11,620
High-speed screw pump	7,500	5,675	2,160	15,335	5,400
Axial-flow pump	16,720	5,675	2,160	24,555	8,646