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Hydrodynamics of a Large-scale Mixed-Cell Raceway (MCR): Experimental studies

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Abstract

The Mixed-cell Raceway (MCR) is a design that intends to combine the best characteristics of circular tanks and linear raceways in a single production system. The conceptual idea is to convert traditional linear raceways into a series of hydraulically separated cells, each of which behaves as an individual circular tank. The MCR can take advantage of the solids removal ability of circular tanks and can be managed as either a partial reuse or intensive recirculation system. This study investigated the hydrodynamics of a large-scale (90 m^3) MCR composed of three in-series 5.5 m × 5.5 m mixed-cells (~1 m water depth). Water velocity measurements of the entire tank were used to generate velocity-magnitude contours and vector plots, investigate the distribution of water velocities, and evaluate the self-cleaning characteristics and related management issues of an MCR.

The grand mean of the water velocities of the three MCR in-series cells was 16.5 cm/s (16.1, 15.5, and 17.8 cm/s for cell 1, cell 2, and cell 3, respectively). Results showed that water velocities decreased somewhat in a linear manner from the tank bottom to the top, i.e., 18.9, 15.8 and 14.7 cm/s, and in the same way from the periphery (21.9 cm/s) to the center of the cells (3.7 cm/s). Analyses indicated that these water velocities were in the optimum range to promote fish health and condition as well as to achieve tank self-cleaning. For a water exchange rate of 1.7 volumes per hour and an operating head of 1.36 m in the jet port manifolds, the power requirements of the MCR reached 8.9 W/m^3. Contour and vector velocity plots showed that the mixed-cells develop a well-defined rotational pattern around the center drain. Also, strategically located water jets directed across the width of the MCR were able to limit the rotational flow to each cell and create the required counter-rotational pattern between adjacent cells. Velocity vectors showed a relatively low turbulence in the corners of the cells, even in the middle cell (cell 2) that had solid-walls on only two sides. Velocity vectors and contour plots also suggested an absence of dead volumes or short-circuiting within the cells, indicating that adequate mixing was being attained in the MCR.

Keywords: Aquaculture; Mixed-cell Raceway; Design; Hydrodynamics; Water velocity; Measurement; RAS

1. Introduction

Uniform water quality, rapid solids removal and ease of husbandry and maintenance tasks are among the most sought-after characteristics of an aquaculture tank. Linear raceways are one of the most popular tank designs for fish production, mainly because they utilize the footprint area much more efficiently and allow easier handling and sorting of fish than circular tanks. Raceways operate as plug-flow reactors (PFR), i.e., water enters one end, flows longitudinally through the tank, and exits the other end. However, a problem of operating in plug-flow mode is that there is minimal mixing or diffusion ahead or behind the flow path

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Nomenclature

A_o	nozzle cross-sectional area (m^2)
C_d	coefficient of discharge (dimensionless)
D_o	nozzle diameter (m)
g	acceleration due to gravity (9.81 m/s^2)
h	hydraulic head (m)
P	power required per volume of water (W/m^3)
Q	total system flow rate (m^3/s)
Q_o	nozzle discharge flow rate (m^3/s)
U_o	nozzle discharge velocity (m/s)
U_R	resultant water velocity (cm/s)
V	water volume in the MCR (m^3)

Greek symbols

η	pump and mechanical efficiency combined (0.7, decimal)
ρ	water density (kg/m^3)

Abbreviations

HDPE	high-density cross-laminated polyethylene
MCR	Mixed-cell Raceway
MFR	mixed-flow reactor
PFR	plug-flow reactor
RTD	residence time distribution

(Levenspiel, 1999), thus creating gradients of decreasing dissolved oxygen and increasing ammonia along the longitudinal axis and producing disparity in the distribution and quality of fish (Watten and Beck, 1987). Therefore, large volumes of water are required to keep water quality parameters within acceptable levels (by dilution). Furthermore, linear raceways usually do not have the appropriate velocities for self-cleaning (Westers and Pratt, 1977; Timmons et al., 2002), and so sedimentation and accumulation of uneaten feed and feces occurs, causing poor overall water quality, increased mortalities and decreased growth rates. High water exchange rates and/or the use of structures, such as baffles (Timmons et al., 2002), can diminish these effects, but in practice, raceways fail to produce optimum water velocities recommended for fish health, muscle tone, and respiration (Timmons et al., 2002; Totland et al., 1987).

Quite the opposite is the case of circular tanks, where hydraulic behavior approximates that of a mixed-flow reactor (MFR). These characteristics have been well established in traditional circular tanks (Watten and Beck, 1987) and in more recent studies on the Cornell circular dual-drain tank (Davidson and Summerfelt, 2004), especially at high fish densities (>80 kg/m^3). Circular tanks also exhibit good self-cleaning and the capability to maintain optimal velocities for fish health and conditioning (Davidson and Summerfelt, 2004), which ultimately leads to improved growth rates and food conversion efficiencies (Timmons et al., 1998, 2002). Unfortunately, husbandry tasks are not only more difficult to achieve in circular tanks as compared to linear raceways, but are less efficient in utilizing the footprint space.

The Mixed-cell Raceway (MCR) was developed by Watten et al. (2000) to combine the best characteristics of circular tanks and linear raceways in a single vessel design, e.g., uniform water quality, rapid solids removal, and easier husbandry and maintenance. Vertical discharge manifolds along the sidewalls of an MCR allows converting linear raceways into a series of hydraulically independent mixed-cells, each having a counter-rotating hydraulic flow pattern to the next cell and a bottom-center drain that forces each cell to behave as an individual circular tank.

Residence time distribution (RTD) analyses conducted in a small-scale MCR revealed good mixing capacity and the absence of dead volumes for exchanges rates ≥1.3 volumes per hour. Also, fairly low power requirements (6.7 W/m^3) and were found (Watten et al., 2000).

In order to better understand the hydraulics of a commercial size MCR, a large-scale prototype (four times greater than Watten's) was constructed at the Conservation Fund's Freshwater Institute (Shepherdstown, WV). The objective of this study was to characterize fluid flow of this large-scale MCR by conducting water velocity measurements in the entire tank.

2. Methods

2.1. Tank design and operating conditions

An MCR was built inside a greenhouse and constructed of structural lumber and lined with a high-density cross-laminated polyethylene (HDPE) liner; its dimensions were 5.5 m × 16.5 m × 1.2 m (width, length, depth, respectively) (Fig. 1). Additional details on the construction and materials employed for this MCR are found in Ebeling et al. (2005).

The design concept of an MCR is to create a series of adjacent square cells each having an independent rotating hydraulic flow pattern; in this case three cells of 5.5 m × 5.5 m each (with approximate depth of 1 m).