Modulation of Turbulent Flow by Surrogate Asian Carp Eggs

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ABSTRACT

In geophysical flows, the presence of sediment in suspension and transport can play an important role in modifying the turbulent properties of the carrier fluid. Much research has focused on the effects of relatively small diameter (less than 1 mm) quartz-density (2.65 g/cm^3) particles on turbulent flow. Asian carp is a wide-spread invasive aquatic species in the U.S., causing severe ecological problems in rivers and lakes. Unlike sediment, Asian carp eggs are semi-buoyant particles (~1.05 g/cm^3 when initially spawned and ~1.00 g/cm^3 in the post-water-hardening period) whose diameter stabilizes to approximately 5 mm. This paper examines how turbulent flow is affected by the presence of particles serving as surrogates for Asian carp eggs as a function of turbulence intensity. Experiments were conducted in a mixing box with the oscillating grid placed near the bottom boundary, and 2D PIV was used to quantify the turbulent characteristics of the carrier fluid. Five paired experiments with and without Asian carp egg surrogate particles were conducted. Results show that under different grid oscillation frequencies (2 to 6 Hz), the mean kinetic energy of the carrier fluid decreased slightly in the presence of the particles, but the turbulent kinetic energy of the fluid did not change appreciably. This suggests strongly that Asian carp eggs in suspension do not modify turbulence intensity of the carrier fluid. These experimental results provide important insight into the entrainment, transport, and deposition of Asian carp eggs, which can inform models to predict the future spread of this invasive species.

Keywords: Turbulence, modulation, Asian carp eggs, mixing box, semi-buoyant particles

INTRODUCTION

Asian carp, mainly composed of grass carp, silver carp, bighead carp, and black carp, is a widely-acknowledged invasive species in the U.S. Its most common habitat lies in the Mississippi River and its tributaries [1]. While preventing the further spread of Asian carp is a primary goal, the DNA of these fish has already been detected in the Great Lake region [2]. Much work has been done to understand Asian carp behavior, especially how hydrologic factors influence spawning decisions [3-5]. Currently, common actions to mitigate the spread of Asian carp are to catch their eggs during the spawning season and by regulating flow through dams [6].

FluEgg [7, 8] is a numerical model developed to simulate the drifting behavior of Asian carp eggs in freshwater systems. Both forward simulation, in forecasting possible egg locations after spawning, and backward simulation, in predicting possible spawning locations, can be realized in FluEgg [8, 9]. Compared with neutrally buoyant particles, the complexity of the biological properties of Asian carp eggs makes the problem harder. Previously, lots of research have been done to better understand Asian carp's biological characteristics including factors influencing spawning[10, 11], death of the eggs [12–14], and the evolvement of the eggs' density and diameter from their early age in different water temperatures [14, 15]. When the eggs are spawned in the river, they are apparently denser than water and have smaller diameter as well. While, during the first 4 hours after fertilization, eggs absorb water actively from their surroundings to swell and grow up. After the swelling period, the density and size of Asian carp eggs get stabilized. Although, the final diameter and density may vary among species of Asian carps, the variance is not significantly obvious and could be ignored in this research. Finally, as our study subject, one density (1.04~1.06g/cm^3) and diameter (5mm) is employed as substitutes of real Asian carp eggs taking the availability of surrogate materials into account.

An important assumption in the transport model of Asian carp eggs is that the presence of eggs in suspension has no effect on the carrier fluid. That is, the movement of Asian carp eggs in rivers and lakes is identical to the movement of the fluid. Yet studies on two-phase turbulent flow provide clear evidence that flow properties and turbulent statistics can be altered by the presence of suspended sediment [16], including changes to the vertical velocity profile near the wall [17], [18], von Karman coefficient [19], bed friction [20, 21], and turbulence intensity [22–24]. In a related study, turbulence suppression in a mixing by the suspension of quartz-density sediments with a mean size of 0.4 mm has been observed [25]. Therefore, the objectives of this paper are to assess if the presence of Asian carp eggs modifies the turbulence characteristics of the carrier fluid and to test the passive particle assumption applied in current modeling technology.

EXPERIMENTAL DESIGN

The experimental setup comprises a particle image velocimetry (PIV) system and a standard mixing box (Figure 1). PIV is the main technology employed to measure velocities of the fluid in the experiment. The 50 mJ Nd-YAG dual-cavity laser system producing 532 nm light is used to generate a thin laser sheet. A single high-speed camera is used to collect images of the flow field. The PIV system is set to capture 4800 paired images in 60 s at a frequency of 80 Hz. The time lapse between pulses for paired images is 900 μs, and the interrogation area in the cross-correlation algorithm is 16×16 pixels. Commercial software (DANTEC Dynamic Studio) is applied to collect the raw data and to process the 2D flow vectors.

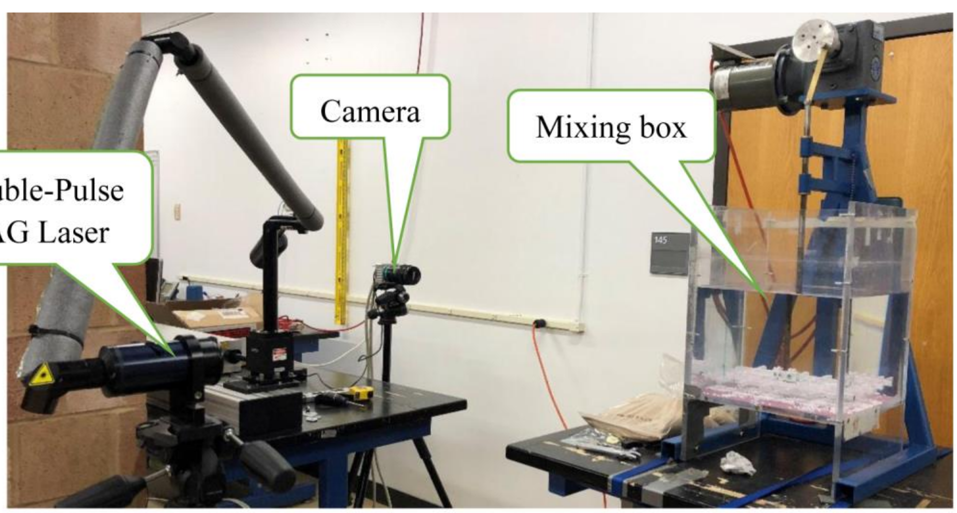


Figure 1 Image of experimental set-up system.

The mixing box used in this experiment is similar to those used in the previous turbulence and sedimentation studies [16], [25], [26]. The mixing box is a cubic tank whose length and width are 0.32 m and whose height is 0.40 m (Figure 2). Turbulence within the mixing box is generated by oscillating a grid placed near the bottom. The mesh size of the grid is 0.05 m and the square-bar thickness is 10 mm. The oscillation frequency of the grid is controlled by a motor connected to a cylindrical bar. In this experiment, stroke length *S*, the distance of the vertical movement of the grid, is fixed at 0.05 m. Flow depth *d* represents the distance from the top of the moving grid to the water surface. The only parameter varied here is grid oscillation frequency *f* [27]. Five grid frequencies, 2, 3, 4, 5, and 6 Hz, are applied using clear-water and particle-laden conditions.

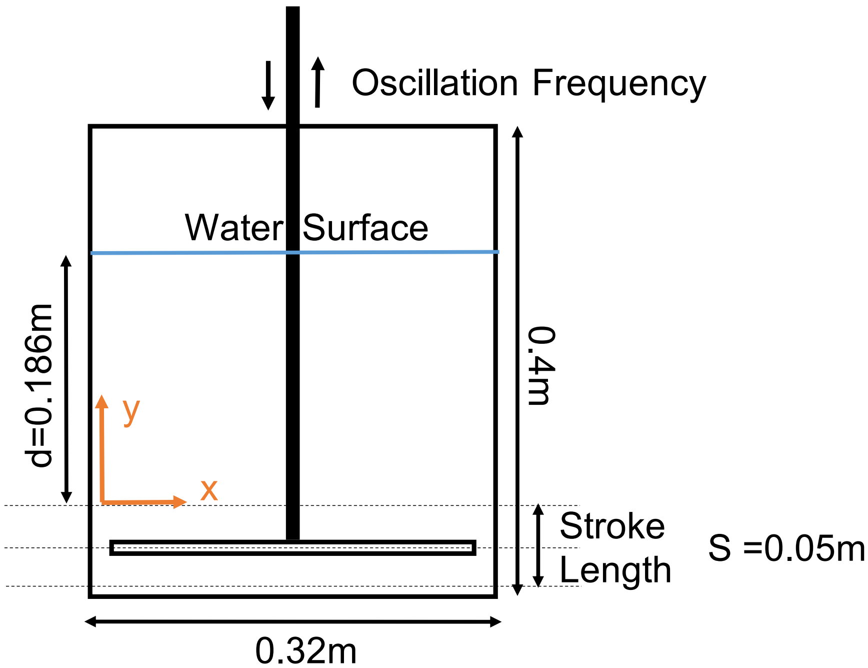


Figure 2 Schematic diagram of the mixing box.

(a) Surrogate particles for Asian carp eggs (b) Fluid tracer particles

Figure 3 Particles employed in the experiment.

Two kinds of particles are used in the experiment. Fluorescent Rhodamine-B-FRAK-KM426-7 particles are used as fluid tracers whose diameter ranges from 20 to 50 μm . Although the size and density of Asian carp eggs are not constant with time, an equilibrium state is reached for the four kinds of common Asian carp eggs [10-12]. In this study, one combination of size and density of eggs is used [29]. Specifically, commercially-available polystyrene plastic spheres (5 mm in diameter with a density of 1.04 to 1.06 g/cm^3) are used as surrogate particles for Asian carp eggs (Figure 3).

RESULTS

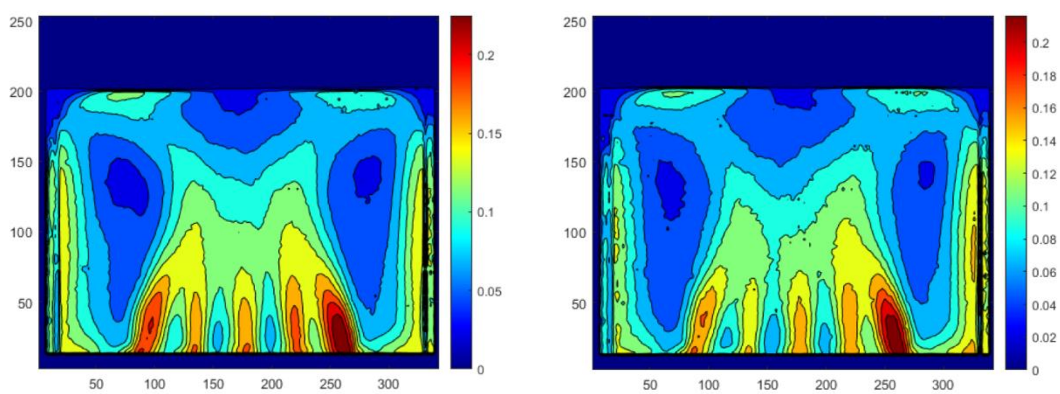
After employing the PIV system and processing the data in DANTEC Dynamic Studio, instantaneous cross-stream u and vertical v flow velocities within the mixing box are derived at-a-point. These velocities can be time-averaged at-a-point, $[u]$ and $[v]$, respectively, and the fluctuating terms, u' and v', and velocity magnitude U_{mag} can be derived using:

$$u' = u - [u] \tag{1}$$

$$v' = v - [v] \tag{2}$$

$$U_{mag} = \sqrt{[u]^2 + [v]^2} \tag{3}$$

The magnitudes of velocity in clear-water and sediment-conditions for one oscillation frequency are shown in Figure 4. While a secondary flow is present, no observable changes in the flow field are detected.



(a) Clear-water condition (b) Particle-laden condition

Figure 4 Contour maps of velocity magnitude for (a) clear-water and (b) particle-laden flow conditions at a grid oscillation frequency of 5 Hz.

The mean kinetic energy of the fluid per unit mass MKE is linearly correlated with the sum of the square of $[u]$ and $[v]$, which can be horizontally-averaged $\langle MKE \rangle$ using:

$$MKE = 0.5\left([u]^2 + [v]^2\right) \tag{4}$$

$$\langle MKE \rangle = \frac{1}{B}\int_{x=0}^{B} MKE\,\mathrm{d}x \tag{5}$$

where B is the width of the box. Values of $\langle MKE \rangle$ for all flow conditions are shown in Figure 5 as a function of y/d, where y is height above the grid. In general, maximum values of $\langle MKE\rangle$ occur near the grid and decrease toward the water surface. Yet $\langle MKE\rangle$ tends to decrease in the presence of the suspended surrogate particles, especially near the grid, and this reduction in magnitude appears to increase with grid oscillation frequency.

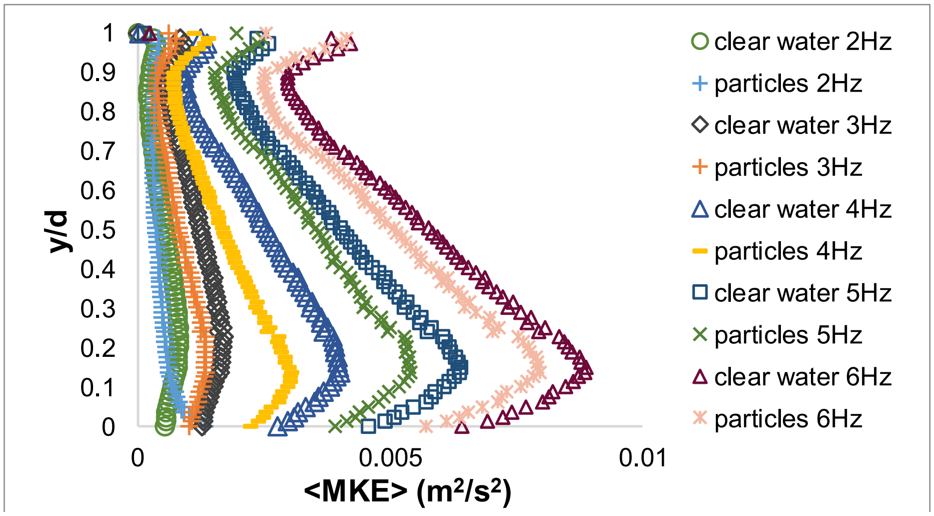


Figure 5 Comparison of $\langle MKE\rangle$ for clear-water and particle-laden flow conditions for five grid oscillation frequencies.

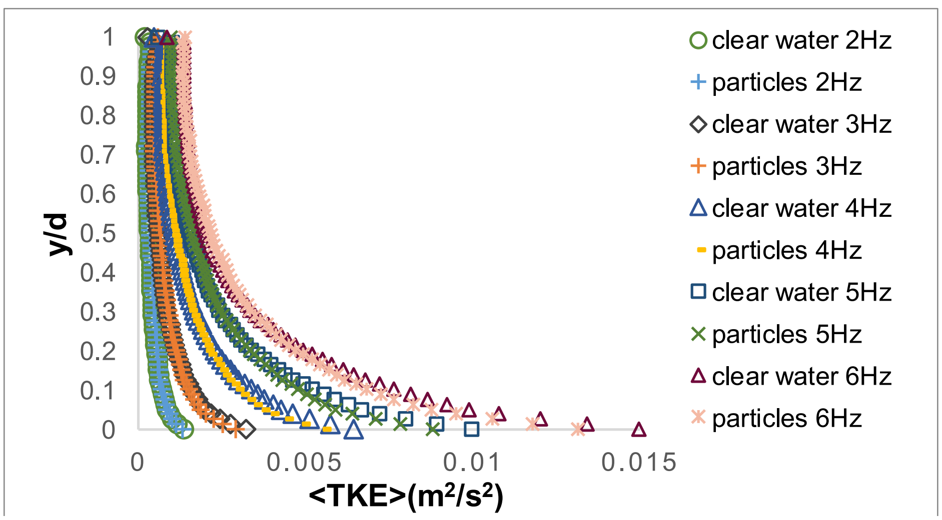


Figure 6 Comparison of $\langle TKE\rangle$ for clear-water and particle-laden flow conditions for five grid oscillation frequencies.

Turbulent kinetic energy of the fluid per unit mass TKE is proportional to the sum of the square of two horizontal and vertical instantaneous velocities, u' and v', of the fluid phase, which also can be horizontally-averaged $\langle TKE\rangle$, using:

$$TKE = 0.5\left(\left[u'^2\right]+\left[v'^2\right]\right) \tag{6}$$

$$\langle TKE\rangle = \frac{1}{B}\int_{x=0}^{B} TKE\,\mathrm{d}x \tag{7}$$

Figure 6 shows the variation of $\langle TKE\rangle$ for all experimental conditions. In general, $\langle TKE\rangle$ is a minimum near water surface and it increases toward the grid for all frequencies. Most importantly, the magnitudes and distributions of $\langle TKE\rangle$ for the particle-laden flows are nearly identical to the clear-water conditions at the same grid oscillation frequency. That is, the addition of suspended surrogate particles of Asian carp eggs do not affect the turbulent kinetic energy of the carrier fluid for the experimental conditions examined here.

Total horizontally-averaged kinetic energy $\langle T_{KE}\rangle$ is defined as the sum of $\langle TKE\rangle$ and $\langle MKE\rangle$,

$$\langle T_{KE}\rangle = \langle MKE\rangle + \langle TKE\rangle \tag{8}$$

Figure 7 shows the variation of $\langle T_{KE}\rangle$ for all experimental conditions. In general, the addition of the surrogate particles has only a minor impact on the carrier fluid, primarily by reducing $\langle MKE\rangle$ as noted in Figure 5.

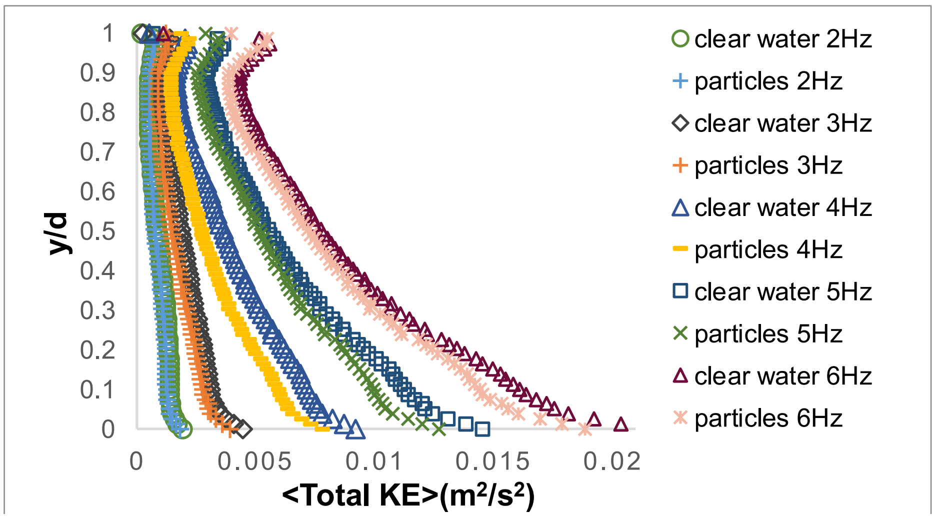


Figure 7 Comparison of $\langle T_{KE}\rangle$ for clear-water and particle-laden flow conditions for five grid oscillation frequencies.

DISCUSSIONS AND CONCLUSIONS

The influence of suspending surrogate particles of Asian carp eggs on the turbulence characteristics of the carrier fluid is investigated in a mixing box using 2D PIV. Grid oscillation frequency is the only variable in the experiment; all other boundary conditions are fixed. Clear-water and particle-laden experiments are conducted using five grid oscillation frequencies.

The presence of suspended semi-buoyant surrogate particles reduces the value of horizontally-averaged mean kinetic energy of the fluid $\langle MKE\rangle$ within the mixing box in comparison to the clear-water conditions using the same grid oscillation frequency. But these suspended particles do not measurably alter the horizontally-averaged turbulent kinetic energy of the fluid $\langle TKE\rangle$. As such, the horizontally-averaged total kinetic energy of the fluid $\langle T_{KE}\rangle$ is reduced only slightly.

Due to the different characteristics of Asian carp eggs and sediment particles, this study has great practical importance. The unique properties of Asian carp eggs include their distinctive semi-buoyant densities and extraordinary large sizes [14, 28, 30]. Yet the presence of these particles in suspension do not measurably alter the turbulence characteristics of the carrier fluid. Although the experimental conditions explored here are limited in scope, the results strongly justify the passive particle assumption in the transport of Asian carp eggs in rivers and lakes using modeling technology.

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