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Experimental validation of a novel bio-inspired particle separator

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ABSTRACT

Laboratory-scale prototypes have been made to verify the performance of a bio-inspired particle separator developed using computational fluid dynamic (CFD) simulations in a previous study. The design of the particle separator is based on crossflow filtration, a particle retention mechanism used by suspension-feeding fish to harvest food particles from their mouths. The geometric structure of the separator consists of a cylindrical body with a number of slits and baffles and a hole cut through the posterior bottom of the separator to be the particle collection zone. In this study, several external structures have been designed and added to the particle collection zone of the model mentioned above for future application purposes. CFD simulations have been done to reveal the effect of the modifications on particle removal efficiency. Prototypes with those external structures were also built using 3D printing technology for the validation of simulation results.

The results show that the geometry of external structures caused significant effects on the flow patterns inside the separator and the associated particle removal efficiencies. However, the observed flow patterns and particle trajectories and obtained particle removal efficiency show a high level of agreement with the CFD simulation results with spherical particles. This suggests that it is possible to use CFD simulations to predict the results in future applications or modifications to reduce separator development cost and effort.

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1. Introduction

Biomimetics is a technique that uses ideas inspired by phenomena observed in nature to develop new technologies or to improve existing ones. Many studies have achieved promising results using biomimetic concepts (Condon, 2003; Bulger et al., 2008; Baleen Filters, 2011; Hung et al., 2012). The authors were inspired by the way in which suspension-feeding fish retain small food particles inside their mouths by separating the particles from the engulfed water to design a particle separator (Hung et al., 2012). The separator applies the concept of one of the particle retention mechanisms, crossflow filtration, used by the fish to separate the particles from the surrounding water (Sanderson et al., 2001; Callan and Sanderson, 2003).

Computational fluid dynamics (CFD) has been used to explain how crossflow filtration takes place inside a fish oral cavity and how the filtering structures affect the flow field in their vicinity (Cheer et al., 2004, 2012). Cheer et al. (2012) showed the importance of flow speed and incident angle of the approaching flow relative to the gill rakers in a fish mouth. By adjusting those factors, fish could generate vortices that partially block the flow of water between and over the gill rakers. The vortices reduce the effective size of the gap between rakers and make a row of gill rakers act like a leaky wall that helps to retain food particles inside a fish mouth. The bio-inspired particle separator was developed using CFD simulations (Hung et al., 2012).

The geometric structure of the separator consists of a 2.5 cm diameter cylindrical body with a length of 8.5 cm and a conical cap at the end. This model has several pairs of slits with flow-obstructing baffles on the sides of the body (Fig. 1). The slits and baffles are slanted with the lower parts toward the inlet. The sizes of the slits were determined based on the dimensions of a fish mouth (Sibbing, 1988; van den Berg et al., 1992). The inlet consists of a small cylindrical tube surrounded by another tube, creating an annulus around the smaller tube. Particle-laden flow is introduced through the inner tube while clear water is injected through the outer tube. In addition, a hole is cut through the posterior bottom of the separator to be the particle collection zone, and a slight suction is used to carry the concentrate out of the separator, such that there is no return flow from the collection zone to the separator cavity (Hung et al., 2012).

The simulation results show that as particle-laden flow enters the separator, the first pair of slits plays an important role in triggering the rotation of the flow. The slanted direction and angle of the slits lead the flow to move downward and use the back flow of the fluid returned from the end of the device to generate vortices on

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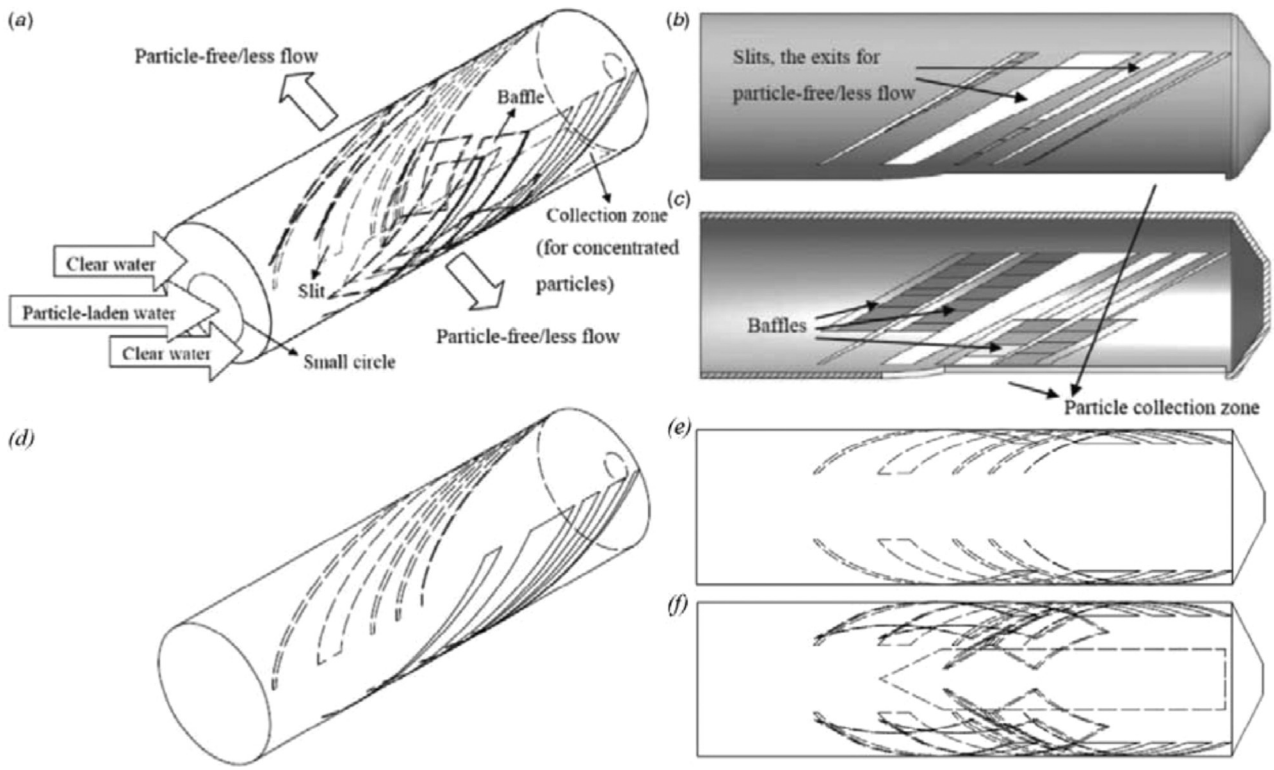

Fig. 1. Drawing of the biomimetic particle separator (a) and its side view (b) and section view (c). An isometric view (d) and a dorsal view (e) of the separator are shown with slits only for clarity, and a dorsal view of the separator with slits, baffles, inlet structures, and collection zone is included (f).

the posterodorsal part of the separator (Fig. 2). This vortex forces the particles entering the separator to go downward toward the particle collection zone directly. The clear flow injected from the annulus section of the inlet (as shown in Fig. 1) acts like a shield flow between the particle-laden flow and the slits to prevent the particles from exiting through the first few pairs of slits. By doing so, 66% of the injected particles (specific gravity 1.04 and 707 μm in diameter) are removed in 8% of the injected particle-laden water flow, and no significant difference on the particle removal efficiency is found by scaling up the diameter of the cylinder body from 2.5 cm to 10 cm.

CFD simulation is a powerful technique to predict fluid flow and particle movements (Bansal et al., 1998; Cheer et al., 2001; Pathapati and Sansalone, 2009). Using CFD simulations over laboratory experiments has the benefits of flexibility, efficiency, and reduction of cost and effort required. The CFD technique has also been used to design devices with various kinds of fluids involved (Fischer-Antze et al., 2001; Veerapen et al., 2005; Ariyaratne and Jones, 2007; He and Marsalek, 2009; Ponpesh et al., 2011). However, CFD simulations are not expected to completely replace physical models even if they have those benefits (Huggins et al., 2005). Therefore, prototypes of the bio-inspired particle separator models

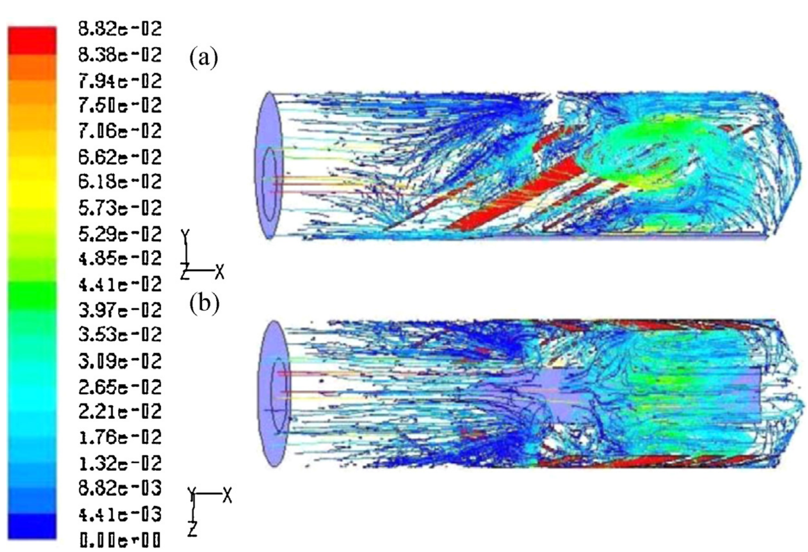

Fig. 2. (a) Lateral and (b) dorsal views of the flow patterns inside the particle separator. The color is coded to the magnitude of the velocity (m/s), and the slits are colored red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)