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Movement characteristics of fish in a jet fish pump

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ABSTRACT

The jet fish pump (JFP), a special utilization of annular jet pump, is a potential tool for conveying fish in the aquatic industry because of its simple structure and lesser tendency toward mechanical injury. Based on high speed imaging, we studied the movement of grass carp in a JFP under different operating conditions including recirculation, normal flow and cavitation. Since the fish are prone to move against the main flow before being suctioned into the JFP, most of the fish transferred by the JFP display reverse body orientation. As the fish moves into the diffuser, an extrusion force combined with the circumferential and axial vortex makes the fish turn around or swirl. Moreover, cavitation, including the transient cavity cloud induced on the body of the fish and the stable cavity cloud in the throat and diffuser, results in a hostile environment for the fish and causes great injury to the body of the fish, which should be avoided in practical application. In this paper, we analyzed the possible damages to the body of the fish caused by these two types of cavity cloud. In addition, the influence of the fish themselves on the inner flow details is studied by monitoring the static wall pressure. An apparent pressure peak is captured at every monitored position caused by fish moving through JFP. The peak value corresponds to the moment that the fish blocks the flow in the throat because the resistance caused by the fish is at a maximum at that time. The results of this investigation provide a basis for the design of a JFP that can be used to minimize injuries to fish by optimizing the size of each component or regulating the operating conditions.

1. Introduction

With the booming aquaculture industry and the prevalence of large-scale deep-water cages, an efficient method of conveying fish becomes increasingly significant. However, the traditional artificial fish conveyance method, which transports fish by heavy lifting and fish container, is very energy-intensive and results in a great loss of fish. Consequently, a fish pump, as an important auxiliary device in aquaculture, which can transfer fish without manual intervention and can preserve the freshness of the fish, tends to be a good substitute for the traditional artificial method. As long ago as the mid-20th century, fish pumps had been widely adopted in cage culture in countries such as Norway, the USA, Japan, Denmark and Russia, the aquaculture of which is considerably advanced (Summerfelt et al., 2009; Valdemarsen, 2001).

According to their working principle, fish pumps can be classified into impeller fish pumps, jet fish pumps and pressure/vacuum fish pumps (P/V fish pumps). The impeller fish pump, which includes both a stationary type and a submersible type, works by means of a specially designed high-speed rotating blade. The advantage of the impeller fish pump is its outstanding fish-moving capability, while the corresponding injury to the fish is also serious and the fish mortality rate is high. The principle of the pressure/vacuum fish pump is that an accumulation tank is exposed to vacuum and high pressure alternately by a water-ring vacuum-pump. The fish are first sucked into the tank by the vacuum pump together with water. After the tank is filled with water, the vacuum pump injects the pressurized air back to the tank and then the fish/water mix is pumped out. The P/V fish pump is claimed to handle the fish more gently than other types of fish pumps, but the capacity is generally lower. The discontinuous operations, such as sucking and discharging, greatly augment energy consumption. The jet fish pump is a particular type of annular jet pump in which the nozzle is annular and the high-velocity working flow encircles the secondary flow. The working flow (primary flow) soars into the suction chamber through the annular nozzle, and then exerts a great entraining force on the secondary flow. The fish can simultaneously be sucked into the suction chamber and be pumped out. Compared with the other

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Nomenclatures

A_j	cross sectional area of annular nozzle
A_t	cross sectional area of throat
C_p	pressure coefficient $C_p = 2\times(p\text{-}p_s)/(\rho v_j^2)$
D_t	diameter of throat
D_d	diameter of diffuser outlet
D_s	diameter of suction duct
P	total pressure
Q	volume flow rate
L_c	length of nozzle tip to throat
L_t	length of throat
m	area ratio $m = A_t/A_j$
v_j	mean velocity of primary flow
v_s	mean velocity of secondary flow
h	pressure ratio $h = (P_c\text{-}P_s)/(P_j\text{-}P_c)$
p	static pressure
q	flow rate ratio $q = Q_j/Q_s$
α	inclined angle of suction chamber
β	inclined angle of diffuser
ρ_f	the weight of fish per unit length
η	pump efficiency $\eta = q^*h$

Subscript

j	primary flow at nozzle exit
s	entrained secondary flow at suction duct
c	mixed flow at diffuser outlet

two sorts of fish pumps, the jet fish pump is simply constructed, and there are no-rotating parts. Thus, it is suitable for conveying various fish with different shapes and the injury to fish can be minimized by regulating the operating conditions of the pump.

Generally the fish passing through fluid machinery (fish pump, pressure passage and hydro turbine) may be subjected to both mechanical injury and barotrauma (injury due to rapid decompression). The mechanical injury is due to the rotating part, such as the blade in a hydro turbine. The barotrauma tends to be much more common, and occurs when fish are exposed to rapidly decreasing pressures (Cada, 1990, 2001; Brown et al., 2009). Gas in the swim bladders of fish expands during decompression, which leads to swim bladder rupture and compression-related injuries. Fish suffering from rapid decompression exhibit characteristic symptoms, including exopthalmia (bulging eyes), external hemorrhaging, everted stomach, intestinal protrusions, and loss of equilibrium (Bruesewitz et al., 1993; Gitschlag and Renaud, 1994; Parrish and Moffitt, 1992; Wilson and Burns, 1996). Tytler and Blaxter (1977) found that upon rapid decompression, fish display positive buoyancy and equilibrium loss and are often unable to return to the depth at which they acclimated before. Resorting to lateral and dorsal X-ray imaging in combination with necropsy, Rummer and Bennett (2005) studied swim bladder overexpansion on red snapper decompressed at a rate of 10.1 kPa/s. Expansion patterns resulted in over 70 different overexpansion injuries with the most severe being to vital organs. There are also some other studies that point out that the rapid recompression of rockfish can significantly decrease discard mortality and potentially enhance rockfish conservation (Parker et al., 2006; Jarvis and Lowe, 2008).

In addition, other factors such as shear flow, dissolved gas and cavitation can also produce a certain amount of injury to the fish. Neitzel et al. (2000) studied the shear effect on various types of juvenile fish by exposing fish to a submerged jet with a velocity from 0 to 21.3 m/s. Using strain rate as the index of intensity to describe the hydraulic force experienced by a fish in a shear environment, they determined no significant injuries occurred to fish subjected to strain rates ≤ 500 cm/s/cm, and found that species sensitivity to strain varied. Then, they (Neitzel et al. 2004) also found that the fish exposed headfirst to high-shear environments had higher injury-mortality rates than fish introduced tailfirst at similar strain rates. Quantifying injuries caused by shear stresses and turbulence, Guensch et al. (2002) indicated that eye, operculum, isthmus, and gill injuries were equally common at the highest nozzle speed, and disorientation was most common, while Bruising and descaling were relatively rare. Subjecting several fish species to a simulated turbine-passage pressure regime after acclimatization at two pressures and three levels of dissolved gas saturation, Abernethy et al. (2001) indicated that higher levels of dissolved gas in the water appeared to increase the amount of injury in some species of fish. Using transmission electron microscopy, Frenkel et al. (1999) investigated the damage of ultrasonic cavitation on the external epithelia of fish skin. The results indicated that the extent and depth of damage to the tissues were correlated with the exposure duration and that the propagation of the damage requires a period of approximately 90 s for the damage to reach as deep as 5 to 6 cell layers. The injury and mortality caused by cavitation is a complex process and none of the flow parameters, such as peak pressure, impulse and energy, alone is a good criterion for the swim bladder damage to fish (Gaspin, 1975).

Hence, how to maintain the injury caused by a fish pump at a relatively low level is of great significance in aquaculture. The jet fish pump (JFP), which is a special utilization of annular jet pump is a potential tool for fish conveying (Shimizu and Kuzuhara, 1983; Shimizu et al., 1987; Elger et al., 1994; Long et al., 2010; Xiao et al., 2013; Xiao and Long, 2015). Because there is no moving component in an annular jet pump, the mechanical injury compared with that in other fish-transferring apparatuses is relatively low. However, other possible harms caused by hydraulic factors, including shearing force, turbulence, sudden change of local pressure, recirculation and cavitation, should not be neglected. The density of fish and the characteristic dimensions of a JFP also affect the injury and mortality of the transferred fish. All of these factors may rupture the swim bladder, cause liver hyperemia, break physical balance and weaken the freshness of fish.

Predictions of the risk to fish passing through the turbine environment are based on identifying the locations and sizes of potentially hazardous regions (Garrison et al., 2002; Cada et al., 2006). However, the process of fish passing through the hydro-turbine passage is unable to be observed. Thus, necropsy and the CFD method are the main methods for researchers to investigate barotrauma to fish during passage through a hydro-turbine (Richmond et al. 2014; Stephenson et al., 2010; Trumbo et al., 2013). In contrast to hydro-turbine passage, the structure of a JFP is quite simplified and visualization is accessible with the main components made of transparent Perspex material. Flow characteristics and fish movement in a JFP under different operating conditions can be captured directly by a high speed imaging method, which is of great importance in identifying and confirming the dangerous zones in a JFP that the fish may have encounter. Consequently, the main contribution of our work is to observe the grass carp crossing a JFP by using the high speed imaging techniques and transparent Perspex material. The movement characteristics of grass carp under different operating conditions, especially when cavitation occurs,