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Impact of the internal flow in a jet fish pump on the fish

Xinping Long[a,b,*], Maosen Xu[a,b], Qiao Lyu[a,b], Jialin Zou[a,b]

[a] Wuhan University, Wuhan 430072, China
[b] Hubei Key Laboratory of Waterjet Theory and New Technology, China

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ABSTRACT

The present paper describes a jet fish pump designed to safely convey fish in the aquatic industry due to its simple structure and reduced tendency to cause mechanical injury. High-speed imaging, physiology investigations and CFD simulations are used to demonstrate the impacts of the flow on the grass carp during transport in the jet fish pump for various operating conditions. The results show that none of the tested fish were dead, had organ injuries or had swimming problems after passing through the jet fish pump. The respiratory rates and most of the blood indexes of the tested fish were affected by the flow field in the pump, but they were able to recover to normal levels after just 24 h. The surface injuries such as descaling and operculum injuries were mainly caused by recirculation flows, shear flows and pressure gradients. Further analyses indicated that bruising was caused by the flow direction changes, with cavitation potentially causing eye injuries. A deflection number, C_d, was proposed to describe the amount of flow direction changes for various operating conditions in the jet fish pump. The results show that, even though shear flows and pressure gradients are inevitable, the jet fish pump operating conditions can be optimized to reduce the risk of fish injuries. Recirculation regions and intensive cavitation should be avoided since they may cause serious injuries in the fish, reduce the fish transport rate and reduce the flow efficiency. These results provide a basis for improved jet fish pump designs.

1. Introduction

Fish have been an important human food source for a long time. In recent years, the development of high tech fisheries such as large-scale deep-water cages has led to a dramatic increase in the global supply from capture fisheries (inland and marine) from 19 million tons in 1950 to around 90 million tons in 1990 (Valdemarsen, 2001). However, the fish transport methods from capture fisheries have many limitations. In traditional transport methods, the fish are transported by heavy lifting in a fish container, which is energy intensive and leads to great fish loss. Fish pumps have been developed as an efficient substitute for aquaculture to transfer the fish using less energy intensive systems and fewer losses that preserve the fish freshness. Fish pumps are being used in various countries such as Denmark, Norway, Japan, Russia and the USA (Summerfelt et al., 2009; Xieming and Junzhou, 2005). According to the operating principle, fish pumps can be classified as impeller fish pumps, pressure/vacuum (P/V) fish pumps and jet fish pumps. The impeller fish pumps have a specially designed high-speed rotating impeller that provides high fish flow rates, but with high fish injury and mortality rates. The P/V fish pump operation characteristics lie in the alternate vacuum and high pressure regions. The fish are first sucked into an accumulation tank by the vacuum pump with water and then the fish-water mixture is pumped out by pressurized air after the tank is filled with water. The P/V fish pump treats the fish more gently, but such pumps have lower capacities due to the discontinuous operations for the suction and discharge which increases the energy consumption. The jet fish pump is a variation of the annular jet pump that is used in aquaculture. The primary flow goes into a suction chamber via an annular nozzle which creates a suction force on the secondary flow carrying the fish. The fish-water mixture then flows through the nozzle, the throat and the diffuser and is finally pumped out.

The jet fish pump is much simpler than the other fish pumps, has no rotating parts (Long et al., 2010; Long et al., 2012; Shimizu et al., 1987) and is suitable for transferring various types of fish. Thus, the jet fish pump has the lowest fish injury rate. However, the injury rate in the jet fish pump has not been reported. In addition, the internal flow characteristics of the jet fish pump are quite complex with large pressure gradients, cavitation, shear flows, flow direction changes and recirculation zones (Xiao et al., 2013), all of which can be potential risks for the fish during transport. Although the impacts of some of these flow phenomena on fish have been investigated in other types of fluid machinery or flow passages, the effects of few of these factors on fish have been reported for jet fish pumps, let alone the integrated effects of these effects on the fish.

Rapid decompression due to the large pressure gradients may result

* Corresponding author at: School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, China.
E-mail address: xplong@whu.edu.cn (X. Long).

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Nomenclature

A_j	annular nozzle cross sectional area
A_t	throat cross sectional area
C_d	deflection number $C_d=R_t/L_o$
C_p	pressure coefficient
D_d	diffuser diameter
D_s	suction duct diameter
D_t	throat diameter
D_p	dynamic duct diameter
H	outlet pipe lift
L_d	diffuser length
L_o	deflection characteristic length
L_t	throat length
P	total pressure
P_m	statistical significance
Q	volumetric flow rate
R_t	throat radius
V_t	mean velocity at the throat entrance
U_p	primary flow velocity at the annular nozzle
e	exposure strain rate
h	pressure ratio $h=(P_c-P_s)/(P_j-P_c)$
m	area ratio $m=A_t/A_j$
p	static pressure
q	flow rate ratio $q=Q_j/Q_s$
q_d	critical flow ratio
α	suction chamber inclination angle
β	diffuser inclination angle
ρ	water density
η	pump efficiency $\eta=q{\cdot}h$

Subscripts

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

in barotrauma which is quite common when fish are exposed to rapidly decreasing pressures (Brown et al., 2009; Čada, 1990; Čada, 2001). Tytler and Blaxter (1977) checked the swim bladders of fish by X-ray photography and found that after rapid decompression, the fish showed equilibrium loss and were often unable to return to the depth where they had previously lived. Rummer and Bennett (2005) used lateral and dorsal X-ray imaging in combination with anatomy to investigate swim bladder overexpansion on red snapper decompressed at a rate of 10.1 kPa/s. The expansion patterns showed over 70 different overexpansion injuries, most of which involved severe damage to vital organs. Another study (Parker et al., 2006) pointed out that rapid recompression of rockfish significantly decreased the mortality rate and potentially enhance rockfish conservation. Frenkel et al. (1999) studied the effects of ultrasonic cavitation on the external epithelia of fish skins using a transmission electron microscopic to show that the extent and depth of the tissue damage were correlated with the exposure duration. Neitzel et al. (2000) studied the effect of shear flows on various types of juvenile fish, introduced either headfirst or tailfirst, by exposing the fish to a submerged jet with velocities from 0 to 21.3 m/s. They used the strain rate as an index of the shear intensity to describe the hydraulic force experienced by a fish in the shear environment and found no significant injuries in fish subjected to strain rates less than 495 cm/s/cm but did find that different fish species had different sensitivities to strain. They (2004) then related the fish injury to the fluid force. Guensch et al. (2002) looked at the effects of inertia and found that eye injuries and operculum injuries were equally common at the highest nozzle speed and disorientation was very common, while bruising and descaling were relatively rare. Compared with these studies of the effects of the internal pump flow characteristics, there are few papers focusing on fish injuries caused by flow direction changes and recirculation flow in jet fish pumps.

This study investigates the risks to fish of these flow characteristics in a new jet fish pump with a controllable ring to adjust the area ratio. Parts of the jet fish pump, including the suction chamber, the throat and the diffuser, were made of transparent Perspex for visualization so that the fish movement could be captured directly by a high-speed camera. As in fish barotrauma research in hydro-turbines (Richmond et al., 2014; Stephenson et al., 2010; Trumbo et al., 2014), anatomy and CFD studies were also used to investigate organ injuries and the flow field. In addition, blood indexes were used to study the stress experienced by the fish caused by the internal flow characteristics. The main target of this work is to demonstrate the potential injuries caused by the internal flow characteristics in jet fish pumps and to provide guidelines for optimizing jet fish pumps to minimize the fish mortality and injury rates.

2. Experimental and CFD plans

2.1. Jet fish pump design

A schematic drawing of a jet fish pump with a suction duct, a primary duct, a controllable ring, an annular nozzle, a suction chamber, a throat and a diffuser, is shown in Fig. 1. The operating principle is that the high-velocity primary flow exits the annular nozzle at low pressure and entrains fluid from the secondary flow mixed with fish into the flow stream. These two flows exchange momentum and mix in the suction chamber and in the throat, with the mixed flow then passing through the diffuser as the pressure increases. Previous studies of annular jet pumps (Long et al., 2012; Lyu et al., 2016) gave the main structural parameters in Fig. 1 as L_d=500 mm, D_p=100 mm, D_t=60 mm, D_d=125 mm, D_s=80 mm, α=20° and β=6°. The pressure variations were monitored by ten pressure taps located along the pump. The main difference between a traditional jet fish pump and this new jet fish pump is the controllable ring that has a fixed outer diameter but different inner diameters. The area ratio, m, is a key parameter in a jet pump. Since the throat area is fixed, the controllable ring provides a convenient way to adjust the area ratio by varying the inner ring diameter. The present research used a controllable ring (m=1.75).

2.2. Test rig and device

A sketch of the experimental rig is shown in Fig. 2. The test pool, with a length of 9.0 m, a width of 4.7 m and a height of 1.6 m, was divided into a main pool, a filter pool, a buffer pool and an overflow pool. The main pool was the main part of the experiment and the temporary culture location for the tested fish. The overflow pool was used to keep the water level fixed during the experiment. The filter pool and the buffer pool kept the water clean during the 14 d temporary culture before the experiment. The temporary culture housed the fish in feeding cages (1.6 m×1.0 m×1.0 m) to acclimate the fish to the conditions in the test pool, where the average water temperature was 25.11 ℃, the mean pH was 8.25 and the average dissolved oxygen was 8.32 mg/L. Before the experiment, the fish were gently transferred into a conical net tube. Because, compared with feeding cages, the conical net tube is a smaller space to keep a higher fish density just as a practical application of fishing. The high pressure primary flow was pumped by a centrifugal pump and entrained the secondary flow from the main pool, with the mixed flow back to the main pool. During this process, fish were transferred from the conical net tube to a recycling tank. The suction tube and the delivery tube had no valves to protect