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Experimental evaluation of the effect of decompression on crucian carps injury during turbine passage

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Abstract. A continuing environmental concern for hydropower development is the injury and mortality of fish that passes through turbines. It is well established that the rapid decompression process inside turbine passage is one of the main reasons that lead to fish injury and mortality. The knowledge of mechanisms for pressure-induced injury is required in fish-friendly turbines design. Several experiments were implemented in a specially designed pressure regulation system to simulate the pressure change in a hydraulic turbine to identify the lethal nadir pressure and lethal pressure change speed. Different sizes of Crucian Carps were tested and the results were slightly different between them. Smaller Crucian carps have higher survival rate than the larger ones during the same simulated turbine passage tests. Operations that would optimize the survival of Crucian carps, such as higher nadir pressure and slower decompression speed, were also tested to provide more details in further design works. Nadir pressure higher than a pressure value turned out to be friendlier for all sizes of Crucian Carps. The results of the experiments will be beneficial to the fish-friendly turbine design and optimization.

1. Introduction

The survival rate of fish passing through turbines has been paid more and more attention in the early stage of both new hydropower construction and old hydropower station upgrading in recent years. Injury and mortality of downstream migrating fish that pass through turbine passages can result from mechanisms such as rapid and extreme pressure changes, cavitation, shear stress and blade strike [1]. Many studies have described injury mechanisms associated with turbine passage over the past years [2], integrating the results into tools for fish-friendly turbine design, however, was difficult and slow. This was because fish injury mechanisms were strongly related to turbine types, water head, operation conditions, fish species and fish size. Most of the studies were just performed in specific turbines and under specific conditions. Turbines are highly customized equipment that tests performed in one turbine can hardly be applicable for another turbine without modifications. Studying the injury mechanism and quantifying the damage threshold of important economical fish species and fish species at high risk of extinction in specific regions with the commonly approved methods is more helpful for the fish-friendly turbine design, protection of water ecological environment and construction of hydraulic engineering projects. The tested results for different species of fish can be greatly different, such as the damage threshold of Fall Chinook Salmon, Rainbow Trout and Bluegill Sunfish obtained by Pacific Northwest National Laboratory [3] in North America cannot be used directly on crucian carps or other fish in China rivers.



To study the effects of pressure on fish passing through turbines, one of the most commonly used methods is carried out by placing the fish in chambers and exposing them to the desired time-pressure regime [4]. The time-pressure regime was obtained by sensor fish [5] released and recaptured on specific hydropower dams or CFD simulations for hydropower plants in design, the former was more acceptable among researchers for higher accuracy. In this paper, crucian carps were tested in a pressure tank under different time-pressure regime to study their injury mechanism.

2. Pressure Tank Set Up

In order to accurately simulate the pressure-time regime of fish or fish sensors [5] obtained during the passing through of turbine passages, the pressure inside the tank was designed to reach the maximum and minimum pressure in demanded time (less than 0.3s for the quick decompression process). As shown in figure 1, three tanks (T1, T2 and T3) were used in the system, T1 and T3 were the vacuum tank and high-pressure tank, which were connected to four vacuum pumps and one air compressor respectively. Both of T1 and T3 were connected to T2 (the observation tank, designed with an observation window) through electric valves to regulate the pressure inside T2. Crucian carps were placed underwater in T2 with a net, which helped to reduce transfer and recapture time. Vacuum gauge (G1), vacuum pressure gauge (G2) and pressure gauge (G3) were connected to T1, T2 and T3 for the system tuning, pressure sensors were used for data acquisition. A program was used to control the electric valves. The pressure value inside T2 and the pressure change speed were controllable with this program.

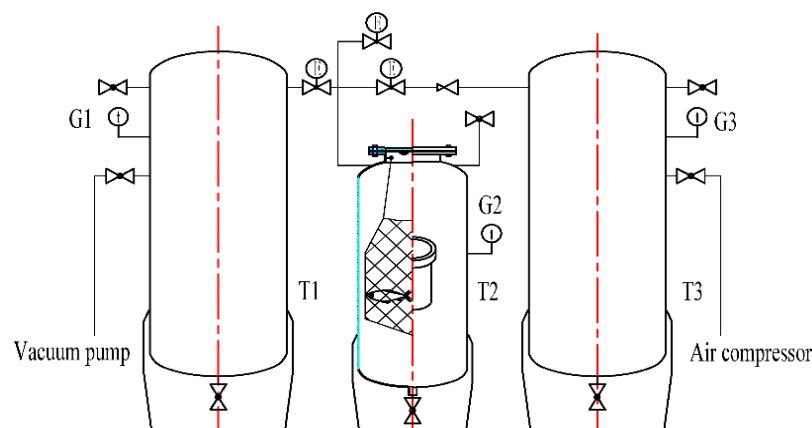


Figure 1. Sketch of the pressure regulating system.

To minimize the influence of casualties caused by fishing and transportation to test results, crucian carps were cultured in a 24 m³ water pool for at least two weeks. There is a high degree of variability in biological response to pressure changes between individual fish with seemingly identical physiological states at exposure[6], temperature, fish size, dissolved oxygen and other conditions would affect the test results. The water quality was checked before every test to make sure that the temperature and dissolved oxygen fluctuate were within the scope of permission, three sizes of crucian carps were tested and recorded separately.

3. Results and discussion

Procedures of the tests and one of the tests result were introduced in another article [7], from that study, conclusions were drawn that study of the injury and mortality mechanism should not only focus on the injury and mortality in short period of time after the experiments but also on the gradually occurring lesions and incentives in a relatively long observation period. In this paper, all tested fish were kept and observed for at least 48 hours.

In order to specify the most primary causes of death during the decompression process, two groups of tests were conducted. Test 1, 2, 3 and 4 were the first group, they were shown as arrows connecting

the pressure from the beginning to the end of tests in figure 2 to make differences between them more significant. Such as the pressure in T2 dropped from nearly 0 Mpa to -0.09 Mpa and -0.06 Mpa respectively in Test 1 and Test 2, while pressure dropped from 0.60 Mpa to -0.09 Mpa and -0.06 Mpa respectively in Test 3 and Test 4. The pressure-time regime of Test 1 and Test 3 obtained by pressure monitors during the test were shown in figure 3. The pressure-time regime of Test 2 and 4 was not shown because of their similarity (compared to Test 1 and Test 3 respectively).

The physiological states were divided into four types, which was named as A, B, C and D to represent normal, failed to keep equilibrium, showed external signs of trauma and died respectively, as shown in figure 4. The results of the first group of tests were shown in figure 5. For each of the tests, 30 Size I ($200\text{g} \pm 20\text{g}$), 40 Size II ($100\text{g} \pm 10\text{g}$), 50 Size III ($50\text{g} \pm 5\text{g}$) crucian carps were tested. Fish states were visually observed and recorded at the first hour, 24th hour and 48th hour after tests.

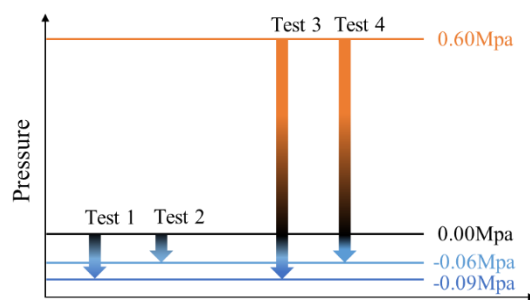


Figure 2. Schematic diagram of pressure change of the first group of tests

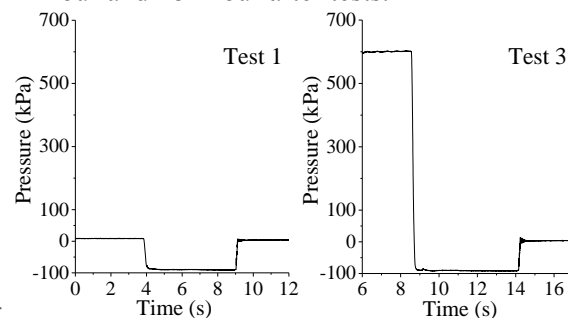


Figure 3. Pressure-time regime of the first group of tests

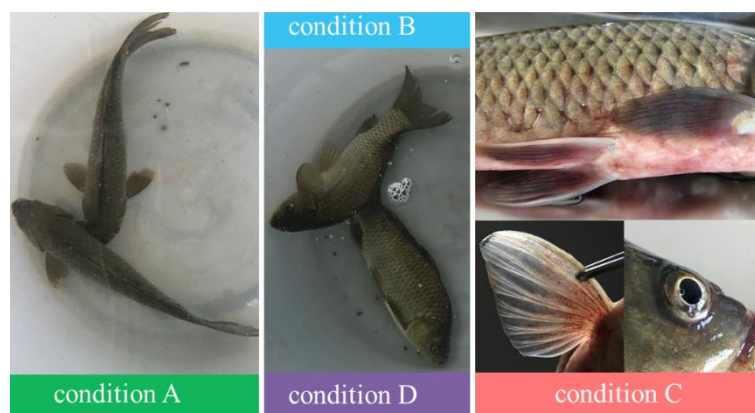


Figure 4. Observed fish states after tests.

The injury and mortality rate of three sizes of fish at three-time points after the tests were shown in figure 5(A). It can be seen that the rate of fish lost equilibrium after the tests were slightly different between three sizes, fewer Size I crucian carps lost equilibrium than size II and size III. It was possibly because that the big size fish have a stronger ability to make an adjustment for pressure change. The smallest fish have very small bladders and were slightly influenced by pressure change, which was the reason why more Size II crucian carps failed to keep balance. Averagely 50% of fish in condition B turned into condition A at 24th hour after tests, the left 50% of fish were still in condition B or in condition C or D. 6.67% of Size I crucian carps showed external signs of trauma at 48th hour, such as loss of surface mucus and hemorrhage in fish belly near the fins. External signs of trauma were difficult to be observed on Size II and Size III fish, the reason was that smaller fish were more possibly killed by internal hemorrhage before external signs appeared than larger fish.

It can be seen from figure 5 (B) that the injury and mortality rate from Test 2 were obviously lower than Test 1. Less than 20% of fish of all sizes lost equilibrium after the tests, and no fish died within 48 hours after the tests. Another interesting phenomenon is that 3.33% of Size I fish showed external signs

of trauma at 48th hour even though no fish was in condition B, which means that barotrauma and loss of equilibrium were caused by damage of different organs. In fact, loss of equilibrium was caused by gas leakage from the bladder and bladder rupture, fish in condition B caused by the former reason may turn into condition A after some time, caused by the latter reason, however, were very likely to die.

The main difference between Test 1 and Test 2 was the nadir pressure, the nadir pressure of Test 1 is -0.09Mpa , while the nadir pressure in Test 2 was -0.06Mpa . And the difference between Test 3 and Test 4 was the same. It means that the nadir pressure was one of the main reasons for causing injury and mortality in the turbine passage. The difference between figure 5 (C) and (D) was similar to the one between figure 5 (A) and (B) because Test 3 and Test 4 were only different in the nadir pressure.

The results of Test 1 and Test 3 shown in figure 5 (A) and (C), Test 2 and Test 4 shown in figure 5 (B) and (D) were quite similar while the difference between Test 1 and Test 3, Test 2 and Test 4 were much larger than that between Test 1 (total pressure drop: 0.09 Mpa) and Test 2 (total pressure drop: 0.06 Mpa), Test 3 (total pressure drop: 0.69 Mpa) and Test 4 (total pressure drop: 0.66 Mpa) as shown in figure 3. Which means that the total pressure drop was not as important as the nadir pressure in the injury reasons during the pressure decrease process.

In the first group of tests, the pressure drop was different between 4 tests. Test 5, 6 and 7 were the second group, as a supplement to the first group. In this group, the pressure-time regime was more similar to the pressure change inside turbine passage, and the pressure drop was set to be the same value, 0.49Mpa . The pressure inside the observation tank was firstly pressurized to $0.4\sim0.48\text{ Mpa}$, fish were then subjected to a sudden (0.1 second) decrease in pressure to $-0.09\text{ to }-0.01\text{ Mpa}$ and a corresponding increase to about 0.2 MPa before returning to surface pressure. Test 5, 6 and 7 were shown in figure 6 to make their differences more significant, while the pressure-time regime of Test 5 and Test 7 were shown in figure 7. The pressure-time regime of Test 6 was not shown to avoid repetition.

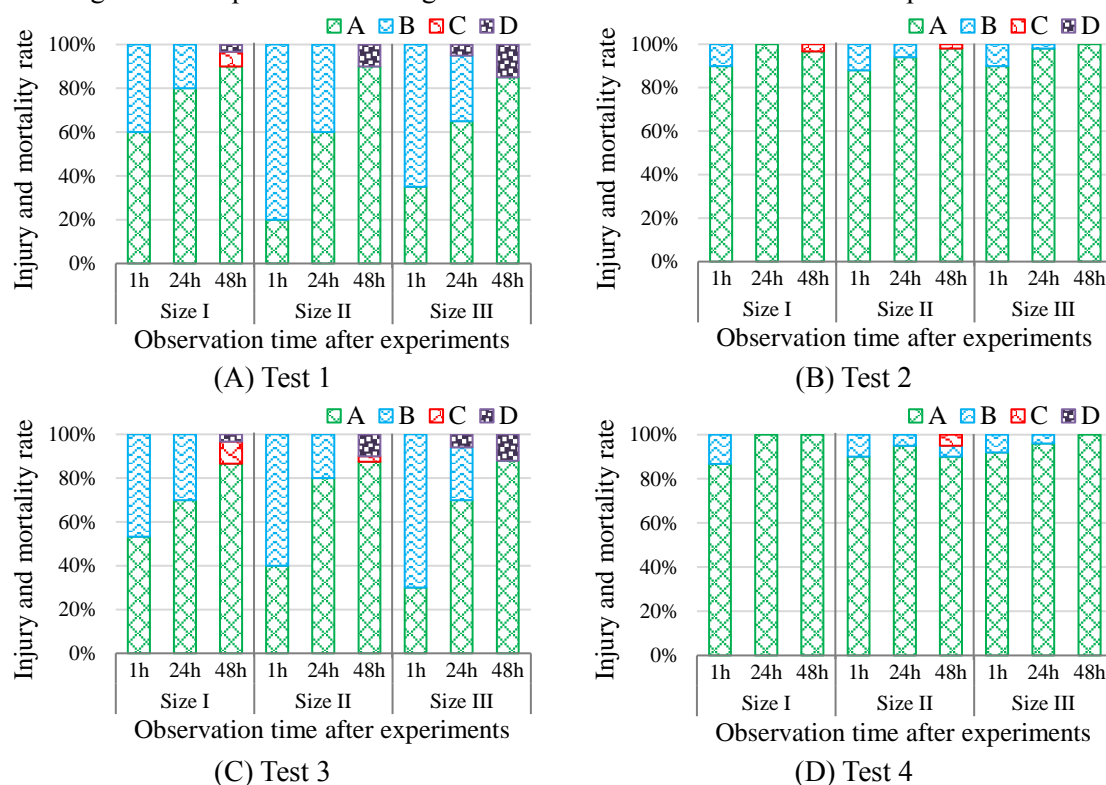


Figure 5. Fish states at different observation time after tests 1~4.

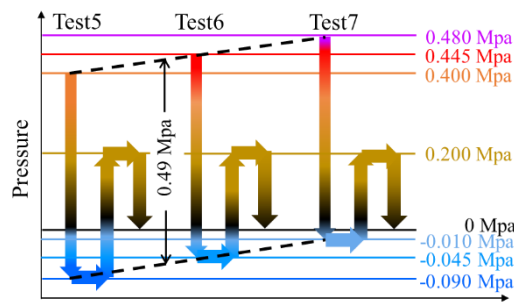


Figure 6. Schematic diagram of pressure change of the second group of tests.

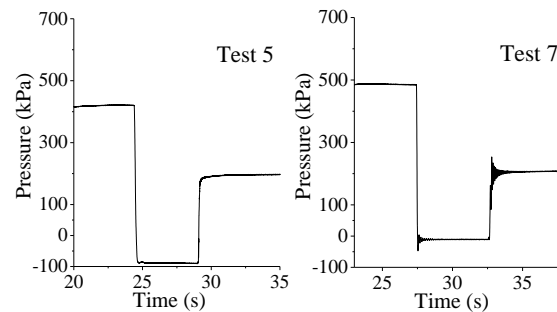


Figure 7. Pressure-time regime of the second group of tests.

The results of the second group of tests were shown in figure 8. Test 5 showed no significant difference in the injury and mortality rate when compared with Test 1 and Test 3. But only 3.33% of Size I crucian carps and 4% of Size II crucian carps were observed in condition B at the first hour after test 6, and all the fish were in condition A after the 24th hour. No fish was found injured after Test 7.

It can be seen from Group 2 tests that the nadir was the key reason for fish injury and mortality when pressure drop value and the pressure drop speed was the same. From the two groups of tests, it can be learned that the nadir pressure was the dominant factor in fish injury during both simplified decompression process and simulated turbine passage pressure change process.

From all these tests it can be seen that only few crucian carps were injured and no one was killed when the nadir was higher than -0.045Mpa. When nadir was -0.06Mpa, lower than 5% of crucian carps were injured by the depression process, and no death was found after 48 hours.

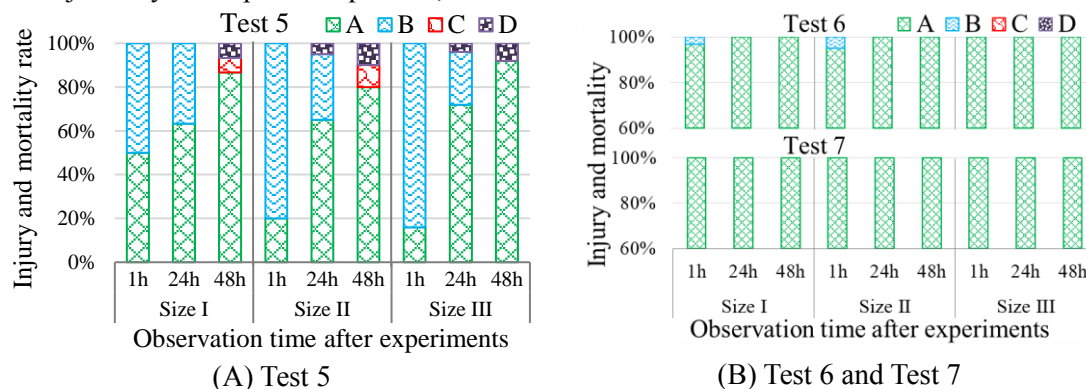


Figure 8. Fish states at different observation time after tests 5~7.

When the pressure decreased to -0.09Mpa, more than 50% of crucian carps lost equilibrium one hour after the tests, more than 50% of the injured Size II and Size III crucian carps recovered in 24 hours, while Size I crucian carps showed different recovery rate according to the pressure drop value, the larger the pressure drop value is, the slower the crucian carps recovered. No Size I and Size II crucian carps was dead in 24 hours, 4% of Size III crucian carps were dead in 24 hours. After 48 hours, 2%~10% of Size I and Size II crucian carps showed external signs of trauma, no Size III crucian carps were found showing external signs of trauma. Totally 5% of crucian carps dead in 48 hours when the nadir was -0.09Mpa.

The fish showed external signs of trauma would probably die in longer observation time according to the states in 48 hours. Fish lost equilibrium was in a higher chance of being injured or killed by other physical injury mechanisms such as blade impact and shear stress, further, was easier to fell in prey to their natural predators. Which means that a higher percentage of crucian carps can be directly or indirectly killed by the pressure drop process in the passing through of turbine passages, especially when the nadir is lower than or close to -0.09Mpa than the tests results.

In the fish-friendly turbine design, the pressure in the runner should be carefully simulated and optimized. The nadir value inside the runner, such as the pressure near the suction side of the blades trailing edge, should be carefully checked. If the nadir was too low, the design should be optimized. One more suggestion is, decrease the running time under partially flow rate conditions will also improve the survival rate of fish passing through turbines.

4. Conclusions

Hundreds of crucian carps in three sizes were tested under different pressure-time regime to study the injury and mortality mechanisms of fish passing through turbine passages. It can be learned from the first group of tests that pressure drop slightly influences the injury rate and recovery speed of the fish, however, the nadir was the key reason for fish injury and mortality. It can be learned from the second group of tests that the lower the nadir is, the higher rate of fish injured or died. Only few crucian carps were injured and no individual was killed when the nadir was higher than -0.045Mpa, when nadir was -0.06Mpa, lower than 5% of crucian carps were injured by the depression process, and no death was found after 48 hours, 5% of crucian carps died and 50% of crucian carps injured when the nadir was -0.09Mpa. In the fish-friendly turbine design that would be applied in China, the nadir pressure should be higher than -0.06Mpa.

Acknowledgments

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