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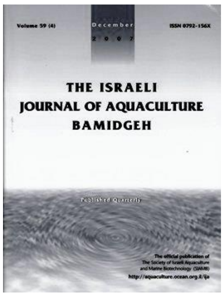

THE ISRAELI JOURNAL OF AQUACULTURE BAMIDGEH

A Preliminary Study of Physical Energy Distribution Model of *Sciaenops ocellatus* During Swimming

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Keywords: physical energy distribution model; *Sciaenops ocellatus;* sea area selections; swimming capacity

Abstract

This study focused on *Sciaenops ocellatus* in deep-water cage culture studying the changes of the main energy substances and metabolites during swimming. Based on our results, a physical energy distribution model was constructed. The main conclusions were as follows: (1) A power function relationship between the maximum swimming time and swimming speed of the red drum was found. (2) At high swimming speed, there was a significant increase in red drum blood glucose concentration, a slight decrease in the amount of muscle glycogen, and a significant decrease in hepatic glycogen. When fish were close to fatigue, hepatic glycogen concentration was close to depletion, so hepatic glycogen concentration in the red drum can be used as an important indicator to determine sustained swimming ability in the fish. (3) There was a significant increase in lactic acid and lactic acid concentration during swimming at a high speed, which indicated that the process of high-speed swimming in the red drum was accompanied by anaerobic respiration and aerobic respiration. (4) This study established a simple swimming physical energy distribution model of red drum based on the energy consumption of hepatic glycogen. The model shows a linear relationship between time and swimming speed. (5) A calculation method for the maximum tidal current velocity in red drum farming areas was put forward based on the physical energy distribution model of the red drum and the rules of the tidal currents. Thish may give practical reference for farming site selection.

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Introduction

Sciaenops ocellatus, also known as red drum, spot tail bass, eyespot corvina, perciformes, or drum, is native to the southern Atlantic and Mexican coastal waters and was introduced into China in 1991. It has the advantage of fast growth, high yield, variation in diets, and adaptability to the environment. It has now been widely cultured in Zhejiang and Fujian provinces (Liu et al., 2002).

Swimming ability is vital for the survival of fish and many aquatic animals. Most fish swim to escape enemies, hunt, migrate, mate, and avoid harmful environments (Stobutzki and Bellwood, 1994; Drucker, 1996; Fu et al. 2013). Swimming ability directly affects the success of farming to a certain degree, especially marine farming. Fish are often confined in a limited space for farming in the sea, in cage aquaculture, and Seine breeding patterns. Farmed fish constantly need to resist the impact of water trends (Ping et al. 2018). Water current in the culture area is beneficial for the promotion of water exchange inside and outside the culture zones and guarantees a good breeding environment, however excessive velocity affects the growth of fish and may even lead to their death. Scientific selection of suitable sea areas for culture is an important prerequisite for successful farming. Although there is awareness of the choice criteria for the maximum velocity involved in sea areas, in many farming practices there are numerous experiences, and scientific reasoning is often not applied. The location of aquaculture areas involving velocity is closely related to the swimming ability of fish, which is usually depicted by swimming speed or swimming time (Wang et al., 2010, Ping et al. 2018). Swimming speed can be divided into Optimum Swimming Speed, Maximum Sustained Swimming Speed, Critical Swimming Speed, Maximum Domed Swimming Speed, and Burst Swimming Speed. However, in the actual sea site, water flow direction and velocity change with time, and this makes it difficult to apply the testing results of the swimming ability of the fish targeting above methods directly to farming site selection. The determinant of fish swimming ability is often marked by the appearance of fatigue (Zhang and Sun, 2012), and there are many hypotheses for the cause of fatigue. Generally, a farmed fish is often in a prolonged swimming state, and the energy depletion theory or metabolite accumulation theory are important bases for determining fish swimming ability. Therefore, we used the main energy material consumption (glycogen) or accumulation of lactic acid metabolism which are often used in research on human movement as a reference (Wang and Hua, 2006). Under swimming conditions, the energy depletion theory reveals a physical distribution pattern, which can be used to determine the maximum tidal current velocity for fish farming waters.

There has been extensive research on fish swimming ability, and there was a special study on fish swimming as early as in 1978 (Beamish, 1978; Plaut, 2001). In 1995 there was some discussion about the various concepts of fish swimming ability, and study into their possible biological and ecological significance (Hammer, 1995). There were also extensive studies on the factors that affect the ability of fish to swim, such as temperature (Zheng et al., 2009; Bernatchez and Dodson, 1985), oxygenation ammonia-nitrogen (Jones, 1971), experimental methods (Gui et al., 2011), caudal fin loss and regeneration (Fu et al. 2013), and brain serotonin (Winberg and Thornqvist, 2016). However, few studies have been conducted on fish physical distribution model and energy metabolism law under swimming conditions. In this paper, we used a typical aquaculture fish (*Sciaenops ocellatus*) for our research. The main energy substance and its metabolites under swimming conditions were studied using flume experimental tests. During the experiments, blood glucose, lactic acid in blood, muscle glycogen, hepatic glycogen, and lactic acid in muscle were measured. Thereafter, fish physical distribution models were established. Based on this model, a theoretical method for calculating the maximum tidal current was given, which helps to give guidance for fish farming site selection.

Materials and Methods

The experimental materials

A total of 200 red drum fish (average weight 300-500 g) were obtained from an aquaculture base in Zhou Shan city, Zhejiang province. The initial weight of fish for the experiment was 403±18.8 g. Before the experiment, the fish were acclimated in the fish behavior laboratory at the National Marine Facility Technology Research Center. There were altogether three round tanks with an effective culture water volume of 25 m^3. Each tank was connected to an automatic drum filter, sand filter system, protein separator, biological filter system, and tower ozone disinfection system. One of the tanks was used for accommodation and the other two for reservoir alternation. The temperature was kept around 18°C using water temperature conditioner. The fish were fed daily at a rate of 1.5% fish weight.

The experimental methods

The experiments were carried out in a vertical circulation tank at the Fish Behavior Laboratory at the National Engineering Research Center of Marine Facilities Aquaculture at Zhejiang Ocean University. The full length of the tank was 350 cm, the glass observation window was 180 cm, the glass section size was 30 cm × 30 cm, and water flow was controlled by a variable speed motor. The flow velocity ranged from 0-2.0 m/s. We set up a monitoring camera on the side of the tank to observe and record the swimming behavior of the fish.

Swimming ability test of red drum

The swimming ability of fish is usually measured by swimming speed or swimming time. During the experiment, fish endurance swimming time at a given flow velocity was recorded. According to one study (Wang et al., 2010), *Sciaenops ocellatus* has strong swimming ability. In this experiment, we set five levels of flow velocity: 0.8 m/s, 0.9 m/s, 1.0 m/s, 1.1 m/s and 1.2 m/s.

Before the experiment, the vertical circulation water flume tank was calibrated, and the water environment was adjusted to the same conditions as in the acclimation tank. Fish were selected randomly from the acclimation tank and put into the flume tank. The fish were then acclimatized for one hour with the water flow velocity controlled at approximately 0.5 BL/s (BL = Body Length). After acclimation, the flow velocity was gradually accelerated to the preset value within 1 min. The swimming state of the fish was monitored by remote monitoring. The experiment was terminated when fish touched the rear net and gave up swimming for approximately 10 s. Each experiment was repeated for five times. In the experiment, only one fish was taken each time to avoid interference. Then fish were reselected for the next flow rate, until all the flow rates were tested over. At the end of each experiment, body weight, body length and other parameters of the experimental fish were measured.

The main physiological indices of red drum during swimming

The main concerns of this study were changes of the main energy substances and its metabolites, including blood glucose, hepatic glycogen, muscle glycogen, blood lactic acid, and muscle lactic acid which are all closely related to swimming ability. The experimental conditions were the same as those described in the result section sub-titled *Swimming ability test of red drum*. In this part, the flow velocity of 0.9 m/s was chosen during the experiment, because fish can swim for a relatively long time (approximately 200min) according to the above initial experiment. Six time points at 30, 60, 90, 120 and 150 min during the whole swimming process were designated, at which the main physiological indices were measured. During the experiment, the flow velocity was accelerated to the designed flow velocity (0.9 m/s) within 1 min after a one-hour acclimation period. The test was stopped at the designated sampling time point, and a fish was taken out quickly for sampling. Tail vein blood and aseptic was drawn, and removing the dorsal muscles was performed aseptically. Thereafter, the blood glucose, blood lactic acid, lactic acid and glycogen in the muscle, as well as hepatic glycogen were detected. Each test was repeated at least five times. The glycemic indices were measured using lactic acid dehydrogenase as per the national standard (ISO, 2010). The concentration of blood lactate and the concentration of lactic acid in the muscles were measured according to the lactic acid dehydrogenase method. The specific method reference kits were acquired from Nanjing-built Biological Engineering Research Institute.

Results

The swimming ability of red drum

The swimming ability was measured according to the duration of swimming at given velocities. Results are shown in Fig. 1. It shows that red drum fish have strong swimming ability, even with a flow velocity of 1.0 m/s.

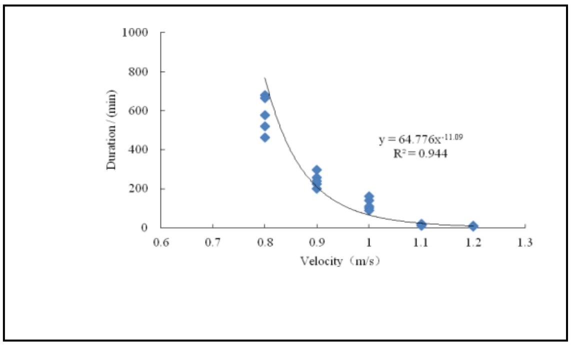

Fig. 1 Relationship between the sustained swimming time and flow velocities for Red Drum.

The average swimming time lasted up to approximately 120 min under the 1.2 m/s velocity. The average swimming time was 8 min. The swimming time duration of red drum decreased with increased swimming speed and a power function formula was obtained:

$$T = 64.78v^{-11.09} \quad (1)$$

Where, T represents the sustained swimming time (min) and V represents the swimming speed or flow velocity (m/s).

The main physiological indicators of red drum

In this experiment, the main swimming physiological indicators of blood glucose, muscle glycogen, hepatic glycogen, blood lactic acid, and muscle lactic acid at different times were tested and the results are shown in Figs. 2 to 6.

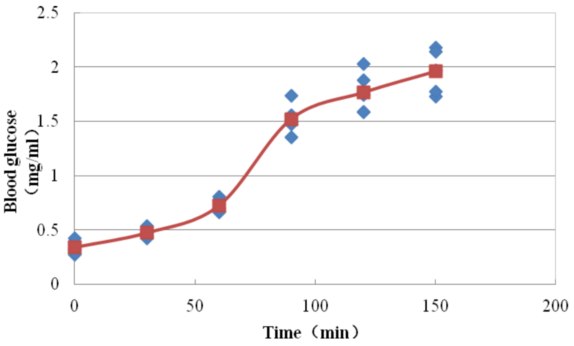

Fig.2 Blood glucose levels over time.

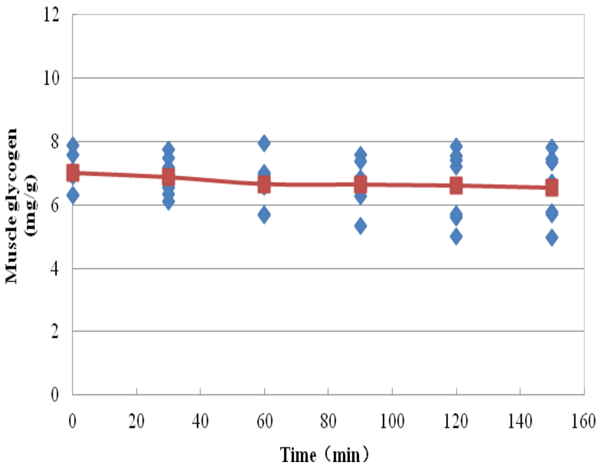

Fig.3 Muscle glycogen levels over time.

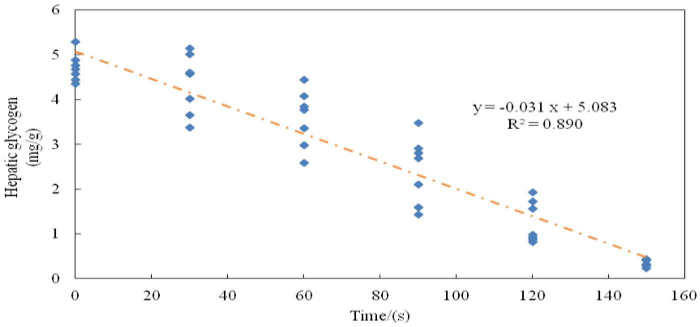

Fig.4 Hepatic glycogen levels over time.

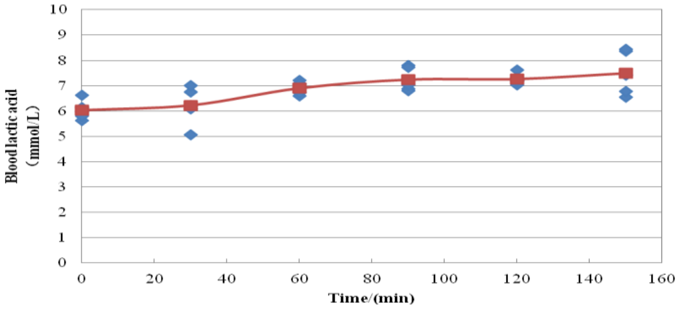

Fig.5 Blood lactic acid levels over time.

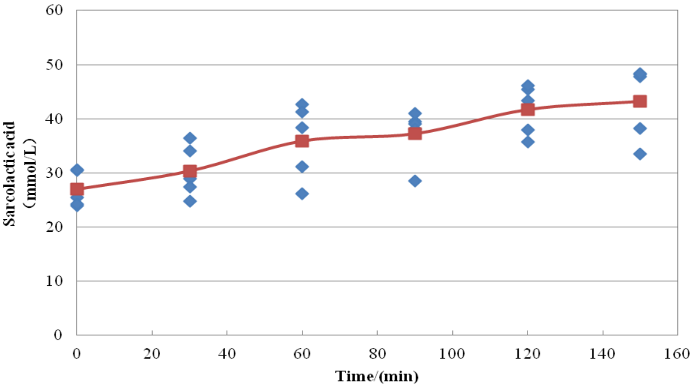

Fig.6 Sarcolactic acid levels over time.

The changes in glycogen content

The results of blood glucose and muscle glycogen and hepatic glycogen concentrations at different times are shown in Fig. 2 to Fig.4. The solid lines indicate the average values showing that the blood glucose concentration increases as time increases. The tests showed that the average blood glucose concentration was initially 0.34 mg/ml and increased significantly to 2.21 mg/ml after swimming for 150 min. The muscle glycogen decreased gradually, from an average of 7.00 mg/g at the beginning to 6.54 mg/g after swimming for 150 min. The results showed that muscle glycogen was rapidly consumed in a linear manner during swimming, and the hepatic glycogen was nearly depleted when the fish were near fatigue. Regarding hepatic glycogen concentrations, the fitting formula for linear matching was obtained as follow:

$$C_h(t) = 5.083 - k_v \cdot t \qquad (2)$$

Where, C_h (t) represents the concentration of hepatic glycogen (mg/g) at time t. K_v is the rate of hepatic glycogen attenuation, which is related to the swimming speed, K_v = 0.031 mg/(g · s) and T represents time.

The changes in lactic acid density

The concentration of blood lactate and lactic acid in red drum was investigated as shown in Figs. 5 and 6, in which the heavy lines represent the average values. The results showed that the blood lactic acid increased significantly from 6.02 mmol/L at the beginning to 7.49 mmol/L at 150 min, increasing by approximately 1.24 times. The muscle lactic acid contents rose from 27 mmol/L at the beginning of the experiment to 43 mmol/L at the end, which was 1.59 times higher.

Discussion

The main swimming physiological changes in red drum

The experimental red drum could swim for a relatively long time at a speed of 0.9m/s, mainly by aerobic metabolism. During swimming, the adrenaline secretion of cortisol increased and the energy materials such as hepatic glycogen and muscle glycogen decomposed into the blood vessels for energy metabolism to maintain high intensity swimming. Blood glucose levels progressively increased to support greater demand for energy (Pagnotta et al., 1994; Eros and Milligan, 1996). The constant consumption of blood glucose was replenished rapidly from hepatic and muscle glycogen. In this study, the muscle glycogen was only slightly reduced during the whole swimming process. However, the hepatic glycogen depleted rapidly which demonstrated that the hepatic glycogen played a leading role in supplementing energy to help maintain the blood glucose level. In this study, the red drum were forced to swim for a relatively long time.Their energy metabolism is mainly aerobic. However, lactic acid accumulation was also detected and showed that the swimming movement was accompanied by anaerobic metabolism. Intense swimming forced the lactic acid in muscle tissues to spread to the blood rapidly and strengthened the continuous exercise capacity of muscle tissue. Therefore, in this experiment, significant accumulation of lactic acid was found both in blood and muscle tissue. These results are similar to those observed in human motion (Hou et al., 2000).

There are several theories about sports fatigue (Zhang and Sun, 2012), in which energy depletion and metabolite accumulation are adopted more frequently. In the metabolic accumulation theory, the main focus is accumulation of lactic acid. Abundant accumulation of lactic acid in the blood and muscle tissue can lower pH, reduce enzyme activity involved in respiratory metabolism, and then cause fatigue. However, there is no clear consensus regarding the level at which lactic acid accumulation can cause fatigue. The theory of energy depletion is centered on the consumption of major energy sources (including blood glucose, muscle glycogen, hepatic glycogen, fat, and protein). Fat and protein are typically considered to provide energy over long periods for low-intensity continuous movement (Wang and Hua, 2006). Therefore, for higher-intensity swimming, fat and protein are expected to contribute less energy supplementation than that from glycogen metabolism. In this study, the blood glucose level rose continuously. Muscle glycogen decreased a small amount however, hepatic glycogen decreased significantly and was close to depletion when the fish were near fatigue. The results may indicate that hepatichepatic glycogen concentration was the key factor in controlling exercise fatigue.

The physical distribution model of red drum

To build a precise and complete physical distribution model of fish during swimming, there are many factors which should be considered. These include water flow velocity, water temperature, light intensity, fish size, fish species, and testing methods. The physical distribution model will become too complicated and less precise without simplification of affecting factors. In this preliminary research, all the above factors were given a fixed value. Their effect on the model is open for future research.

The former testing results showed that the swimming fatigue process of red drum is controlled by hepatic glycogen. Therefore, we took hepatic glycogen as a key factor and built the physical distribution model according to the changes in hepatic glycogen during swimming process. In this study, two assumptions were made: (1) the external source of glycogen was ignored during the swimming process;(2) the hepatic glycogen consumption model of the red drum was the same under different swimming speeds. During swimming, the energy supply was used partly against swimming resistance, and partly to satisfy their physiological needs. Therefore, the values of energy consumption obtained in this study were comprehensive results.

It was assumed that the average liver weight of a red drum was G grams, and the energy produced by one miligram of hepatic glycogen through oxygen metabolism was $\bar{e}$.The energy storage in the liver of a red drum at different times during swimming process was E(t), and it was given as follow:

$$E(t) = G \cdot C_h \cdot e \qquad (3)$$

Substituting formula (2) into (3), we have:

$$E(t) = E_0 - k_e \cdot t \qquad (4)$$

Where, E_0 is the energy storage of the original hepatic glycogen, E_0 = 5.083 G. K_E is the change rate of stored energy in the liver, $K_E = G\bar{e}K_v$. The average liver weight is a constant, so E_0 is a constant.

Because Kv is associated with the swimming speed, the rate of energy storage conversion is also associated with swimming speed. When the hepatic glycogen stores of a red drum are depleted (or close to exhaustion), i.e. E(t)=0, the theoretical maximum duration swimming time under a given current condition is:

$$t_{\max}(v) = \frac{E_0}{K_E} \qquad (5)$$

Divide (4) by E_0 , we have:

$$\frac{E(t)}{E_0} = 1 - \frac{K_E}{E_0} \cdot t \qquad (6)$$

Namely:

$$\bar{E}(t) = 1 - \bar{K}_E \cdot t \qquad (7)$$

According to formulas (1), (5), and (7), a physical distribution curve of red drum can be achieved based on the hepatic glycogen consumption model, as shown in Fig.7.

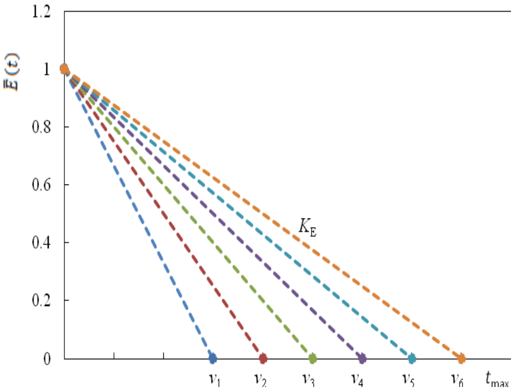

Fig.7 Physical distribution curve for Red Drum at different swimming speed.

Application of the physical distribution model for farming sea site selection

Fish suffer daily due to tidal currents in farming sea sites. Fish need a significant amount of energy to resist the tidal current. Therefore, it is extremely important to find the maximum tidal current in a fish farming site to avoid exhaustion of physical energy. The currents in a sea follow the principals of diurnal tide, semi-diurnal tide, or mixed tide. In this study, for simplicity, a regular semi-diurnal tide was used in building the physical distribution model.

The current velocity of a semi-diurnal tide changes periodically. The current velocity is controlled by the half-day period and the half-month period, which are included in the following formula (Zheng, 1987).

$$V_t = V_{mn} \cdot \sin(\frac{2\pi}{T_C}t) + K \cdot V_{mn} \cdot \sin(\frac{2\pi}{T_{mn}}t) \cdot \sin(\frac{2\pi}{T_C}t) \qquad (8)$$

Where, V_t is the magnitude of the velocity at time *t*. The first item on the right is the current velocity change in a half–day period. The second item is the current velocity change in a half-month period, in which $T_C = 12.4h$ means the half-day period. When swimming a fish does not need to consider the velocity variation over a long period. Therefore, the second item in formula (8) can be neglected and we have formula (9), in which we use the maximum current velocity $V_{\rm m}$ to replace the average maximum flow velocity $V_{\rm mn}$.

$$V_t = V_m \cdot \sin(\frac{2\pi}{T_C}t) \qquad (9)$$

Throughout the whole semi-diurnal period, $t \in (0, T_C)$, the maximum velocity appears twice with the same value but in opposite directions. Therefore, the time period will be simplified to $t \in (0, T_C/2)$, during which, the current velocity increases from zero to the maximum value and then decreases to zero. Therefore, the maximum current velocity V_m in formula (9) is the value we are seeking.

There is a power function relationship between the maximum sustained swiming time and the swimming speed (Fisher and Bellwood, 2002; Fisher and Wilson, 2004).

$$T = aV^b \qquad (10)$$

Where, V designates fish swimming speed, *T* means the maximum sustained swimming time. a and b are the coefficients. We also obtained the same relationship with a = 64.78 and b = -11.09 as shown in formula (1).

We can obtain the hepatic glycogen storage consumption rate from formula (5) as follow:

$$K_E = E_0 / T \tag{11}$$

The energy consumed by fish in time dt is as follow:

$$dE = K_E \cdot dt \tag{12}$$

Substitute (9), (10), (11) into formula (12), we have:

$$dE = \frac{E_0}{aV_m^b \sin^b(\frac{2\pi}{T_C}t)} dt \tag{13}$$

The dimensionless form of the above formula is as follow:

$$d\overline{E} = \frac{1}{aV_m^b \sin^b(\frac{2\pi}{T_C}t)} dt \tag{14}$$

Assuming that the fish swam in the period (0, $T_C/2$) and the hepatic glycogen storage was consumed, we integrated the formula (14) within (0, $T_C/2$) and obtained the following result:

$$\int_0^{T_C/2} \frac{1}{aV_m^b \sin^b(\frac{2\pi}{T_C}t)} dt = 1 \tag{15}$$

The numerical integration method can be used to solve the problem to obtain the maximum tidal current velocity V_m. The value of a and b should be known in order to get V_m. The parameters a and b are related to factors such as fish species and specifications and may be achieved through the sustained swimming capability tests.

By substituting parameters, a=64.78, b=-11.09, and T_C=12.4 h (=744 min) into the formula (15), we found that the maximum tidal current velocity of red drum should not be greater than V_m=0.973 m/s in a semi-diurnal tide sea area. This indicated that the energy consumption curve is under the conditions of maximum velocity Vm = 0.973 m/s and regular semi-day tide, as shown in Fig.8. As shown in Fig.8, we found that the energy consumption with a proportion of 98% was mainly concentrated in the middle part of AD period (accounting for approximately 43% of the total time), where the corresponding start-stop velocity was 0.76 m/s. During the BC time period (approximately 27% of total time), the energy consumption rate was 80%, and the rate of starting and stopping was approximately 0.90 m/s.

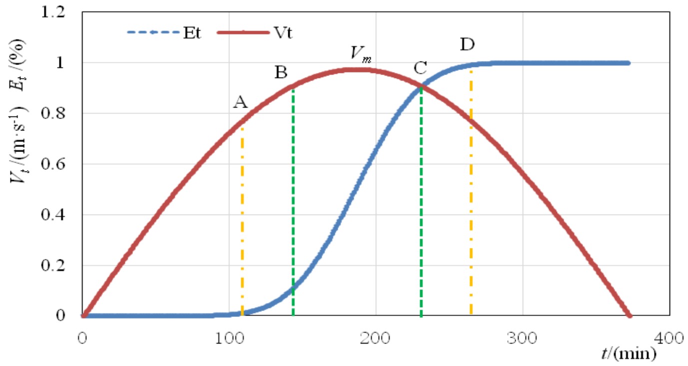

Fig.8 Curve of energy consumption over time for red drum.

For practical use, we need to know the energy consumption of red drum at different maximum tidal currents. To do so, we need to establish the ratio relationship between the maximum tidal current velocity and hepatic glycogen storage energy consumption, as shown in Fig.9. As shown in Fig.9, in the high velocity segment (0.8 – 1.0 m/s), the slight variation in the maximum tidal current will result in larger changes in energy consumption. As to fish growing, the energy consumption should be as low as possible to retain more energy for growth. We therefore suggest that the energy consumption should be no more than 10% and the maximum tidal current velocity not exceed 0.8 m/s.

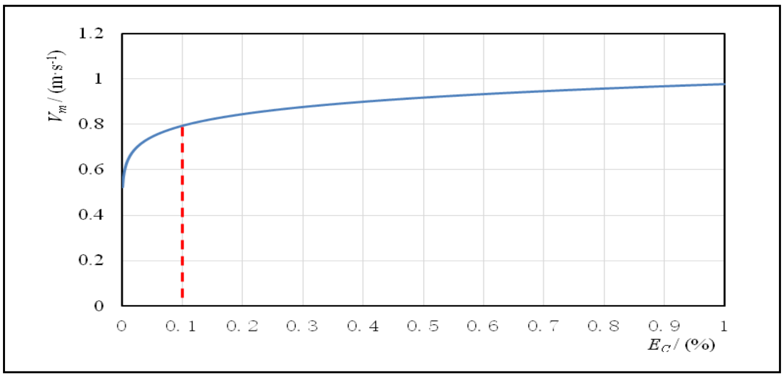

Fig.9 Relationship between the maximum tidal current velocity and fish energy consumption rate.

Conclusion

Marine farming, including sea cage aquaculture and net enclosure aquaculture, plays an important role in marine fishery production in China. Fish constantly need to resist the impact from tidal currents. Therefore, it is important to find out the maximum tidal current velocity in a given farming site for a designated grown species. In this paper, red drum was used as the research object for the study on energy change during sustained swimming. A physical distribution model was established and a theoretical method for farming site selection was given based on the physical distribution model.

In this study, only one species (red drum) was investigated for building the physical distribution model. There are still many factors involved such as size of fish, species, temperature, and current velocity and they are open for further study. In addition, we assumed that the hepatic glycogen storage consumption model was the same under different swimming speed conditions when building the physical distribution model. This must also be validated in future study. Moreover, the research was performed under laboratory conditions and did not take into account the complex water flow in real facilities such as sea cages. This is a complex research problem on the fish physical distribution model and more research is needed.

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