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Fluid Flow Characteristics in the Aquaculture Tank for a Breeding Fish

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The aquaculture tank is used for breeding fish in sea water which was pumped up to land. The flow characteristics in the aquaculture were investigated with varying the tank geometry and flow rate. The numerical analysis has been employed for calculating the velocity and temperature distributions in a water tank of rectangular type. The finite volume method and SIMPLE algorithm with 3-dimensional standard k-ε turbulence model were used for the numerical analysis. For comparison with experimental results, the PIV system was applied to visualize the flow patterns quantitatively. The numerical results showed good agreements with the experimental results. The mean velocity and temperature versus aquarium depth were represented for various circulating flow rates. Especially, the aquaculture environment is recommended that the aquarium depth has to be d=0.5 m, and this case is the condition of higher velocity and temperature in winter season.

Key Words: PIV (Particle Image Velocimetry), Circulating Flow Rate, Flow Characteristics, Standard k-ε Turbulence Model, FVM (Finite Volume Method)

Nomenclature

d : Aquarium tank depth
g : Acceleration of gravity [m/s^2]
H : Length for Z-direction
k : Kinetic energy of turbulence
L : Length for Y-direction
Pr : Prandtl number
Q : Circulating flow rate [m^3/Day], flow rate [L/M]
T : Temperature [℃]
U : Velocity [m/s]
W : Length for X-direction
X : Space coordinates

Greek Letters

β : Thermal expansion coefficient [K^{-1}]
δ_{ij} : Kronecker Delta
ε : Dissipation rate of turbulence
μ : Viscosity [Pa · S]
μ : Eddy viscosity [kg/m/s]
ρ : Density [kg/m^3]

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1. Introduction

The marine pollutions are extremely increased due to rapid industrialization and high-urbanization. The amounts of inshore fishery are decreasing because the sea water pollutions are from the eutrophication, red tide, etc. On the other hands, the importations of marine products are increasing. Thus, the fisheries are gradually turning to the aquaculture for getting more high values.

This aquaculture system is free from the marine pollutions and outside sea water conditions. But a land aquaculture tank requires more wide space and the equipment of circulating sea water system. The design of land aquaculture tank is very important to the growth of fish. Therefore, the water circulating system in a land aquaculture affects to the water temperature and velocity of flow. There are many kinds of the aquarium tank ; the general type is a rectangular shape because of more effective space utilization. But the optimum design of aquarium researches seems to be lacking at the engineering technique.

Several investigations of aquaculture in sea water have been reported. Kim (1997) examined the marine pollutions in view of biology. But, this biological treatment has no problems in aquaculture industry because the aquarium tank is separated from the water pollution. Partridge (1989) and Sannomiya (1987) examined the swimming structure and behavior of fish in aquarium tank. Takaki et al. (1993) considered the affection of the aquarium tank size and shape. Jeong et al. (1998) reported the flow characteristic by comparing a numerical analysis and flow visualization images. Mirashi et al. (1995) examined the affection of water current in aquaculture environment of the seas. Generally, the aquaculture equipment has two types of closed and open flow systems.

The closed type is the system which the sea water is recirculated again in the aquarium tank. But, the water in case of the open flow system is discharged to sea directly. Thus, the first system need a more expensive equipment cost, but this system can be saved the energy for heating the aquarium tank water in winter season. Lee (1994) carried out the experiment of a flow characteristics in the closed aquarium tank. In the design of aquaculture tank, what should be emphasized is the aquaculture environment. This means that the wrong design can cause the mass mortality of the breeding fish.

There are many kinds of important things for breeding fish in aquarium tank, what are especially important are the velocity and temperature condition. The general swimming pattern of fish is intended to be counter flow direction, thus the fish can be exposed to fatigue condition in case of large velocity. Hirashi et al. (1995) reported that there is a velocity limit in aquarium tank, and they experimented the velocity limit has to be under $3.2\sqrt{L}$ (cm/s). Where, L means the length of fish. But the velocity can attribute to cleaning an aquarium bath.

For a temperature condition in aquarium tank, Lee (1994) and industrial filed of fishery recommends the temperature range of 10℃ to 25℃. Therefore, to maintain this temperature the water heating apparatus is required and the growth of fish is very slow or can be died of disease in winter season.

In this study, we performed a numerical analysis for investigating flow characteristics in a aquarium tank of rectangular type, and the numerical results were compared with the experimental results measured by a PIV (Particle Image Velocimetry) system. The PIV was adopted to study the flow characteristics of an experimental model with rectangular type. This paper is intended as an investigation of the flow characteristics in aquarium tank for breeding fish, and we will concentrate on the velocity and temperature distributions. The main parameters are the aquarium tank depths and circulating flow rates in determinating the optimum aquaculture conditions.

2. Study Methods

2.1 Numerical analysis

Figure 1 shows the schematic diagram of numerical analysis model. The geometry of rectangular tank model is $W \times L \times H = 0.2 \times 0.2 \times 0.1$ (m). This model is consisted of two inlets and one outlet with the same size of 0.01×0.01 (m). A $41 \times 41 \times 41$ non-uniform grid was used in the computations, and the grid points were densely packed at near inlets and outlet. There are many

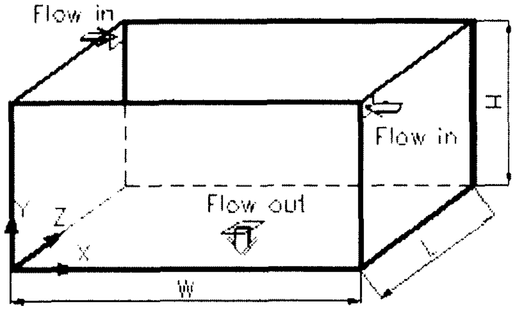


Fig. 1 Schematic diagram for numerical model

kinds of turbulence models for a flow field calculation (Jones et al., 1973 ; Patel et al., 1985), we introduced the two-equation turbulence model by Jones (1973) and Seo (1998). This turbulence model is based on the wall function and very widely used in a large space calculation because of no fine grids near walls and economical CPU time.

The numerical analysis was assumed as 3-dimensional and incompressible flow, and the standard k-ε turbulence model is used for solving flow field. The governing equations are as follows :

Continuity :

$$\frac{\partial U_i}{\partial X_i}=0 \tag{1}$$

Momentum :

$$\frac{\partial(\rho U_i U_j)}{\partial X_j}=\frac{\partial P}{\partial X_i}+\frac{\partial}{\partial X_j}\left[\mu\left(\frac{\partial U_i}{\partial X_j}+\frac{\partial U_j}{\partial X_i}\right)\right] -\frac{\partial}{\partial X_j}[\rho\overline{u_i u_j}]+\delta_{ij}\rho g\beta\Delta T \tag{2}$$

Energy

$$\frac{\partial(\rho U_j T)}{\partial X_j}=\frac{\partial}{\partial X_j}\left[\left(\frac{\mu}{\mathrm{Pr}}+\frac{\mu_t}{\sigma_t}\right)\frac{\partial T}{\partial X_j}\right] \tag{3}$$

Turbulent kinetic energy

$$\frac{\partial(\rho U_j k)}{\partial X_j}=\frac{\partial}{\partial X_j}\left[\left(\frac{\mu_t}{\sigma_k}+\mu\right)\frac{\partial k}{\partial X_j}\right] +G-\rho\varepsilon+g\beta\frac{\mu_t}{\sigma_t}\frac{\partial T}{\partial X_2} \tag{4}$$

Turbulent dissipation rate

$$\frac{\partial(\rho U_j\varepsilon)}{\partial X_j}=\frac{\partial}{\partial X_j}\left[\left(\frac{\mu_t}{\sigma_\varepsilon}+\mu\right)\frac{\partial\varepsilon}{\partial X_j}\right]+C_1\frac{\varepsilon}{k}G -G_2\rho\frac{\varepsilon^2}{k}-g\beta\frac{\mu_t}{\sigma_t}\frac{\partial T}{\partial X_2} \tag{5}$$

Where, G is the turbulent generation term

$$G=\mu_t\left(\frac{\partial U_i}{\partial X_j}+\frac{\partial U_j}{\partial X_i}\right)\frac{\partial U_i}{\partial X_j} \tag{6}$$

Here, the turbulence model constants are given as follows :

$$C_1=1.44,\ C_2=1.92,\ \sigma_\varepsilon=1.3 \quad \sigma_k=1.0,\ C_\mu=0.09,\ \sigma_t=0.7 \tag{7}$$

In this study, we adopted a finite volume method for solving each values from given equations, the SIMPLE algorithm by Patankar (1980) was used to solve the pressure term.

The boundary conditions in numerical calculation are as follows ;

The wall function and adiabatic condition were introduced for near walls, and the energy balance condition at the free surface is expressed as equation (8) :

$$(q_{cond}+q_{conv})_{water}=(q_{cond}+q_{conv})_{air} \tag{8}$$

Where, the subscripts of q_{cond} and$q$ q_{conv} are the heat flux per normal length by conduction and convection at the free surface, respectively.

2.2 Experimental study

Figure 2 shows the photograph of experimental set up for PIV measurement. The experimental test model has a top opening with rectangular shape, and the top surface is opened to atmosphere of 10℃. Also, the working fluid was used by water at 20℃ and flow rate was set to 2L/M. The bottom and side walls were covered with black painting to get a good particle images by CCD camera. The laser source was projected by Argon-Ion laser with 750 mW. Table 1 shows a condition of the present experimental study. The particle tracers are PVC (Poly Vinyl Chloride) and the average diameter is 200 μm. The CCD camera with model of CV-M50 was used for image capturing. The numbers of image are 277 frames to get an average image.

Table 1 Experimental condition for PIV measurement

Item	Specification
Image grabber	DT3155 (640×480 pixel, B&W)
Light source	750 mW, Ar-Ion Laser
Particle seed	PVC (Poly Vinyl Chloride : 200 μm)
Working fluid	Water (20℃)
Sheet light	Cylindrical Lens
Image recorder	SDR-2000
Computer	Intel Pentium III PC (800MHz)
Frame number for Time-averaged	277 Frames
Identification	Two-Frame Gray-Level Cross Correlation Algorithm

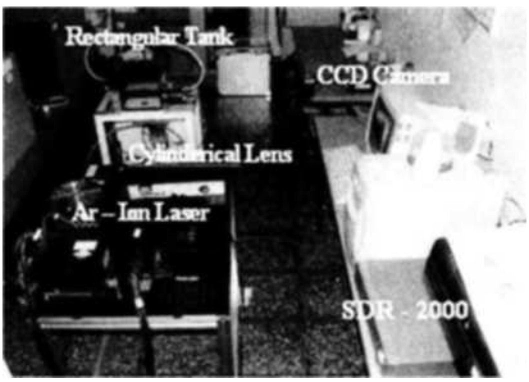


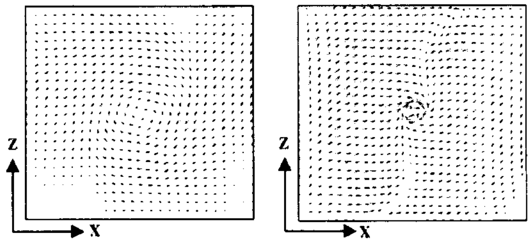
Fig. 2 Photograph of experimental set up for PIV

The cross-correlation algorithm was adopted to calculate the coefficients from two consecutive images (Daichin, 2003). 277 consecutive image frames were captured successively and digitized with a frame grabber into arrays of 640× 480 pixels.

3. Results & Discussions

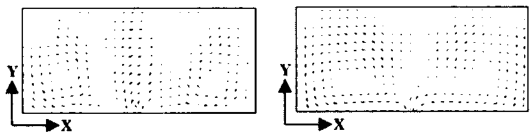
3.1 Comparisons of the experimental and numerical results

The numerical code was validated by PIV results in experimental aquarium tank as shown Fig. 1. The experimental and numerical results are compared at Q=2.0L/M. Figures 3~6 represent the velocity vectors between the experiment and numerical results.



(a) Experimental result (b) Numerical result

Fig. 3 Comparison between experimental and numerical result at near bottom in X-Z plane, Y=0.003 m



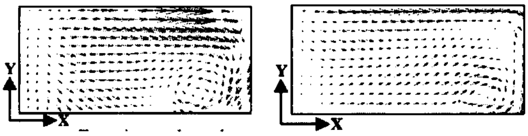
(a) Experimental result (b) Numerical result

Fig. 4 Comparison between experimental and numerical result at near center in X-Y plane, Z=0.1 m

Figure 3 shows the time-averaged velocity vectors between the experimental and numerical result at near the bottom wall, Y=0.003 m. The general breeding fish inhabit at near bottom of aquarium tank. Thus, the velocity distributions at near bottom wall were selected as a horizontal plane. The entire flow patterns have a swirling flow, and this results from the inlet flow that have a opposite inflow direction. The unique flow pattern was appeared at near center of X-axis, and the opposite velocity direction was observed in this area. The velocity values at center of X-Z plane have some difference between experiment and calculation, the reason of this difference is considered by the PIV resolution errors because of high velocity around the outlet.

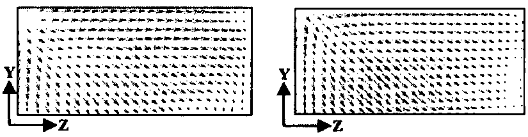
Figure 4 shows the comparisons of the velocity distributions at center section in X-Y plane, Z= 0.1 m. Centering around Z=0.1 m, the pair of vortex was appeared with a small velocity values than horizontal plane as shown Fig. 3(a).

Figure 5 shows the velocity vectors at near wall of X-Y plane, Z=0.195 m. The large and paralleled velocity was represented at top half area, this has a connection with a inertia force



(a) Experimental result (b) Numerical result

Fig. 5 Comparison between experimental and numerical result at near wall in X-Y plane, Z=0.195 m



(a) Experimental result (b) Numerical result

Fig. 6 Comparison between experimental and numerical result at near wall in Y-Z plane, X=0.01 m

of inlet flow from the left top corner, and the clockwise rotation vortex was formulated at right bottom corner. The calculated velocity distributions are slightly smoother than those of the experiments, although the general flow pattern is predicted fairly satisfactorily.

The Figure 6 shows the velocity vectors at near wall in Y-Z plane, X=0.01 m. The diagonal flow pattern was observed in this plane because of encounter flow from inlet. In order to clarify the applicability of the foregoing numerical code, comparative studies with experimental results have been carried out in aquarium tank model, and the calculated results had good agreements with experiment.

3.2 Flow characteristics of actual aquaculture tank

As mentioned above, we analyzed and verified the flow field in aquaculture tank model. One of the main purpose of this study is to obtain the flow and temperature profile in the actual aquaculture tank. In the aquaculture industry, the length of aquaculture tank is ranged about 3 m~10 m. The tank depth is variable, but it is taken under 1m. The general circulation flow rate per day to aquarium tank is about ten times of aquarium tank volume and the optimum temperature for breeding fish is about 20℃ in winter season. Thus, in this study, the size of aquaculture tank for calculation was set to W×L×H=5.0×5.0×d(m), and the circulation flow rates per day were changed to the ranges of 8~12 times of tank volume. The main parameters are the aquarium depth, the values depth d was varied over a wide range, from 0.5 to 1.0 at 0.1 meter intervals. In the case of actual aquaculture tank for a breeding fish, the aquaculture tank depth is not used below 0.5 meter. Therefore, the aquaculture tank depth was selected at the range of 0.5 to 1.0 meter in this study. Figure 7 shows the photograph of actual aquaculture tank. The breeding fish in aquarium tank behave at near bottom of tank. Thus, the main flow characteristics were investigated at near bottom in X-Z plane, Y=0.15 m. As a general circulating flow rate is selected by 10 times of tank volume, the next figures of velocity and temperature represented in case of 10 times of tank volume.

Fig. 7 The photograph of actual aquaculture tank

Figure 8 shows the velocity distributions at near bottom in X-Z plane. The flow pattern in case of d=0.5 m have a one large circulation cell, but the flow pattern was changed to a diagonal direction flow when the aquarium depth becomes deeper.

Figure 9 shows the streamline patterns at near bottom in X-Z plane for the different values of depth. The apparent swirl motion is observed in case of a shallow tank. As the depth is deeper, the swirl motion is disappeared due to high inlet velocity. Consequently, for a fixed circulation flow rate, when the depth is very deep the flow

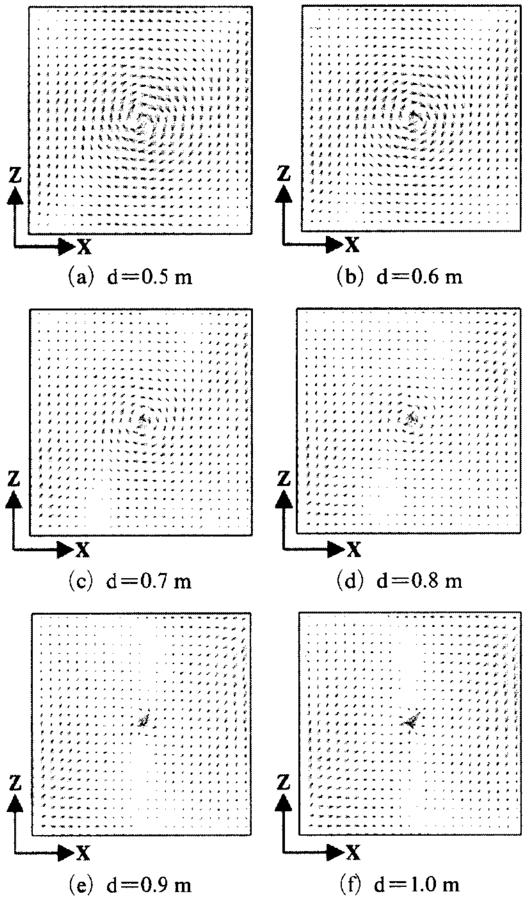


Fig. 8 Velocity distributions for various tank depth at near bottom in X-Z plane, Y=0.15 m

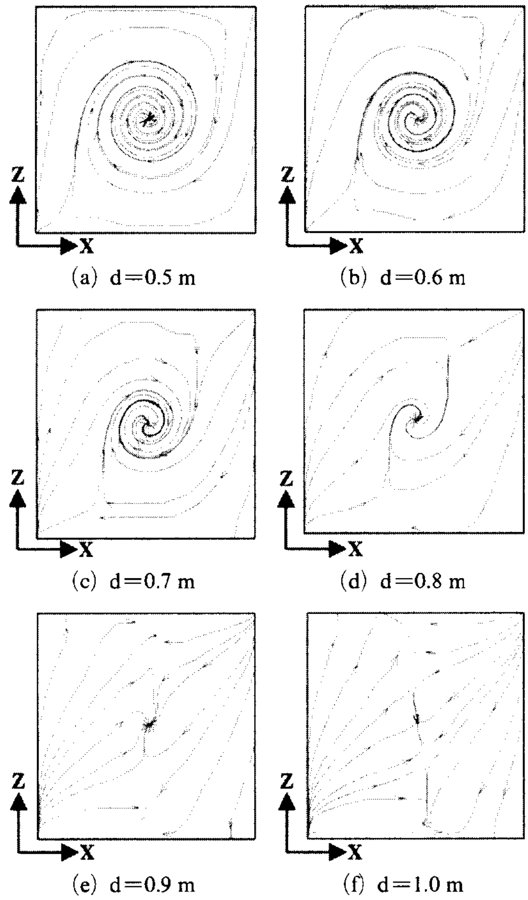


Fig. 9 Streamline for various tank depth at near bottom in X-Z plane, Y=0.15 m

at near the bottom wall can be showed the stagnation area. Therefore, this region can cause the stagnation of a pollutants and excrements, etc.

Figure 10 shows the distributions of temperature at near bottom in X-Z plane for different tank depth. This temperaturc is a dimensionless temperature values by inflow and ambient temperature. This temperature is a dimensionless temperature values by inflow and ambient temperature, and this temperature is defined as

$$\frac{T-T_a}{T_w-T_a} \tag{9}$$

Where, T, T_a and T_w are the calculated value, ambient and inflow temperature.

As shown in Fig. 10(a), the high temperature appears at near the each walls of the X-direction, and this high temperature is distributed widely in the plane by the swirling flow. As the tank depth is deeper, the high temperature can not be propagated to other region. This results from the separated flow pattern as shown Fig. 9(f). Thus, in order to distribute the high inflow temperature to the bottom, it is one of method to design or maintain a shallow water level.

3.3 The optimum conditions for aquarium tank

The mean values of velocity and temperature of a horizontal plane are more useful in aquaculture tank because the breeding fishes are generally acting around the plane.

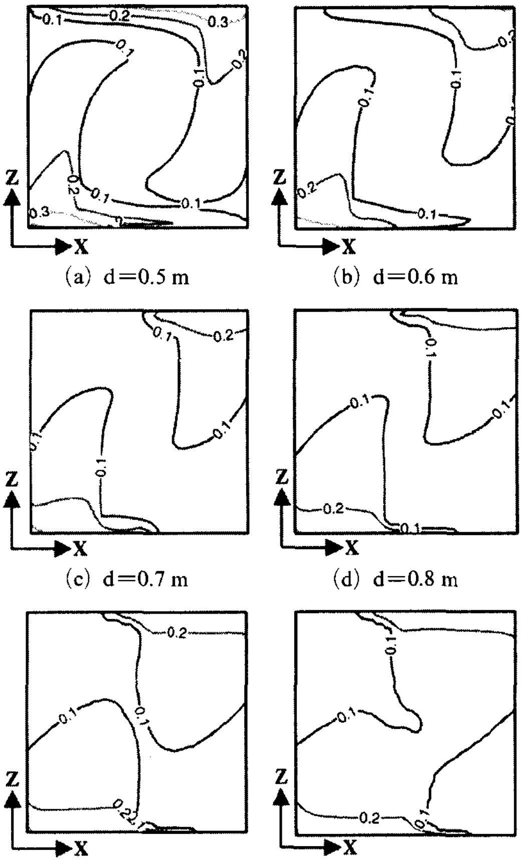


Fig. 10 Temperature distributions for various tank depth at near bottom in X-Z plane, Y=0.15 m

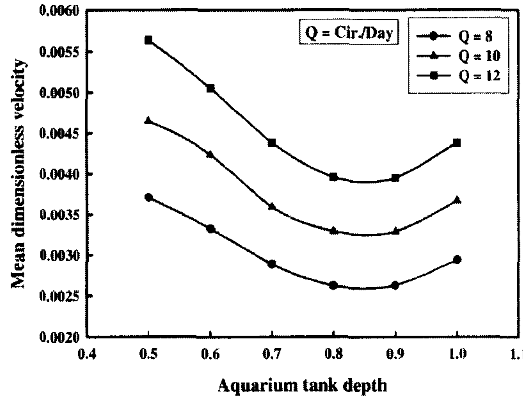


Fig. 11 Mean velocity for various depth in X-Z plane, Y=0.15 m

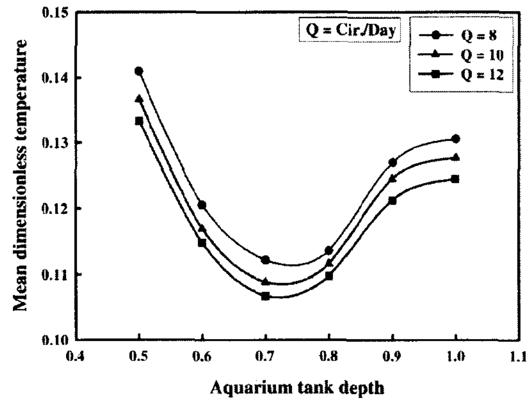


Fig. 12 Mean temperature for various depth in X-Z plane, Y=0.15 m

Figure 11 shows the mean dimensionless velocity for various circulation flow rates in X-Z plane, Y=0.15 m, and this dimensionless values were obtained by $\sqrt{U^2+W^2}$. The highest and lowest mean velocity was appeared in case of d=0.5 m and 0.8 m, respectively. In these results, the adequate aquaculture conditions will be insuranced in case of a shallow depth, and these conditions can preserve clean water due to a high velocity. As the circulation flow rates are increased, the velocity is changed in proportion to flow rate.

Figure 12 shows the mean dimensionless temperature in X-Z plane. The high mean dimensionless temperature value appears in the case of d=0.5 m and 1.0 m. This calculation study was intended for obtaining the temperature environment in winter season, thus, the temperature in case of d=0.5 m is more useful for a breeding fish. The good aquaculture environment is defined in case of d=0.5 m, this case is satisfied in velocity and temperature at the same time.

4. Conclusions

In order to verify the calculation code, the numerical analysis and experimental PIV data were compared in the aquaculture tank model of rectangular type. Based on this calculation code, the flow field in aquaculture tank was carried out for various tank depths. Some important results can be summarized as follows.

(1) The comparative studies with experimental results have been carried out, and the calculated results had good agreements with experiment.

(2) When the depth of aquarium tank becomes deeper, the flow field near bottom wall was separated with two large vortex, but, in opposite case, one large circulation was appeared.

(3) As the depth of aquarium tank is shallow, the maximum temperature is appeared near wall of the X-direction, and this high temperature is distributed widely due to large swirling flow. The temperature in aquarium is increased when the depth of aquarium becomes shallower.

(4) The case of $d=0.5$ m, the high mean velocity and temperature was appeared, and this conditions can be recommended as a good aqua cultural environment.

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