Numerical Simulation of Ballast Water Exchange

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ABSTRACT

In February, 2004, at International Maritime Organization (IMO), LONDON, a new international convention "International Convention for the Control and Management of Ship's Ballast Water and Sediment 2004" was adopted. It is called "Ballast Water Management Convention (BWM)". Ballast water means charged seawater or fresh water in ship's special tanks (ballast tank) to keep safety navigation and ship's maneuverability. However, from 1980, it was point out the serious problem for marine ecosystem and human life that ballast water includes harmful marine species (and small organisms) and these species are also discharged along with ballast water. These species were released with discharged ballast water in water areas, where species are different from discharged ballast water. The problem is that released species increase when released species are more powerful than native species and consequently, marine ecological system is destroyed in released water area.

Authors have inspected the validity of the ballast water exchange using pumping-through method that is one of the methods of ballast water management. In this paper, the numerical simulation of the motion and density of the fluid at the time of exchange of the fluid in a 2-dimensional tank using the pumping-through method was carried out by using two different type numerical methods. One method is MPS method that is one of the particle methods. Other one is Finite Different Method (FDM). Authors were compared with result of two numerical method calculations and experiment result and reported some knowledge from these results.

1. Introduction

Ballast water is indispensable for the ship navigation because to adjust ship draft and keeping ship maneuverability. Seawater is used for ballast water. Ballast water is ballasted in ballast tanks at shipment port, gulf and the like coastal sea. And after the end of navigation for shipping port, this water is released. In recent years, the ballast water is making a big problem in the world. That problem is the destruction of ecological system with released sea area[1) 2) 3)].

The released ballast water includes some of small animals and microorganisms. If these creatures that came from other sea area stay in the sea area, it is possible that they expel the native species of creatures. This matter is causing a great harmful influence to the human and society.

In view of this problem the International Maritime Organization (IMO) was adopted "REGULATIONS FOR

THE CONTROL AND MANAGEMENT OF SHIP'S BALLAST WATER AND SEDIMENTS" in 2004. The purpose of this is to minimize and ultimately eliminate the risks to the environment, human health, property and resources arising from the transfer of Harmful Aquatic Organisms and Pathogens through the control and management of ships' Ballast Water and Sediments[4].

According to this treaty, it is mandatory that all the ships should comply with "Ballast Water Performance Standard" shown in Table.1 by 2016. By using this method, it is assumed that 95% of the ballast water exchange is possible if seawater of 3 times of ballast tank capacity is overflowed. However there are only few studies on the verification of the volume of ballast water discharge using this method. Thus it is necessary to check the efficiency of this procedure. On the other hand, according to this regulation, a ship must remove and discard sediments in a ballast tank. It is assumed that many microbes are included in sediments, so management of sediments is important in order to fulfill " Ballast Water Performance Standard". Then, ballast water exchange may be performed as preprocess for management of sediments after 2016.

From above reasons, Authors experimented as fundamental research of verification of the ballast water exchange by using Pumping-Through method. In this experiment we used a 2- Dimensional square tank model of 1 (m) in all sides and measured the dilution rate of the inside fluid with an optical method. Also we analyzed the motion of inside fluid of tank using MPS method and Finite Different Method (FDM) as a numerical calculation and compared with the experiment results.

Table.1 Ballast Water Performance Standard

TARGET		STANDARD
Organisms $\geq 50\mu m$		$10/m^3$
$50\mu m >$ Organisms $\geq 10\mu m$		10/ml
Microbes	Toxicogenic Vibrio cholerae	1cfu/100ml
	Escherichia coli	250cfu/100ml
	Intestinal Enterococci	100cfu/100ml

2. Out of Experiment

2.1. Experiment Equipment

As the basic experiment for verification of ballast water exchange by using Pumping-Through method, we experimented by using the 2-Dimensional model tank which is all sides 1 (m) as shown in the Fig.1.

The front view and side view of the 2D model tank are shown in Fig. 2 and Fig. 3. This tank has laminating structure that piled up hard rubber, an aluminum frame, hard rubber, and the acrylics board on the stainless steel board in order to maintain watertight. Because the thickness of the aluminum frame and hard rubber are 10 (mm) and 2 (mm) each the actual depth of the 2D model tank is 14 (mm). Also, The airpipe for outflow is attached in the aluminum frame of the left upper part of this tank, and the "L" shape pipe for inflow is attached in the aluminum frame of the right lower part as shown in Fig. 3, And Pumping-Through method that is one of a ballast water exchange can be reproduced.

The pipe for inflow water to the 2D model tank is shown in Fig4. This pipe has the form that the pipe mouth of an actual tank's pipe form. The pipe is made of stainless steel pipe of an outer diameter 6 (mm) and an inner diameter 4(mm), and the position of the pipe mouth is 20 (mm) from the bottom wall and 35 (mm) from the right wall. The airpipe is attached to the upper wall, and the position of the airpipe is 20 (mm) from the left wall.

Sampling equipment consists of 16 injectors that operate all at once by the air cylinder, and can be operated by the controller at arbitrary time. Therefore, extraction (sampling) of the inside fluid from 16 points is possible while exchanging the fluid in this 2D model tank.

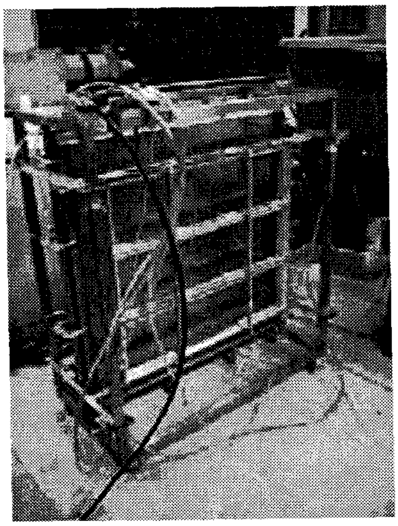

Fig.1 2D Ballast Model Tank

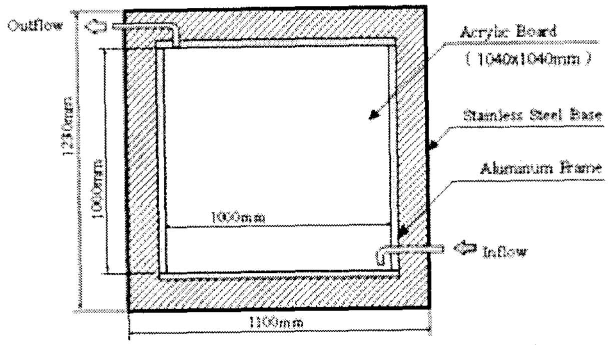

Fig.2 2D Model Tank Front View

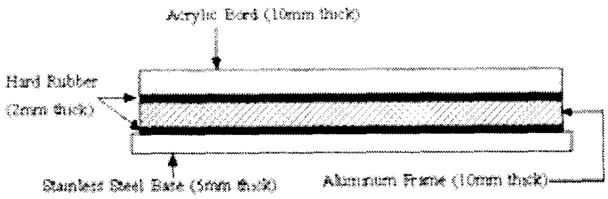

Fig.3 2D Model Tank Side View

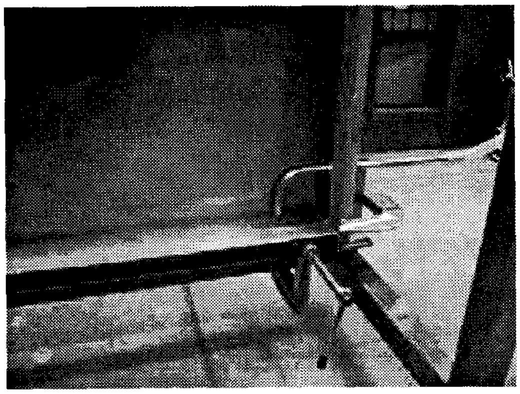

Fig.4 Inflow Pipe

2.2 Experiment Procedure

The experiment procedure to measure the dilution of the inside fluid is carried out as follows.

First of all, the 2D model tank is filled with fluid that colored evenly with Methylene blue. Then fluid, which is not colored, is pumped in the 2D model tank by using a pump from the storage water tank. And the inside fluid is overflowed. The storage water tank is set at above 2 (m) of 2D model tank and can pour water with the constant volume by gravity and pump.

Next inflow is stopped at arbitrary time, and the extracted inside fluid is mixed until density becomes even. The Difference of density of the extracted inside fluid and the initial fluid is measured by using the optical technique. We estimated the exchange rate of tank inside fluid by this method.

The arrangement and connection of each tank are shown in Fig. 5.

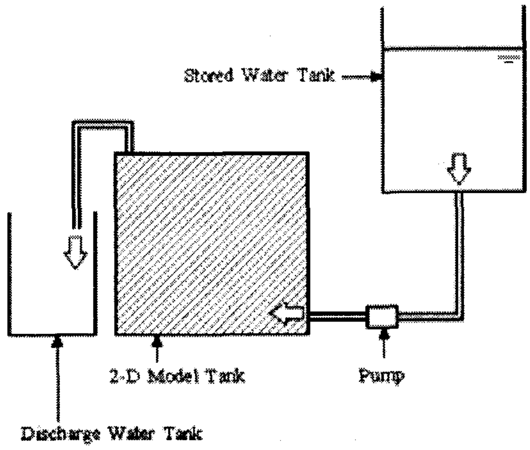

Fig.5 Connection of Tanks

2.3 Measurement Method

To estimate the density of the inside fluid in the 2D model tank, absorbance rate and transmission rate was measured by the sample of extracted inside fluid by using digital colorimeter (Mini photo 5: SANSHIN INDUSTRIAL CO.). The maximum absorption of Methylene blue is about 670 (nm), so the 660 (nm) filter of digital colorimeter was adopted. Furthermore, the absorption spectrum of Methylene blue is shown to Fig. 6. The measuring is possible even if the density becomes low, because the absorbance coefficient of Methylene blue is high and the absorption of the light is strong, and this dyeing method is suitable for this experiment. Relation between the density and transmission rate of Methylene blue that were measured actually are shown to Fig. 7.

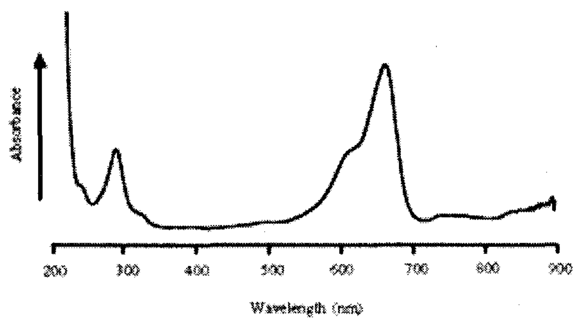

Fig.6 Absorption Spectrum of Methylene Blue

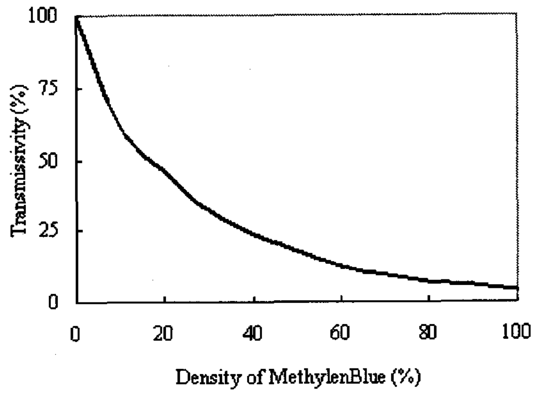

Fig.7 Transmissivity Change by Density Change (660nm filter)

3. EXPERIMENT RESULTS

3.1. Experiment Conditions

Inflow rate was set up as 1.3 [l/min] as experiment conditions. At this inflow rate, the inside fluid of three times of the capacity of the 2D model tank can be overflowed at about 32 minutes.

In this experiment, we assumed that inertia force and viscous force controlled movement of fluid. When the inflow rate for this experiment is calculated using the similarity rule of Reynolds, the inflow rate is about 510 (m3 / hour) as shown in Table 2[6].

Table.2 Experiment Conditions

	MODEL	REAL
Inflow	1.3(l/min)	510(m^3/h)
Inlet Velocity at Pipe End	1.8(m/sec)	0.18(m/sec)
Bore of Pipe	4.0(mm)	1.0(m)
Tank Representative Length	1.0(m)	10.0(m)
Reynolds Number	$1.8\text{x}10^6$	

3.2. Internal Average Density

Experiment results are shown in Fig8. The rate of exchange of the inside fluid when overflowing the inside fluid of three times of the capacity of the 2D model tank is about 95%. The vertical axis of Fig8 shows the ratio of the average density of the initial inside fluid and the extracted inside fluid, and shows the rate of dilution of the initial inside fluid in the 2D model tank. Moreover, the horizontal axis shows the numerical value which is the inflow divided by the capacity of the 2D model tank.

4. Numerical Computation by MPS Method

In order to examine dilution of the fluid in a tank, we simulated of the exchange of the fluid in a tank by using Pumping-Through method. MPS (Moving Particle Semi-implicit) method was adopted in this simulation.

By the MPS method (Koshizuka・Oka 1995)[7], An interaction model between the particles (calculating points) that arranged to the calculation domain is used to calculate the movement of the fluid in the MPS method. Specifically, The interaction model between particles corresponding to the governing equation is made, and the variable of each particle is calculated based on the interaction between particles. The law of mass preservation is satisfying by keeping the number of particles constant, and the condition of incompressibility are satisfying by keeping particle density constant value.

As calculation conditions the tank that is 2 dimensional and all sides 0.3 (m) as shown in Fig.9 was adopted. There is a 20mm inflow mouth in this tank at the lower right, and the flow rate is fixed at 50 (mm/sec). The water that pumped in is overflowed from the 15(mm) outflow mouth in the upper left of the tank. In calculation, the distance between initial particles was set up 5mm and 4482 particles were used. In addition, the density diffusion between particles was calculated by some diffusion coefficients, and circulation boundary condition was adopted in the outflow mouth and the inflow mouth. Calculation results are shown in Fig.8 [8].

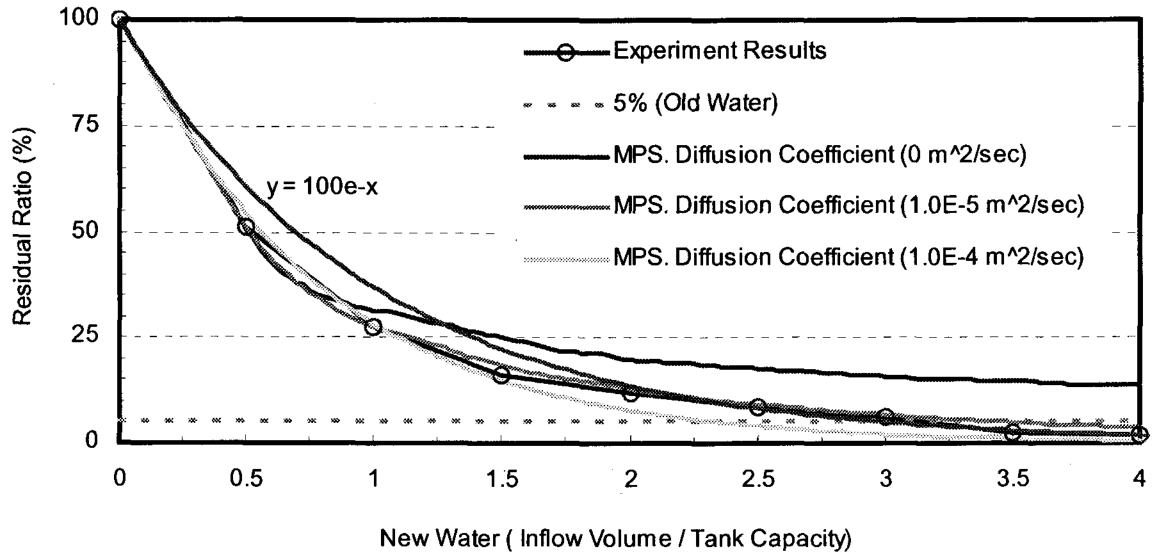

Fig.8 Residual Ratio of Inside Fluid of the Model Tank

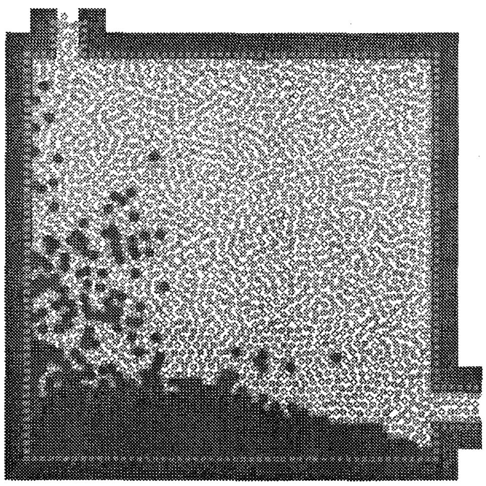

Fig.9 2D Tank for MPS Method

5. Numerical Computation by FDM

In the simulation that uses the MPS method, if we calculate on the same scale as the model tank used by the experiment, the particle increases and the calculation time becomes very long. Then, We simulated the fluid in the tank by using the Finite Difference Method (FDM) that could be calculated on the same scale as the model tank in the experiment. The MAC scheme was adopted as a calculation scheme.

As a calculation condition, the regular grid was adopted in the calculation grid. The number of grids used to calculate is 501*501, and the interval in the vertical direction and the horizontal direction of each grid is 2*10-3.The Reynolds number is 1.8*106 as well as the model experiment. The No-slip condition was adopted as a boundary condition in the wall, and the condition at constant flow velocity was given at the inflow part and the outflow part in the wall1[9].

As a concrete computational method, the flow velocity in the model tank can be obtained by solving the equation of rule of two-dimension incompressibility viscous fluid of Navier-Stokes equation and equation of continuity by using the finite difference method. And, the density of the fluid in the model tank can be obtained by calculating the equation of transfer- diffusion by using the obtained flow velocity in the tank.

Fig.10 shows the rate vector of the regular flow in the model tank obtained by the calculation. It is seen form this figure that there is a whirl by a fast flow in the vicinity of the inflow part under the model tank. Moreover, The flow is slow in the areas other than the inflow and the outflow part, and the flow stagnates at the edge in the model tank. Fig.11 shows the comparison between the experiment results and the calculation results.

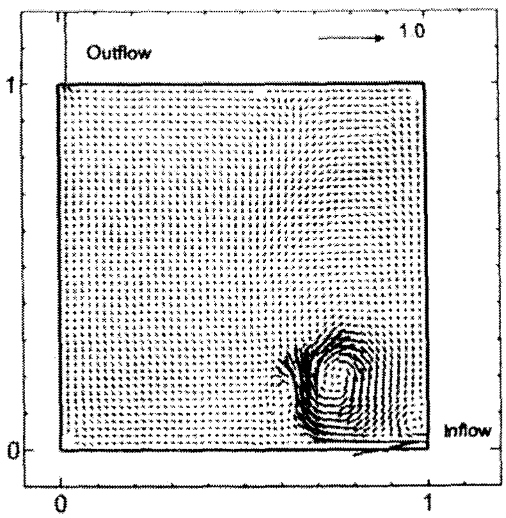

Fig.10 Velocity Vector Distribution of Flow in the Model Tank

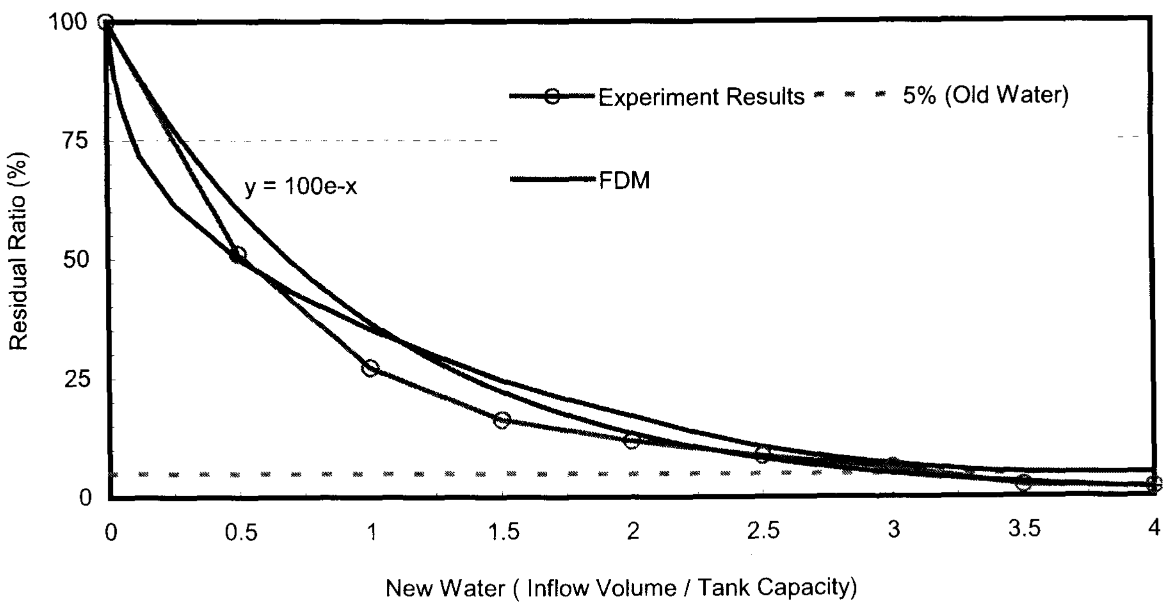

Fig.11 Residual Ratio of Inside Fluid of the Model Tank

6. Considerations

When the fluid of inflow rate Q flows with density D1 into the tank of capacity V with density D, if it assumes that the fluid that flowed into the tank diffuses immediately, Density D of the fluid in the tank is calculable with the following formula.

$$\frac{dD}{dt} = \frac{D_1 Q - DQ}{V} \qquad (1)$$

When the initial value of the fluid in a tank is set to D0, the solution of formula (1) is as follows.

$$D = D_1 + (D_0 - D_1)\exp(-\frac{Q}{V}) \qquad (2)$$

The amount of inflow Q will be three times of the tank capacity, When the fluid of density D= 0% flows into a tank that filled with the fluid of initial density D0=100%, and the fluid in the tank is diluted to 5% compared with initial density (D= 5%), by solving formula (2). Generally this method is used as a method of calculating dilution of the fluid in a tank. Calculation results are shown in Fig8 and Fig10.

Although it assumes that the fluid that flowed into the tank diffuses immediately by these calculation methods, the fluid within an actual tank is not diffused in an instant. Especially it is thought that the fluid that flowed into the tank remains in a tank when inflow started.

Also, from experiment results the density is 51% when 0.5 times of tank capacity flow in, the density is 27% when 1 time of tank capacity flowed in, and those values are lower than calculation results about 10%. Assumption that the fluid that flows into the tank diffuses immediately is not materialized when inflow is started. When the more than twice of tank capacity flow in, Calculation results and experiment results are well in agreement. This can be considered because the fluid that flowed into the tank fully diffused.

Consideration is shown as follows.

- □ A formula (2) that is assumed that the fluid that flowed into a tank diffuses immediately is not realized when the amount of inflow is 1.5 or less times of tank capacity.
- □ When the amount of inflow in a tank is two or more times of a tank capacity, the formula (2) approximates the density of the fluid in a tank well.
- □ When fluid of three times of tank capacity is overflowed using the Pumping-Through method, about 95% of the liquid in a tank can be exchanged.
- □ Calculation results by using MPS method are well in agreement with experiment results, when the diffusion coefficient is 1.0E-5(m^2/sec).
- □ Calculation results by using FDM are well in agreement qualitatively with experiment results. The calculation results by FDM are less at time when 0.5 times the tank capacity were injected into the tank, and a little high value after that, And it can be considered that one of the causes is a difference of shape at the inflow pipe by the experiment and the calculation.

7. Conclusions

For the validity of the ballast water exchange by the Pumping-Through method, we experimented by using the 2-dimensional model tank and considered. From results, the conclusion in this study is as follows.

- □ If three times of tank capacity flow in when exchanging the fluid in a 2-dimensional square tank using the Pumping-Through method, about 95% of exchange of the fluid in a tank is possible.
- □ When the amount of inflow in a tank is two or more times of a tank capacity, the formula (2) that is assumed that the fluid that pumped into a tank diffuses immediately approximates well the relation between the volume of inflow, and the density of fluid in a tank when the fluid in a tank is exchanged using the

Pumping-Through method.

- □ MPS method and FDM are effective in the simulation of exchange of the fluid in a tank.
- □ The technique of measuring dilution of the fluid in a tank using Methylene blue and a digital colorimeter is effective.

In addition, difference of tank form, difference of salt density, difference of seawater temperature, movement of ship, etc. influence the rate of exchange at ballast water exchange on the ocean. As the next subject, we want to study these influences on ballast water exchange.

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