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DISPLACEMENT EFFICIENCY OF WATER IN A CYLINDRICAL TANK

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ABSTRACT

The objective of the present study is to improve the design of a cylindrical water supply tank in order to achieve better displacement efficiency of old water in a cylindrical tank. The present paper describes the results of an experimental study of the flow pattern and the residual concentration of old water in a tank. The effect of the shapes of the inlet and outlet pipes on the displacement efficiency of old water in the tank was investigated. The displacement efficiency of old water in a tank that has inlet and outlet pipes at one end of the tank (Type 2) is better than that in a tank that has inlet and outlet pipes at the center of the tank (Type 1). The displacement efficiency of water inside the tank that has an inlet pipe with a diverging nozzle and an outlet pipe with a circular baffle plate (Type 5) is better than that of the other tank. The replacement efficiency of old water with new water in the tank depends on the location, the length of the inlet nozzle, and the diameter of the baffle plate. The entrainment of the old water to the jet of new water is found to decrease with the addition of the diverging nozzle, and the baffle plate is found to prevent the diffusion of old water.

Keywords: Cylindrical Tank, Displacement, Jet, Flow Measurements, Concentration, Flow Control, Flow Visualization

INTRODUCTION

Earthquakes cause damage to lifeline facilities, such waterworks, gas lines, and electrical facilities. Water is indispensable for human life, and, in the event of an earthquake, drinking water must be secured by the earthquake victims until relief supplies become available. The cylindrical water supply tank is used to supply drinking water in the event of a natural disaster. This tank normally functions as a part of the water supply system and is located on the water supply pipe under the house, as shown in Fig. 1. The tank is airtight, and safe, sanitary water can be obtained from this tank. In the case of a disrupted water supply, a check valve installed in the tank enables the tank to act as an independent storage tank. It is important that the water stored in the tank be fresh. However, the flow in the tank is complicated because of the mixture of old water in the

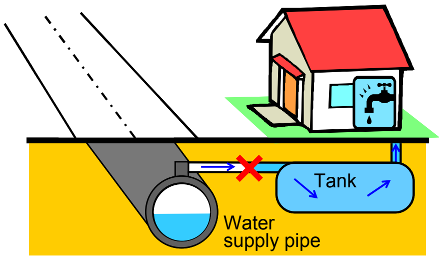

Fig. 1. Household water supply tank

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tank and new water from the inlet nozzle. Water supply tanks have been developed by several researchers and companies, e.g., the swirl inlet jet type (Fuji Robin Co.), the swirl and straight inlet jets type (Sumitomo Metal Pipeline and Piping, Ltd.), the baffle plate type (Shah and Furbo, 2003; Tanaka, 2004), and the division plate type (Niigata Shipbuilding and Repair, Inc.), among others (Hatanaka *et al.*, 2001; Kubota Co., 2002). We designed a water supply tank with a diverging nozzle and a circular baffle plate. The goal of the present paper is to clarify the effects of the nozzle shape of the water inlet and the circular baffle plate of the water outlet on the displacement efficiency of old water in the tank. The present paper describes the results of an experimental study on the residual concentration of old water and flow visualization in the tank.

APPARATUS AND EXPERIMENTAL TECHNIQUES

Experimental Setup

As shown in Figs. 2 and 3, the experimental setup consists of various tanks, a pump, valves, an electromagnetic flowmeter (FD-M10AT, Keyence), and a colorimeter sensor (Model PE-01, Coper Electronics). The experiment was carried out using a half-scale model of the tank. The cylindrical tank has an inner diameter of 251 mm and a length of 897 mm. The volume of the cylindrical tank is $V = 43.25$ l. The cylindrical tank was placed in a rectangular open water tank (435 mm × 435 mm × 1,000 mm) in order to reduce the effect of light refraction. The tanks are made of acrylic resin. Tap water was used to supply clear water from the inlet pipe to the cylindrical tank. The inner diameter of inlet pipe was $d_0 = 9.5$ mm (3/8 in). The flow rate was maintained at a prescribed value by valves and an electromagnetic flowmeter. The flow rate was changed from $Q = 5$ to 15 *l/min* in order to consider the amount of water needed for a standard family. The Reynolds number Re based on the pipe diameter d_0 and the mean velocity U_0 of the inlet pipe was from $Re = 9.8 \times 10^3$ to 2.9×10^4. The concentration of discharged water, c, was measured by the colorimeter sensor. According to the Lambert-Beer Law, the absorption α (= $\varepsilon c d$) of a dissolved substance is a linear function of its concentration c (Sakai, *et al.*, 2008). The length of the light path (thickness of the cell) d and the extinction coefficient (a substance specific constant) ε determine the slope of the linear relationship. However, note that the Lambert-Beer Law is not valid at high concentrations. Therefore, we calibrated the colorimeter sensor using solutions of Methylene blue in water with concentrations ranging from 0 to 10 ppm, as shown in Fig. 4. The test tanks are shown in Fig. 5. We examined six types of tanks. Type 1 has water supply and drain pipes in the center of the tank. Type 2 is a Type 1 tank that has a circular baffle plate installed in front of the outlet pipe. Type 3 has water supply and drain pipes at one end of the tank. Type 4 is a Type 3 tank that has a circular baffle plate installed in front of the outlet pipe. Type 5 is a Type 4 tank that has a diverging nozzle installed in the inlet pipe. Type 6 is a Type 5 tank with an access hole. The interval between the inlet and outlet pipes was fixed at 100 mm in order to insert the inlet and outlet pipes together through an access hole. The length of the diverging nozzle was varied as $L = 100$, 150, and 300 mm. The diverging angle of nozzle was 6°. The diameter of the circular baffle plate was also varied as $D = 100$, 150, and 200 mm.

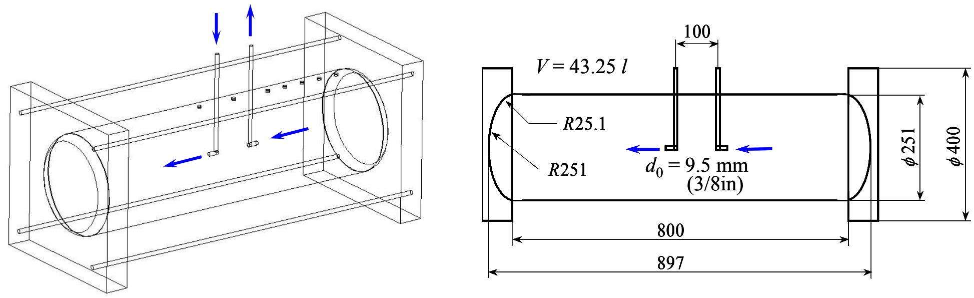


Fig. 2. Cylindrical tank

Experimental Method

In the experiment, the tank was initially filled with a 10-ppm solution of Methylene blue in water. A valve was then opened to allow clear tap water to enter the tank. Discharged water was sampled by syringes until the concentration in the tank became less than 0.1 ppm. The ratio of the tank volume to influent new water volume (replacement number), R, is as follows:

$$R = Q_1/V, \tag{1}$$

where Q_1 is the volume of influent new water. The ratio of tank volume to remaining old water volume in the tank (residual concentration), C, is given by:

$$C = Q_2/V, \tag{2}$$

where Q_2 is the volume of remaining old water (equivalent to a 10-ppm solution of Methylene blue in water) in the tank. The flow patterns in the tank were visualized by a digital camera. Images were captured every 5 seconds.

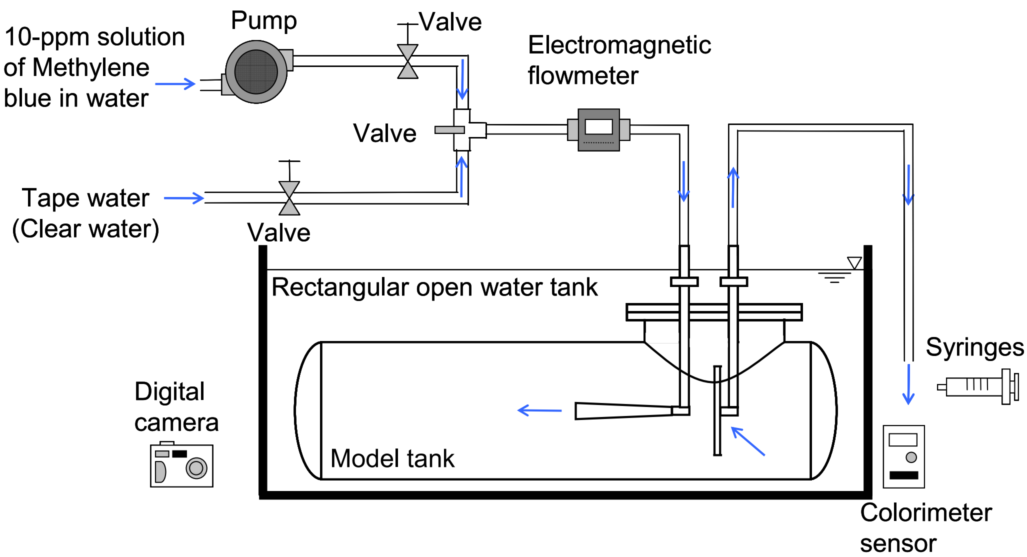


Fig. 3. Schematic diagram of the experimental apparatus

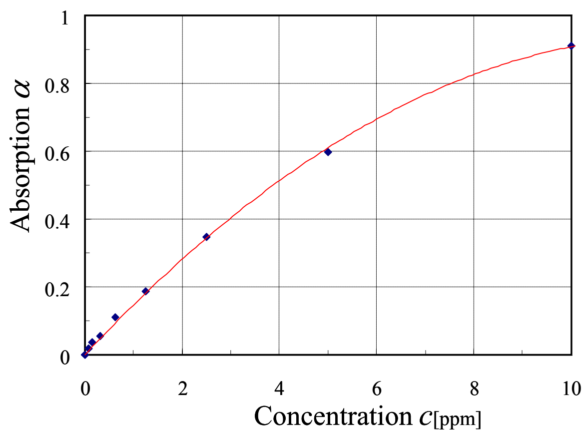


Fig. 4. Absorption *vs.* concentration of solutions of Methylene blue in water

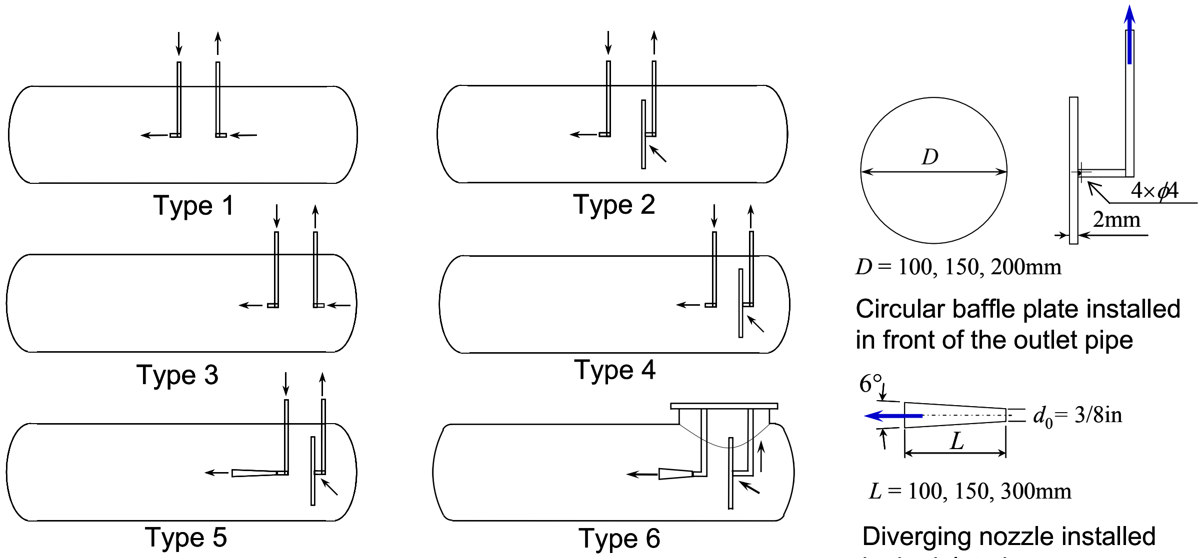


Fig. 5. Test tanks

RESULTS AND DISCUSSION

Effect of location of pipes

We investigated the effects of the location of the inlet and outlet pipes on the displacement efficiency of old water. Figure 6 shows the variation of the residual concentration of old water in the tank with respect to the replacement number. The flow rate was fixed at Q = 10 *l/min*. The Type 1 tank has water supply and drain pipes in the center of the tank, whereas the pipes of the Type 3 tank are located at one end of the tank. If the old water in the tank is replaced with influent new water in an ideal manner, the characteristic curve becomes linear, as shown in Fig. 6. In actuality, the characteristic curve gradually approaches the $C = 0$ line as the replacement number increases due to the mixing of old and new waters. The displacement efficiency of water in the Type 3 tank is better than that in the Type 1 tank. The replacement number at C = 1% of Type 3 tank was 4.23. This indicates that we must supply a volume of new water equivalent to 4.23 times the volume of the tank in order to replace the entire volume of old water in the tank.

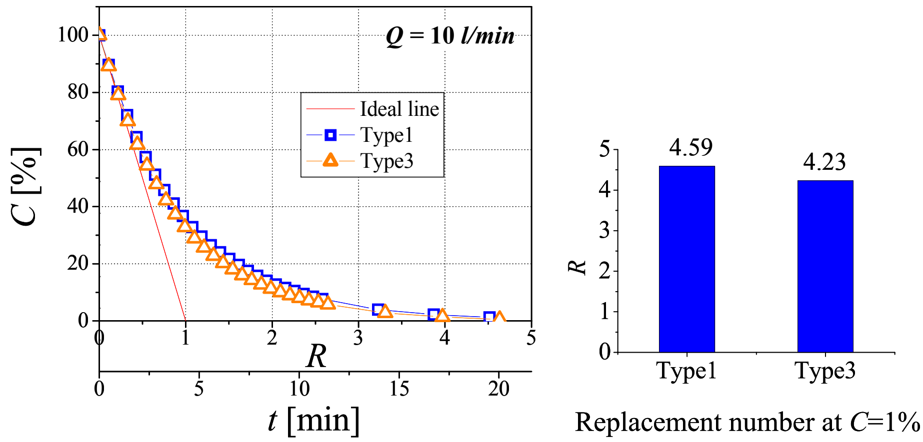


Fig. 6. Variation of residual concentration with replacement number (Types 1 and 3)

Effect of a circular baffle plate

The displacement efficiencies of old water in the tank with and without the circular baffle plate are shown in Fig. 7. The mean residual concentration in the tank with the baffle plate is lower than that without the baffle plate. The replacement number at C = 1% of Type 4 tank was 3.81. The replacement number of the Type 4 tank is better than those of the other tanks. The displacement efficiency has improved by the placement of a circular baffle plate at the end of the tank.

Since the circular baffle plate is effective for replacing old water in the tank, the effect of the diameter of the circular baffle plate on the displacement efficiency of old water was investigated. The diameter of the circular baffle plate was varied as D = 100, 150, and 200 mm. The curves of residual concentration are shown in Fig. 8. Although the mean residual concentrations in the tank with any baffle plate are lower than those without a baffle plate (Type 3 tank), the difference in the replacement number among the plates with D = 100, 150, and 200 mm is small.

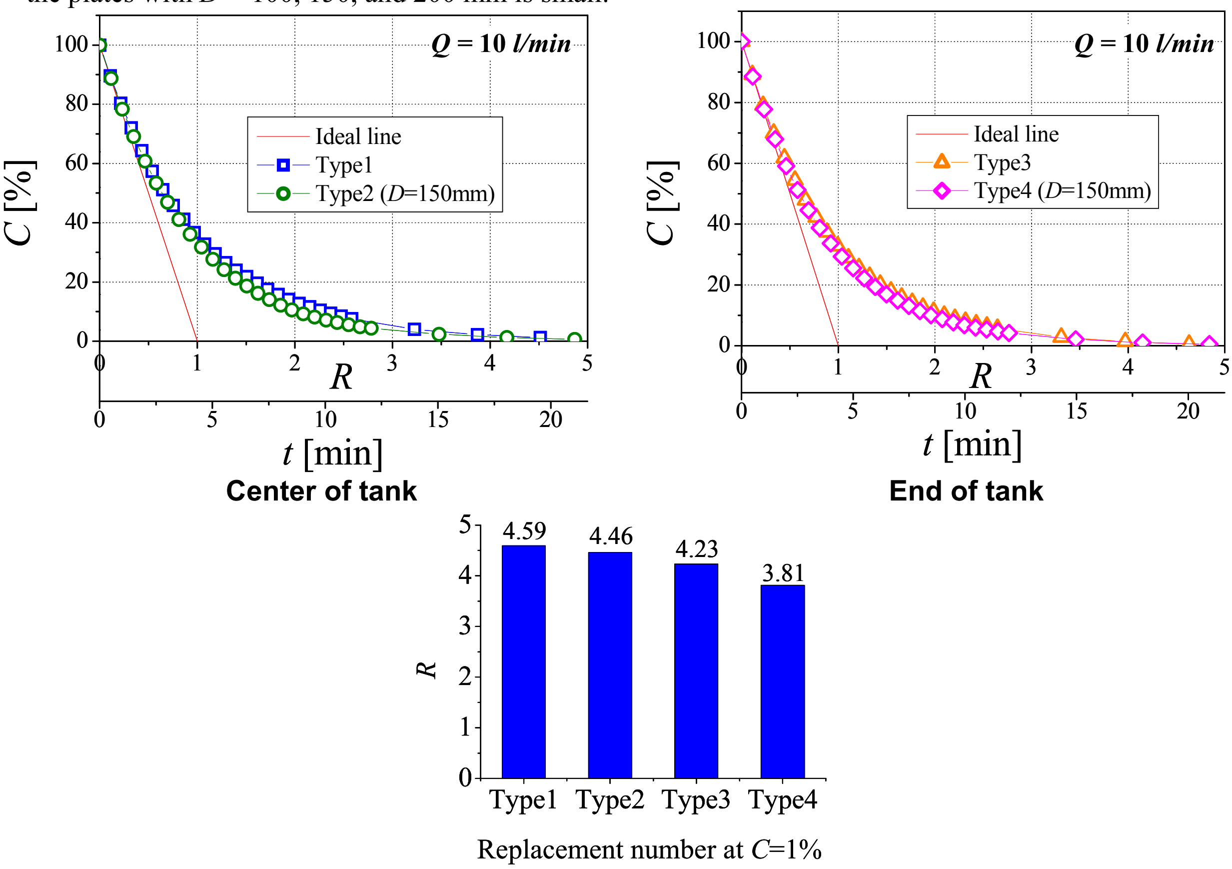


Fig. 7. Variation of residual concentration with replacement number (Types 1 ~ 4)

Effect of a diverging nozzle

In order to prevent entrainment of ambient fluid (old water) in the tank, we installed a diverging nozzle on the inlet pipe. Figure 9 shows the effect of the length of diverging nozzle. The mean residual concentrations of old water in the tank with any diverging nozzle are lower than those without a diverging nozzle. The replacement numbers are approximately the same value for all of the diverging nozzles examined herein.

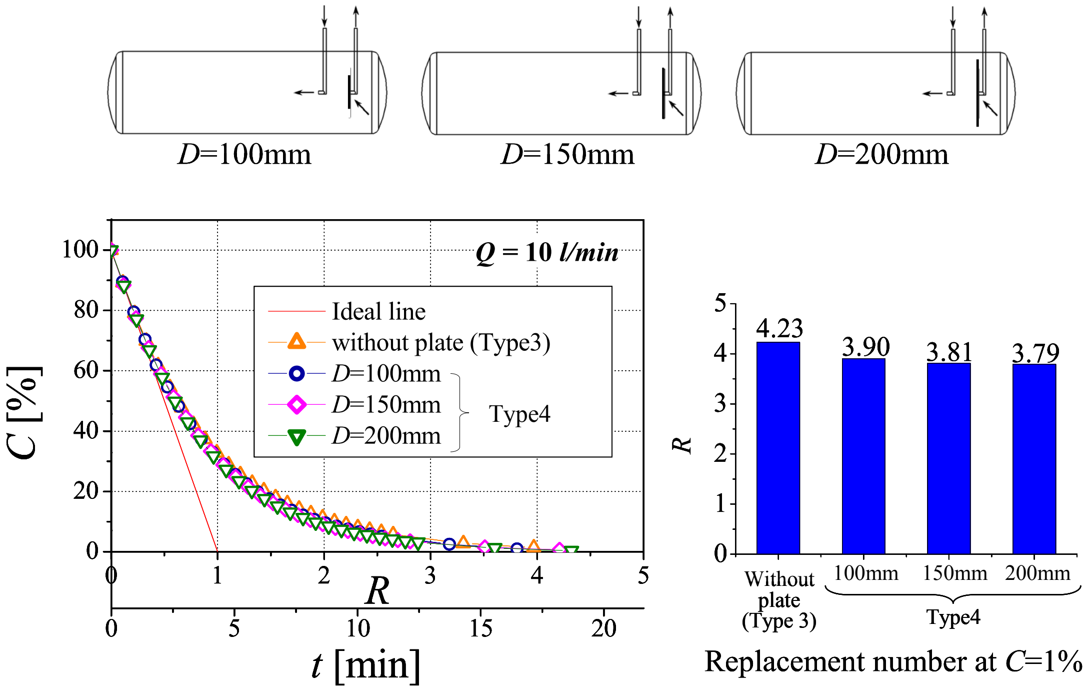


Fig. 8. Effect of the diameter of the baffle plate on residual concentration (Type 4: *D* = 100 ~ 200 mm)

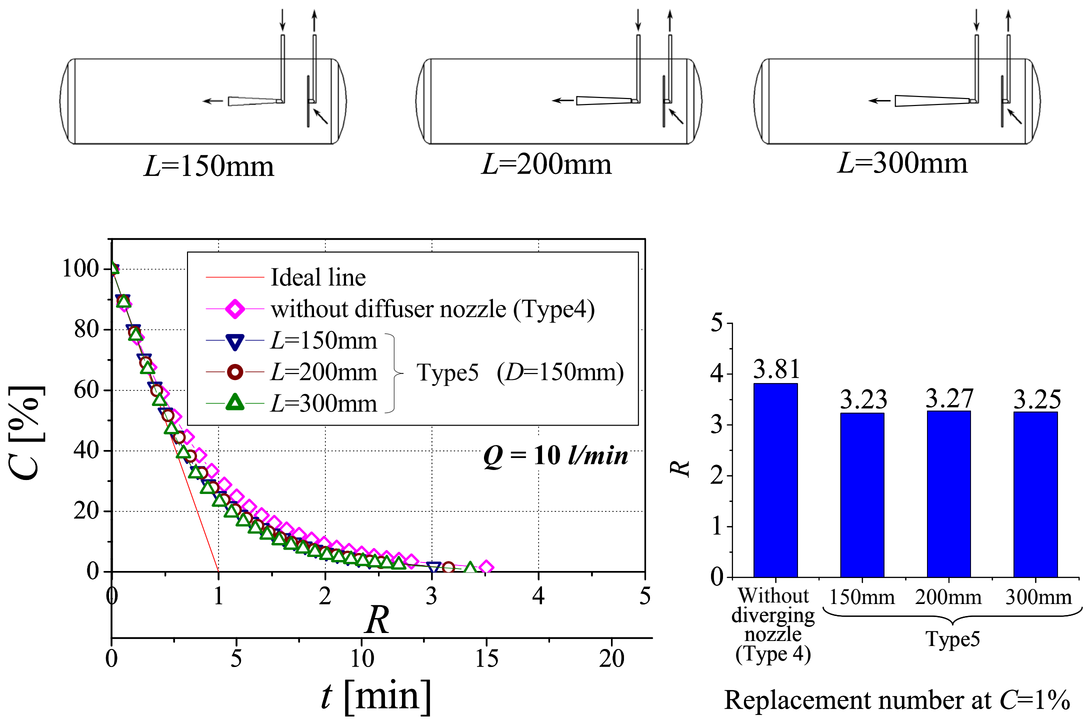


Fig. 9. Effect of length of the diverging nozzle on residual concentration (Type 5: *L* = 150 ~ 300 mm)

The variation of the concentration of drained water with respect to time is shown in Fig. 10. For the Type 5 tank, which has a baffle plate with D = 150 mm and a diverging nozzle with L = 150 mm, the concentration of drained water is higher than that for the other tanks until 6 minutes passes. The entrainment of old water to the jet of new water appears to have decreased as a result of the diverging nozzle.

Figure 11 compares the flow patterns of Type 1 and Type 5 tanks every 5 minutes. Initially (t = 0 min.), the brightness of blue water in the Type 1 tank is the same as that in the Type 5 tank. As time passes, a difference in brightness between the Type 1 and Type 5 tanks is recognized. At 15 minutes, the water in the Type 1 tank is uniformly light blue. On the other hand, in the Type 5 tank, slightly dark blue water remains near the right-hand side of the baffle plate. The baffle plate prevents the diffusion of old water and accelerates the drainage old water.

Characteristics of the tank having an access hole

To turn the tank to practical use, the displacement efficiency of old water in the tank with an access hole was examined. The Type 6 tank has an access hole of ϕ 290 mm, a diverging nozzle with L = 150 mm, and a circular baffle plate with D = 150 mm. As shown in Fig. 12, the line graphs of mean residual concentration of Q = 5 to 15 *l/min* are similar to the function of the replacement number R, which indicates the similarity of the flow fields in the tank. The replacement number at C = 1% of the Type 6 tank was 3.86. This value is slightly greater than that of the Type 5 tank due to the cavity of the access hole.

Figure 13 shows the residual concentrations of old water in the tank for a steady flow rate （Q = 5 *l/min*） and an intermittent flow rate. The variation of the amount of water for a standard family over one-day is also shown in Fig. 13. The intermittent flow rate was reproduced as an amount of water per hour. The integrated volume of the intermittent flow rate is the same as that of the steady flow rate. The variation of residual concentrations for the intermittent flow rate agrees approximately with that of the steady flow rate. The displacement efficiency does not decrease due to the intermittence of the flow rate.

CONCLUSIONS

The effects of the structure of the cylindrical tank on the displacement efficiency of old water were investigated experimentally, and the following conclusions were obtained:

(1) The displacement efficiency of old water is affected by the location of the inlet and outlet pipes, the length of the diverging nozzle, and the diameter of the circular baffle plate.

(2) The displacement efficiency of old water in the tank having an inlet pipe with a diverging nozzle (L = 150 ~ 300 mm) and an outlet pipe with a circular baffle plate (D = 150 ~ 200 mm), i.e., the Type 5 tank, is better than those of the other tanks. The entrainment of the old water to the jet of the new water decreases as a result of the diverging nozzle, and the diffusion of old water is prevented by the baffle plate.

(3) The displacement efficiency of old water in the tank having an access hole agrees approximately with that in the tank without an access hole. It was confirmed that the difference in displacement efficiency between the steady and intermittent flow rates was small.

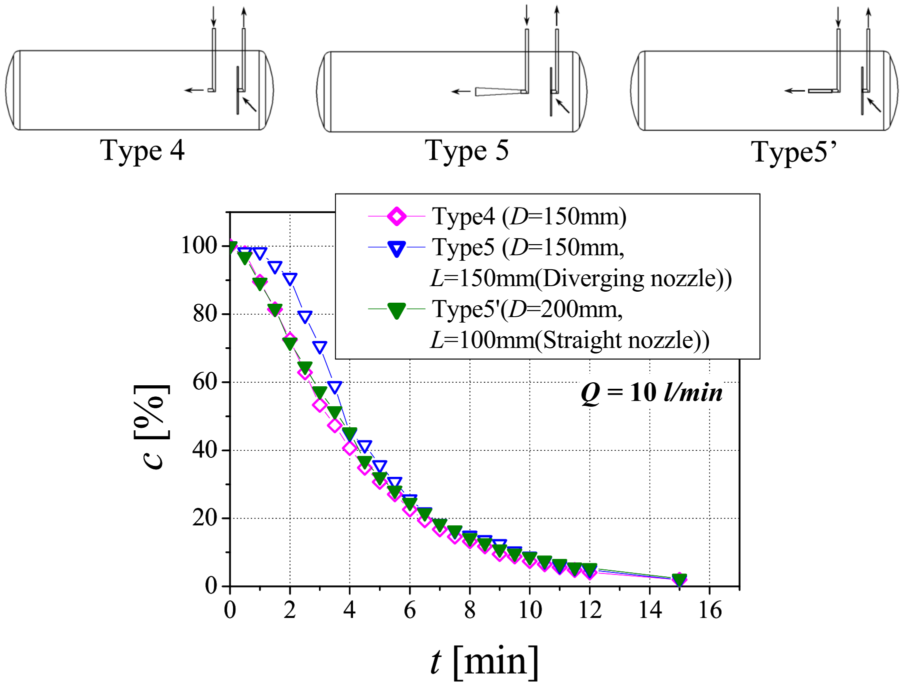


Fig. 10. Variation of concentration of drained water with time (Types 4, 5, and 5')

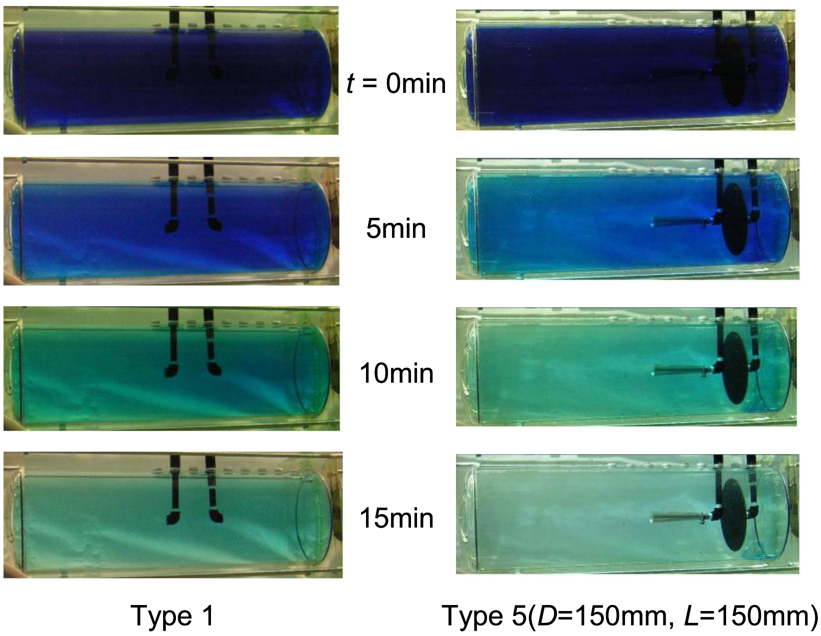


Fig. 11. Flow visualization in the tank (Types 1 and 5)

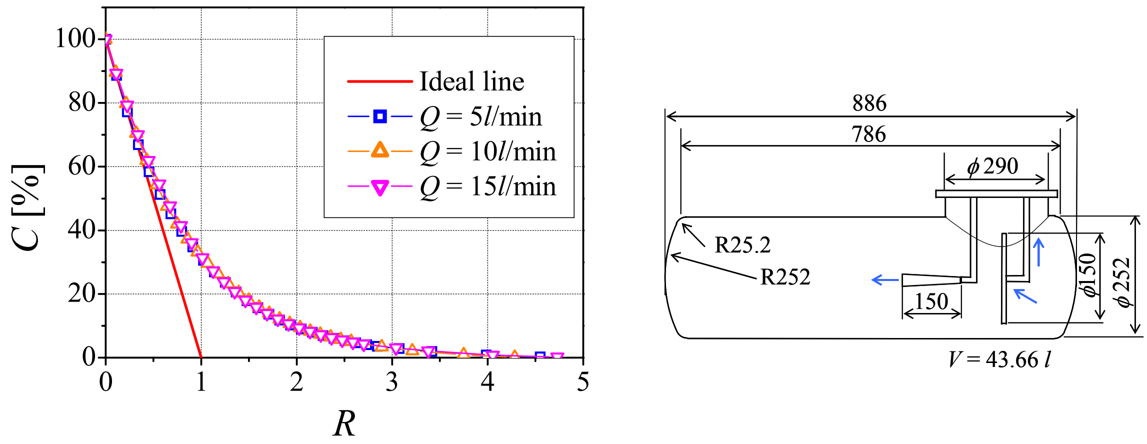
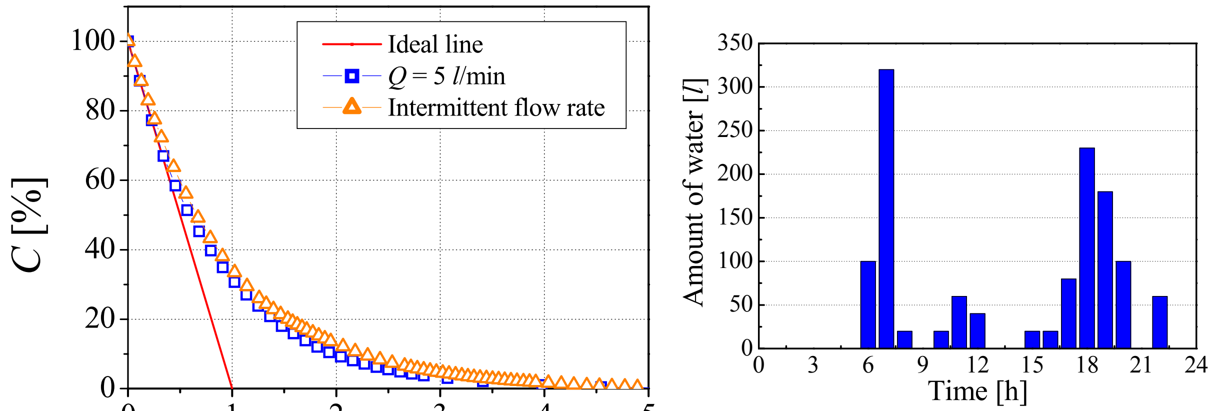


Fig. 12. Effects of flow rate on residual concentration (Type 6)



Amount of water every one hour
for a standard family

Fig. 13 Residual concentration with respect to a constant flow rate and an intermittent flow rate for a standard family

NOMENCLATURE

c : Concentration of a solution
C : Mean concentration of the solution in the tank (residual concentration) (= Q_2/V)
d : Length of the light path (thickness of the cell)
d_0 : Inner diameter of the inlet pipe
D : Diameter of the circular baffle plate
L : Length of the diverging nozzle
Q : Flow rate
Q_1 : Volume of influent new clear water
Q_2 : Volume of remaining old water (an equivalent 10-ppm solution of Methylene blue in water)
R : Replacement number (= Q_1/V)
Re : Reynolds number (= d_0U_0/ν)

t : Time
V : Volume of a tank
α : Absorption (= $\varepsilon c d$)
ε : Extinction coefficient (a substance specific constant)
ν : kinetics viscosity

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