

## Tank Washing of Chemical Tanker

By

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### Abstract

A tank wash procedure on a chemical tanker was considered in this investigation. Tanks should be washed by means of a rotary water jet operated at sufficiently high water pressure and in locations to ensure that all tank surfaces are washed. The primary emphasis was placed on the development of a fundamental understanding of the tank washing that is of interest in engineering design problems. It is desired to get the relation between the concentration and the amount of washwater. As washwater had been discharged before the international convention was enforced, the problems of the tank washing have not been studied previously.

This approach requires an assumed relation for ideal mixing process of the tank washing, and also depends upon experimental evidence to estimate values for coefficients to correct the assumed relation. A major objective of this investigation is to estimate the necessary quantity of the washwater. A simple analysis was performed to define the basic problem and to provide the approximate estimation of amount of the washwater. Experimental results are presented in a unified manner to facilitate the application to design problems. The experimental evidence indicated that amount of the necessary washwater was somewhat dependent upon the jet nozzle diameter that has not been previously studied by other researchers. This variation can be expected from the simple analysis and is shown to be significant in some instances.

The following conclusions are obtained.

- (1) At the beginning of the tank washing, the estimation of the necessary washwater by the ideal mixing model gives good agreements with the experimental results.
- (2) At the later half of the tank washing, it is necessary that ideal mixing model is modified by the factor of the washing efficiency or the sufficient washing is done by the recirculation of the washwater.
- (3) The necessary washwater quantity can be decreased by using the washing machine with small diameter nozzles.

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## NOTATIONS

Ab	Area of tank bottom ( $m^2$ )
Ad	Horizontal area facing down wards ( $m^2$ )
Aw	Area of tank walls ( $m^2$ )
B	Breadth of the tank (m)
C	Concentration of the substance in the effluent (—)
D	Depth of the tank (m)
FW	Amount of washwater fed to tank by washing machine per hour ( $m^3/h$ )
FD	Amount of water rejected from tank by pump per hour ( $m^3/h$ )
g	Gravity acceleration ( $m/s^2$ )
K0	Coefficient of correction for initial concentration in the later washing by $\phi$ 7 mm nozzle washing machine
K1	Coefficient of correction for decreasing rate of concentration in the later washing by $\phi$ 7 mm nozzle washing machine

K2	Coefficient of correction for the beginning by $\phi$ 4 mm nozzle washing machine
K0s	Coefficient of correction for initial concentration in the later washing by $\phi$ 4 mm nozzle washing machine
K1s	Coefficient of correction for decreasing rate of concentration in the later washing by $\phi$ 4 mm nozzle washing machine
K3	Coefficient of correction for washing of high viscosity in the beginning washing by $\phi$ 4 mm nozzle washing machine
K0sn	Coefficient of correction for initial concentration in the later washing of high viscosity adherings by $\phi$ 4 mm nozzle washing machine
K1sn	Coefficient of correction for decreasing rate of concentration in the Later washing of high viscosity adherings by $\phi$ 4 mm nozzle washing machine
L	Length of the tank (m)
QDH	Quantity of the dynamic holdup of slops in the tank during washing ( $m^3$ )
Q	Amount of the washwater ( $m^3$ )
q	Amount of the water fed to tank through washing machine per second ( $m^3$ )
Qres	Residue quantity in the tank during washing ( $m^3$ )
Qres0	Residue quantity in the tank before washing ( $m^3$ )
Qres(surf)	Residue quantity on the tank surfaces ( $m^3$ )
rN	Radius of the nozzle (m)
U	Water jet velocity (m/s)
V	Tank volume ( $m^3$ )
$\alpha$	FD/FW (-)
$\gamma$	water specific gravity ( $kg/m^3$ )
$\sigma_1$	Water film thickness along the vertical surface (m)
$\sigma_2$	Water film thickness on the bottom during washing (m)
$\mu$	Coefficient of viscosity of water ( $kg\ s/m^2$ )
$\nu$	Kinematic viscosity of water ( $m^2/s$ )
$\phi_1$	Angle of the tank wall inclination ( $^\circ$ )
$\phi_2$	Angle of the tank bottom inclination ( $^\circ$ )

## 1. INTRODUCTION

The discharge into the sea of noxious liquid substances or tank washings containing such substances shall be prohibited except when the standards for the procedures and arrangements for the discharge of noxious liquid substances are satisfied. The standards were regulated by THE INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS, 1973 AS MODIFIED BY THE PROTOCOL OF 1978 RELATING THERETO (MARPOL 73/78) and the concerned domestic law. If tanks containing such substances or mixtures are to be washed, the resulting residues shall be discharged to a reception facility until the concentration of the substance in the effluent to such facility is at or below the residual concentration prescribed for the substances and the tank is empty.

Therefore it is necessary to estimate the amount of the necessary washwater by grasping that the relation between the residual concentration and the amount of the used washwater. The amount of the necessary washwater mainly depends on the quantity of clingage residue and the amount of the water which is remaining in the tank during the tank washing. In this investigation, the quantity of clingage residues in the tank was investigated experimentally concerning the liquid viscosity. As the viscosity of liquids is influenced by the temperature, the experiment was done through a year. The amount of the dynamic holdup of slops in the tank is affected by the nozzle diameter of washing machine. The washing machine with  $\phi$  7 mm nozzle and the washing machine with  $\phi$  4 mm nozzle were used for comparison.

Then the relation between quantity of the water needed for the tank washing and the concentration of residues was estimated.

## 2. ESTIMATION OF THE WASHWATER QUANTITY BY IDEAL MIXING MODEL

### 2.1 Relation between Amount of Washwater and Residual Concentration

If one assumes that the washing process approximates an ideal mixing process, then the amount of washwater needed to reach the required concentration can be estimated as follows. The amount of the residue before washing  $Q_{res0}$  and the amount of the remaining water quantity of the steady state during tank washing  $Q_{DH}$  are shown schematically in Fig.1.

(1) In the case that the remaining water quantity in the tank during washing is larger than the residue before washing;

$$Q_{DH} > Q_{res0}$$

$Q_{DH}$ ; Remaining water quantity in the tank during washing ( $m^3$ )

$Q_{res0}$ ; residue in the tank before washing ( $m^3$ )

1) In the case of  $C > Q_{res0}/Q_{DH}$

$C$ ; Concentration of the substance in the effluent

$$C = Q_{res0}/(Q + Q_{res0}) \dots\dots\dots(1)$$

Eq.(1) is rewritten as

$$Q = Q_{res0}/C - Q_{res0} \dots\dots\dots(1')$$

$Q$ ; Quantity of the washwater( $m^3$ )

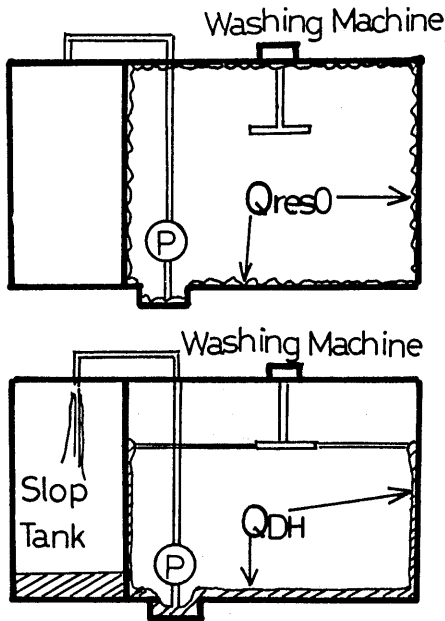
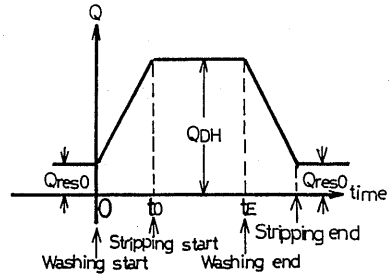
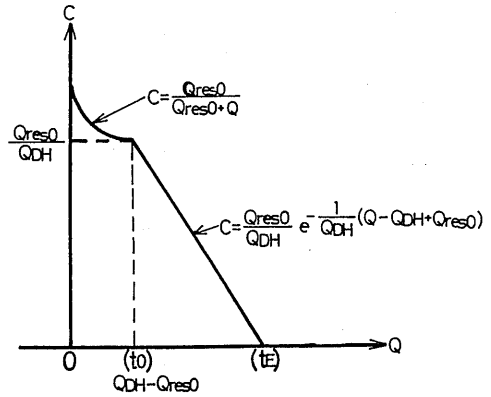


Fig.1 Washing Model



(a) Amount of remaining water in the tank during washing



(b) Concentration in pumping out during washing

Fig.2 Amount of the remaining water in the tank and the concentration in the pumping out during washing

Eq.(1) is indicated from  $t=0$  to  $t_0$  in Fig.2.(b). (In the case of remaining water during washing Residue is not discharged and only diluted. is more than the amount of residue.)

At the steady state; <sup>(1)(2)</sup>

$$\frac{d Q_{res}}{d t} = -\frac{Q_{res}}{Q_{DH}} \cdot F_w \dots\dots(2)$$

Here  $Q_{res}$  is the residue quantity in the tank.

$F_w$  is the water quantity which is injected into the tank through the washing machine and is pumped out from the tank at the same time. Eq.(2)is transformed and integrated;

$$\ln Q_{res} = -\frac{F_w \cdot t}{Q_{DH}} + A_1 \dots\dots(3)$$

where  $A_1$  is an arbitrary constant.

Placing  $F_w \cdot t=Q$ , Eq(3) becomes

$$\ln Q_{res} = -Q / Q_{DH} + A1 \dots\dots\dots(4)$$

Substituting  $Q = Q_{DH} - Q_{res0}$  and  $Q_{res} = Q_{res0}$  as initial condition,

$$Q_{res} = Q_{res0} \exp \left( \left( Q - ( Q_{DH} - Q_{res0} ) \right) / Q_{DH} \right) \dots\dots\dots(5)$$

or

$$Q = Q_{DH} - Q_{res0} - Q_{DH} \cdot \ln \left( \frac{Q_{DH} \cdot C}{Q_{res0}} \right) \dots\dots\dots(6)$$

is obtained.

The quantity of the residue  $Q_{res}$  and the one of the washwater in the tank  $Q_{DH}$  are indicated from  $t_0$  to  $t_E$  in Fig.2(a) and the relation between  $C$  and  $Q$  are indicated from  $t_0$  to  $t_E$  in Fig.2(b). In the most of the case, Eq.(6) is used. To obtain the dimensionless profile variables, Eq(6) divided by  $Q_{res0}$  gives <sup>(3)</sup>;

$$\frac{Q}{Q_{res0}} = \frac{Q_{DH}}{Q_{res0}} \left( 1 - \ln \left( \frac{Q_{DH} \cdot C}{Q_{res0}} \right) \right) - 1 \dots\dots\dots(7)$$

Eq.(7) is represented in Fig.3.

- (2) In the case that the residue is larger than the remaining washwater quantity in the tank ( $Q_{DH} < Q_{res0}$ ).

1) And in the case of  $C > (Q_{DH}/Q_{res0})^{1/(\alpha-1)}$ .

$$\alpha = FD / FW \quad (\alpha \approx 1.1)$$

FW; Amount of washwater injected into tank through the washing machine per hour ( $m^3/h$ )

FD; Amount of water rejected from tank by pump per hour ( $m^3/h$ )

$$\frac{d Q_{res}}{dt} = - \frac{Q_{res}}{Q_{res0} - (\alpha - 1) Fw \cdot t} \alpha \cdot Fw \dots\dots\dots(8)$$

where,  $Fw$  is the discharged water quantity  $Fd$ .

Eq(8) is transformed and integrated;

$$\ln Q_{res} = \frac{\alpha Fw}{(\alpha - 1) Fw} \ln(Q_{res0} - (\alpha - 1) Fw \cdot t) + A2$$

where  $A2$  is an arbitrary constant.

Substituting  $t = 0$ ,  $Q_{res} = Q_{res0}$  as the initial condition;

$$Q_{res} = \frac{(Q_{res0} - (\alpha - 1) \cdot Fw \cdot t)^{\frac{\alpha}{\alpha - 1}}}{Q_{res0}^{\frac{1}{\alpha - 1}}}$$

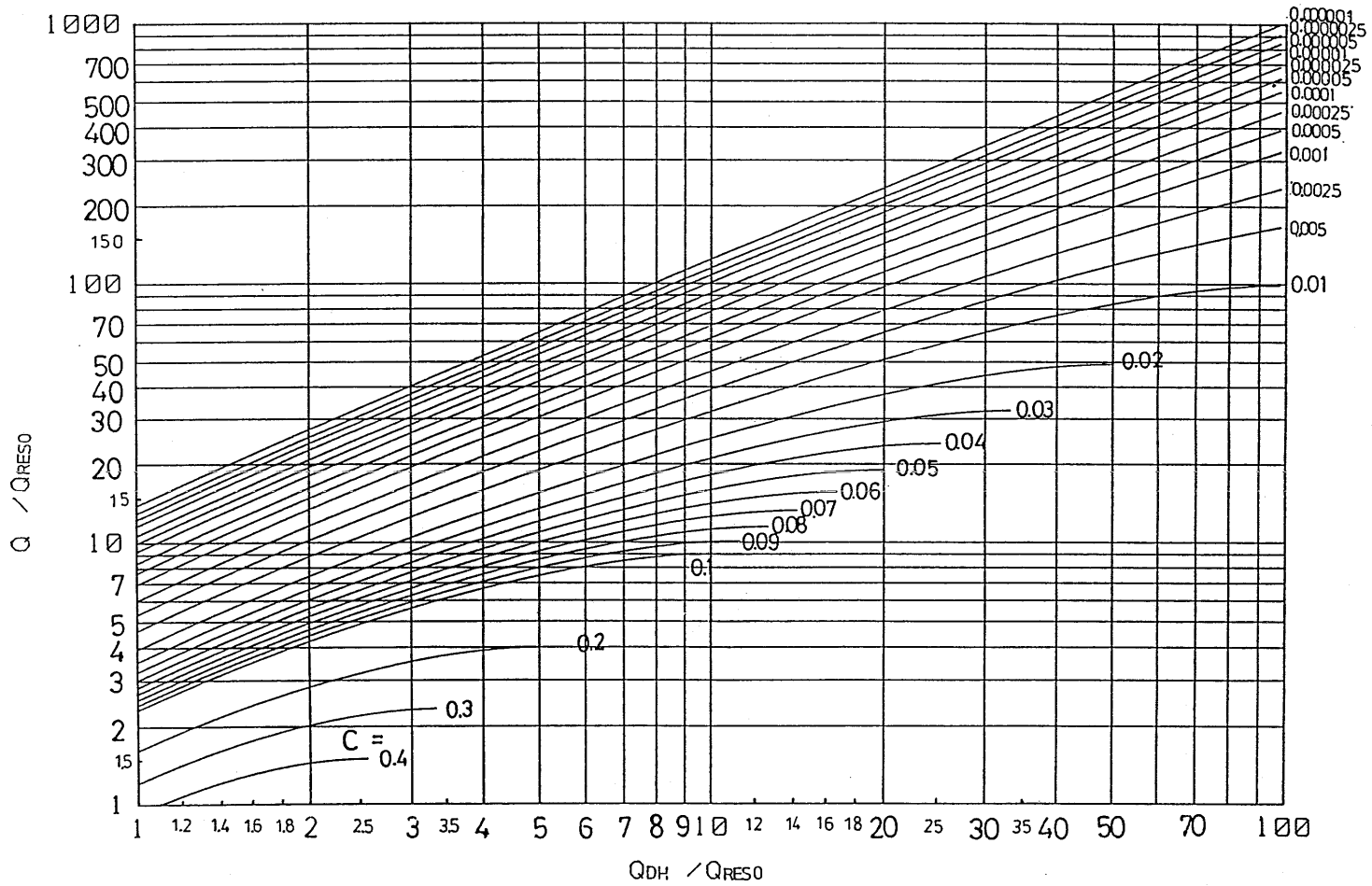


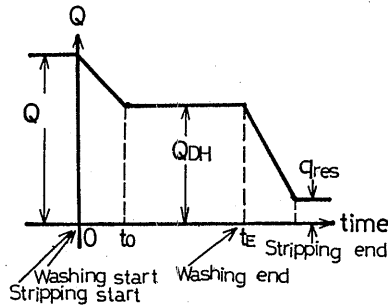
Fig.3  $Q/Q_{RESO}$  VS  $Q_{DH}/Q_{RESO}$

is obtained. The concentration C after time t is given by Eq.(9).

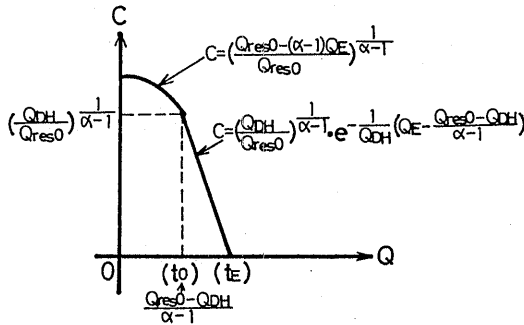
$$C = \left( \frac{Q_{res0} - (\alpha - 1) \cdot Fw \cdot t}{Q_{res0}} \right)^{\frac{1}{\alpha - 1}} \dots\dots\dots(9)$$

If tanks are to be washed until the concentration of the substance in the effluent is at or below the residual concentration C, the necessary quantity of the washwater Q is given by Eq.(9').

$$Q = \frac{Q_{res0}(1 - C^{\alpha - 1})}{\alpha - 1} \dots\dots\dots(9')$$



(a) Amount of remaining water in the tank during washing



(b) Concentration in pumping out

Fig.4 Amount of remaining water in the tank and the concentration in the pumping out during washing

2) In the case of  $Q_{DH} < Q_{res0}$  and  $C < (Q_{DH}/Q_{res0})^{1/(\alpha - 1)}$ .

At the steady state (in Fig.4, Q is larger than  $(Q_{res0} - Q_{DH}) / (\alpha - 1)$ ), Using Eq.(2) and initial conditions;

$$Q = (-Q_{DH} + Q_{res0}) / (\alpha - 1) \text{ and } Q_{res} = Q_{DH},$$

$$Q_{res} = \frac{Q_{DH}^{\frac{\alpha}{\alpha - 1}}}{Q_{res0}^{\frac{1}{\alpha - 1}}} \exp \left( -\frac{1}{Q_{DH}} \left( Q - \frac{Q_{res0} - Q_{DH}}{\alpha - 1} \right) \right) \dots\dots\dots(10)$$



is obtained. C is obtained from Eq.(10);

$$C = \frac{Q_{res}}{Q_{DH}} = \left( \frac{Q_{DH}}{Q_{res0}} \right)^{\frac{1}{\alpha-1}} \exp \left( -\frac{1}{Q_{DH}} \left( Q - \frac{Q_{res0}-Q_{DH}}{\alpha-1} \right) \right) \dots\dots\dots(11)$$

or

$$Q = \frac{Q_{res0}-Q_{DH}}{\alpha-1} - Q_{DH} \ln \left( \frac{C}{\left( \frac{Q_{DH}}{Q_{res0}} \right)^{\frac{1}{\alpha-1}}} \right) \dots\dots\dots(11')$$

In these cases of  $Q_{DH} < Q_{res0}$ , the quantity of the residue and washwater in the tank indicated in Fig.4(a). Eq.(9) and Eq.(11) are indicated in Fig.4(b).

## 2.2 Residual Quantity in Tank before Washing

The amount of the residue in the tank  $Q_{res}$  is given by  $Q_{res0} = Q_{res}(\text{surf}) + Q_{sl}$

in which  $Q_{res}(\text{surf})$  is a quantity of clingage residue on tank surfaces and  $Q_{sl}$  is a quantity of residue in the immediate vicinity of the tank's suction point. According to viscosity, amount of clingage residue on tank surfaces is proposed as followings(4).

For substances with viscosity less than 5 mPa.S

$$Q_{res}(\text{surf}) = 1.1 \times 10^{-4} A_d + 1.5 \times 10^{-5} A_w + 4.5 \times 10^{-4} L^{1/2} A_b \dots\dots\dots(12)$$

For substances with viscosities between 5 and 50 mPa.S

$$Q_{res}(\text{surf}) = 1.8 \times 10^{-4} A_d + 3.5 \times 10^{-5} A_w + 1.4 \times 10^{-3} L^{1/2} A_b \dots\dots\dots(13)$$

For substances with viscosities greater than 50 mPa.S

$$Q_{res}(\text{surf}) = 8.5 \times 10^{-4} A_d + 1.1 \times 10^{-4} A_w + 4.5 \times 10^{-3} L^{1/2} A_b \dots\dots\dots(14)$$

As a general rule, Eq.(12) is used now <sup>(5)</sup>.

Using Eq.(12) and tank shapes represented in Table 1, the relation between  $Q_{res}(\text{surf})$  and tank volume V are given by the regression.

$$Q_{res}(\text{surf}) = 1.96 \times 10^{-3} \times V^{0.671} \dots\dots\dots(15)$$

Here, the tank shapes are assumed as rectangular parallelepiped.

The calculated points and the curve of Eq.(15) are represented in Fig.5

$Q_{sl}$  can be obtained by the on board test with water.

Table 1 Tank Shape

No.	Total ton number	Dimensions of Tank (m)			Tank Volume (m <sup>3</sup> )	Ratio of Dimensions L:B:D	Note
		L	B	D			
1	模型タンク	4.00	2.00	2.00	8.0	2: 1: 1	
2	96.56	6.00	3.60	2.50	53.0	24:14:10	Center B <sup>hd</sup>
3	96.56	8.50	3.60	2.50	76.5	34:14:10	" Type
4	99.77	8.00	3.25	2.90	77.0	28:11:10	"
5	99.77	8.50	3.25	2.90	83.0	29:11:10	"
6	198.86	9.40	4.00	3.30	106.8	28:12:10	"
7	213.42	8.80	4.00	3.30	115.2	27:12:10	"
8	213.42	9.60	4.00	3.30	122.3	29:12:10	"
9	198.86	9.85	4.00	3.30	123.8	30:12:10	"
10	410.0	9.15	4.70	3.10	149.5	30:15:10	"
11	497.0	8.45	5.00	3.45	156.3	25:15:10	"
12	410.0	9.60	4.70	3.10	159.2	31:15:10	"
13	497.0	9.00	5.00	3.45	165.2	26:15:10	"
14	498.0	8.95	5.00	3.40	169.2	26:15:10	"
15	498.0	9.40	5.10	3.20	178.3	29:16:10	"
16	649.81	10.00	5.00	3.60	199.8	28:14:10	"
17	649.81	10.00	5.00	3.60	201.0	28:14:10	"
18	1076.16	9.50	5.70	4.30	246.6	22:13:10	"
19	1076.16	9.80	5.70	4.30	251.0	23:13:10	"
20	999.08	10.00	5.80	4.50	273.7	22:13:10	"
21	999.08	10.05	5.80	4.50	274.2	22:13:10	"
22	2759.0	10.40	3.30	6.20	201.0	17: 5:10	2Long <sup>hd</sup>
23	4943.0	8.40	3.525	8.20	248.0	10: 4:10	" Type
24	4943.0	11.20	3.525	8.20	332.0	14: 4:10	"
25	7145.0	9.00	4.75	9.71	381.0	9: 5:10	"
26	2759.0	8.45	7.80	6.20	402.0	14:13:10	"
27	2759.0	9.10	7.80	6.20	461.0	15:13:10	"
28	7145.0	11.25	4.75	9.71	518.0	12: 5:10	"
29	10804.0	5.76	11.20	10.31	666.0	6:11:10	"
30	11700.0	11.52	5.80	10.25	690.0	11: 6:10	"
31	10804.0	11.52	5.80	10.31	691.0	11: 6:10	"
32	4943.0	8.40	10.15	8.20	747.0	10:12:10	"
33	11700.0	16.32	5.80	10.25	976.0	16: 6:10	"
34	4943.0	11.20	10.15	8.20	985.0	14:12:10	"
35	11700.0	9.50	11.20	10.25	1100.0	9:11:10	"
36	7145.0	11.25	10.50	9.71	1163.0	12:11:10	"
37	13600.0	18.75	5.84	11.81	1300.0	16: 5:10	"
38	10804.0	11.52	11.20	10.31	1353.0	11:11:10	"
39	13600.0	23.52	5.84	11.81	1770.0	20: 5:10	"
40	11700.0	23.04	11.20	10.25	2694.0	22:11:10	"
41	13600.0	18.75	13.32	11.81	2990.0	16:11:10	"
42	4259.0	13.00	9.10	6.80	817.0	19:13:10	Center B <sup>hd</sup>
43	3802.0	14.30	8.25	6.90	831.0	21:12:10	" Type
44	3802.0	14.28	8.25	6.90	843.0	21:12:10	"
45	9088.0	15.00	10.50	9.70	1582.0	15:11:10	"
46	9088.0	18.00	10.50	9.70	1853.0	19:11:10	"

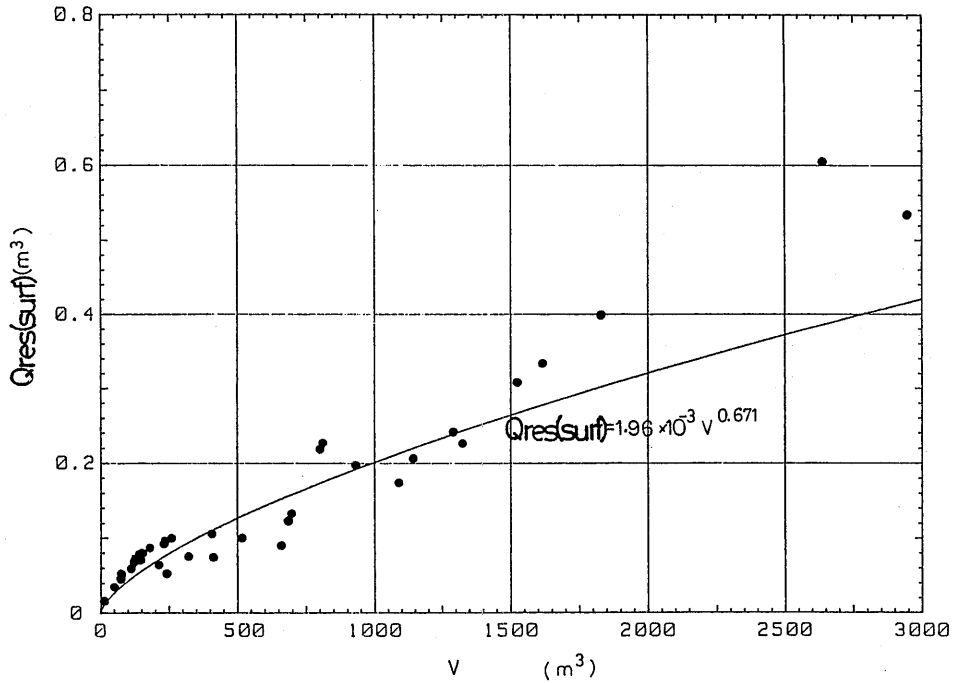


Fig.5 Relation between V and Qres(surf)

**2.3 Tank Washings Quantity Remaining in the Tank during Washing**

The quantity of the dynamic holdup of slops in the tank during washing QDH can be estimated using the following formula.

$$QDH = Q1+Q2+Qs2 \dots\dots\dots(16)$$

Q1 is the remaining water quantity on the vertical surfaces during washing and Q2 is the one on the bottom surface and Qs2 is the one in the tank well.

Q1 and Q2 are obtained approximately using the following formula.

The model of the approximation of Q1 is shown schematically in Fig.6.

$$Q1 = \delta_1 \times b \times \frac{D}{2} \times 2 \dots\dots\dots(17)$$

$\delta_1$  is the water film thickness on the nearly vertical wall.  
 b is the breadth of the water film flow on the vertical wall.  
 b is obtained experimentally by Eq.(18) and shown in Fig.7.

$$b = 4.3r \dots\dots\dots(18)$$

where r is the distance from the center of jet to upper limit and also experimentally obtained by Eq.(19) and shown in Fig.8.

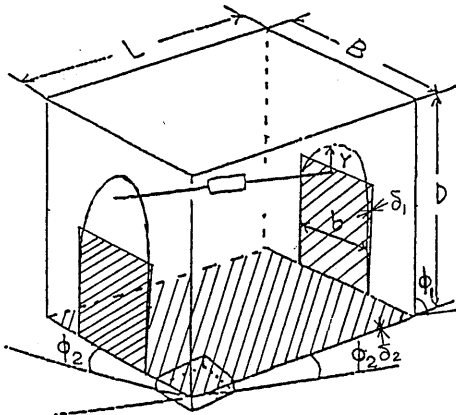


Fig.6 Remaining state on the average during tank washing

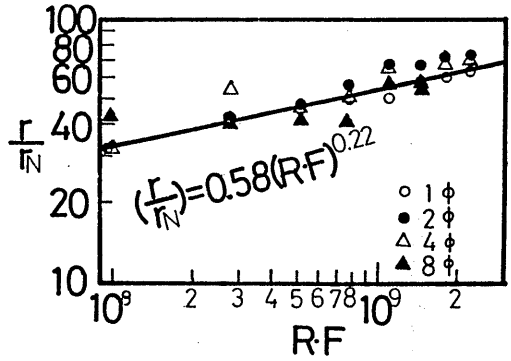


Fig.8 Relation between R\*F and r/rN

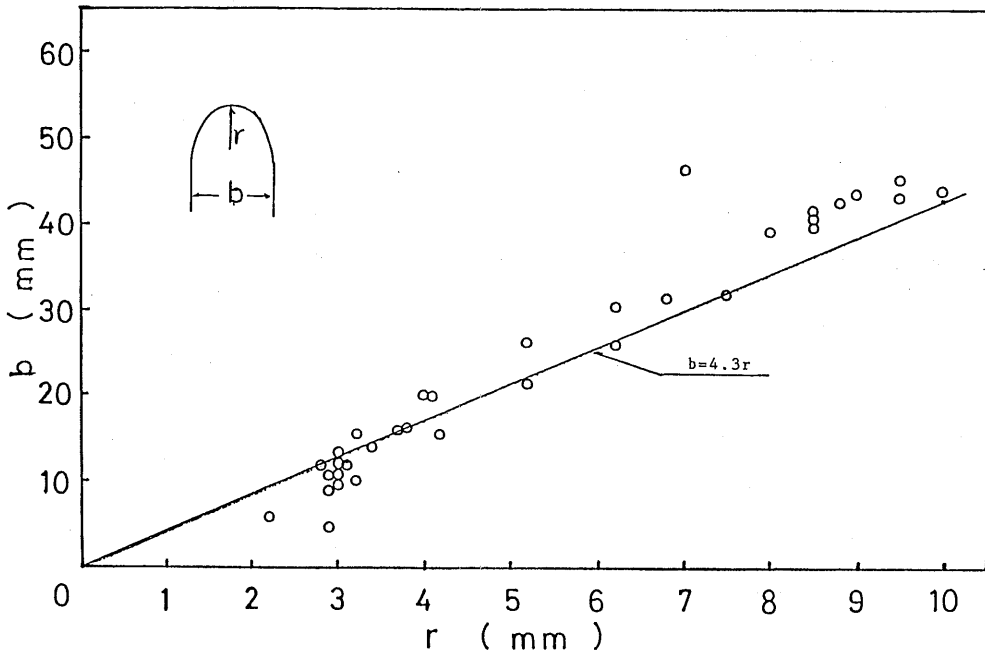


Fig.7 Relation between r and b

$$r/rN = 0.58 (R \cdot F)^{0.22} \dots\dots(19)$$

where  $R = U \cdot r N / \nu$ ,  $F = U^2 / (g \cdot r N)$

Here  $U$  is the water jet velocity at the nozzle,  $rN$  is the radius of the nozzle,  $g$  is the gravity acceleration, and  $\nu$  is kinematic viscosity of water.

$$Q_2 = \delta_2 \times B \times L \dots\dots(20)$$

$\delta_2$  is the water film thickness on the tank bottom.

Falling film average thickness  $\delta_1$  and  $\delta_2$  may give as follows<sup>(7)</sup>;

$$\delta_1 = \sqrt[3]{\frac{3q_1 \cdot \mu}{\gamma \cdot \sin \phi_1}} \dots\dots\dots(21)$$

$$\delta_2 = \sqrt[3]{\frac{3q \cdot \mu}{B \cdot \gamma \cdot \sin \phi_2}} \dots\dots\dots(22)$$

where  $q_1$  is  $q/(2b)$ .  $q$  is amount of water fed to tank by washing machine per second.  $B$  is the breath of the tank.  $\phi_1$  is the angle of the tank wall inclination.  $\phi_2$  is the angle of the tank bottom inclination.

When  $\phi_1$  is  $90^\circ$ ,  $\delta_1$  is the film thickness by W. Nufelt<sup>(8)</sup>.

Let  $Q_1+Q_2 = Q_{12}$ . The relation between the tank volume  $V$  and  $Q_{12}$  can be estimated by Eq(23) by the regression.

The tank shapes shown in Table 1 and the conventional washing machines as shown in Fig. 9 are used.

$$Q_{12} = 281 \times 10^{-3} \times V^{0.633} \dots\dots\dots(23)$$

The points calculated by Table 1 and Eq.(17)–(22), and Eq.(23) are represented in Fig.9.

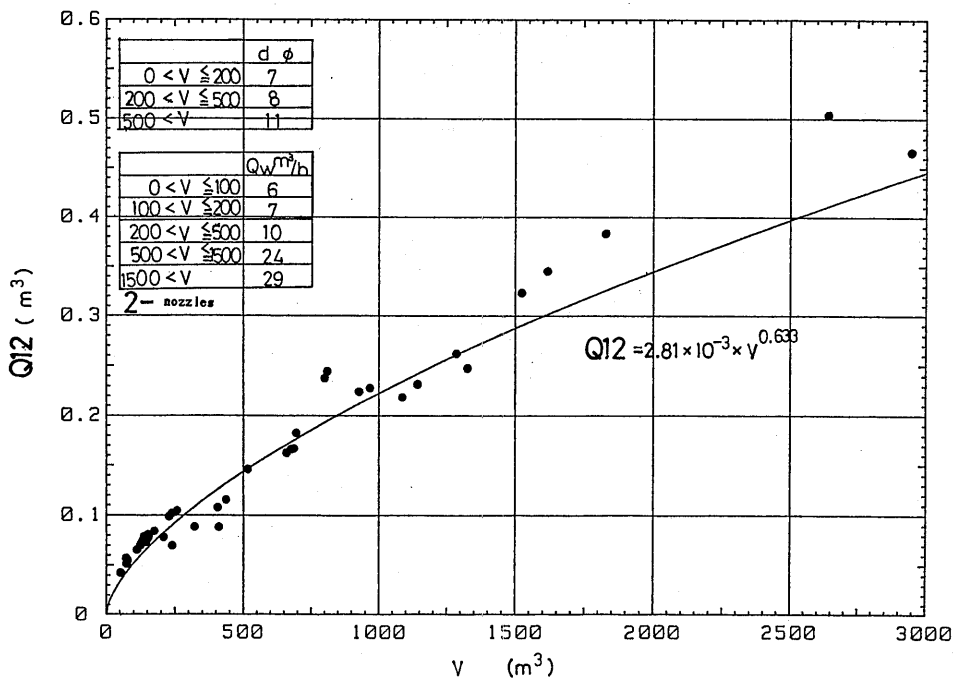


Fig.9 Relation between V and Q12

3. EXPERIMENT

3.1 Test Method

The model tank for this experiment is shown in Fig.10. After sprinkling the test liquid on the tank surfaces, it is withdrawn from the drain of the tank well. The amount of the drainage is weighed by the time elapsed. By subtracting the amount of the drainage from the amount of the sprinkled liquid, the amount of clirage residue on tank surfaces is obtained.

According to the test surfaces, three cases were examined. One is the case of the bottom surface, another is the case of the bottom and vertical surfaces, the other is the case of the all surfaces. In the case of the only bottom surface, the test liquid is sprinkled using the vessel. But in the case of the side surfaces and the horizontal surface facing downwards, a gear pump and hose were used. The vessel, the gear pump and hose were weighed before and after sprinkling and the amount of sprinkled liquid was found. According to the test liquids, red colored water, ethylene glycol and glycerine were used.

The viscosities of ethlene glycol and glycerin were not affected by the dye but the one of water was affected a little by the dye.

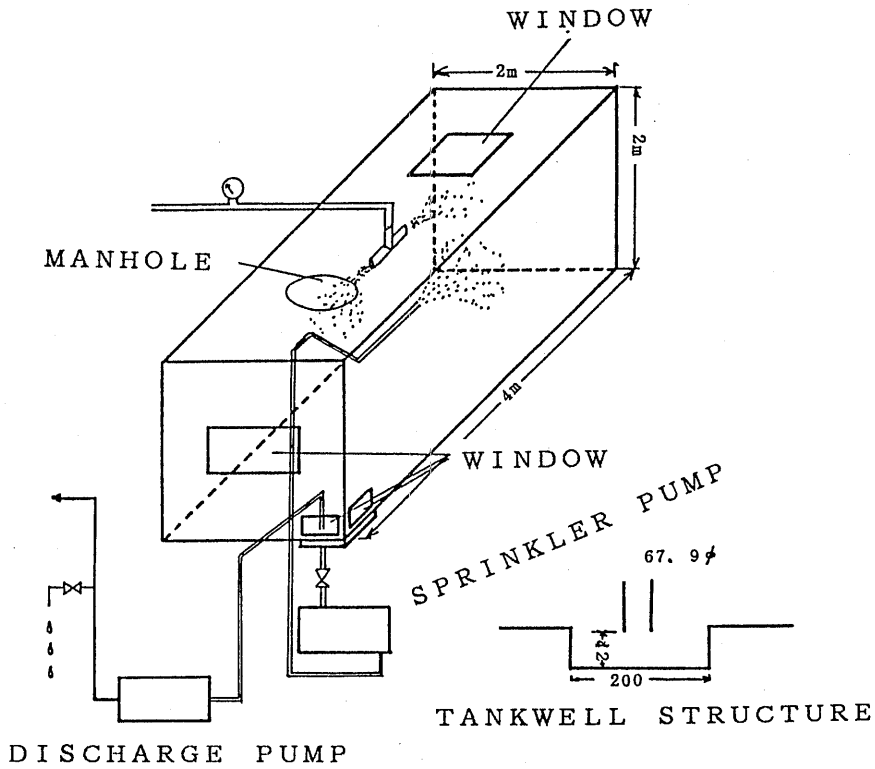


Fig.10 Test Apparatus of the Tank Model

Using the washing machine with  $\phi 4$  mm nozzle and the  $\phi 7$  mm nozzle, tank washing experiments were done and compared. These experiments were done after the weighing of clinging residues.

The movements of washing nozzles are shown in Fig.11. The movements of the nozzles used for these tests are represented in Table 2. An example of the trace of  $\phi 7$  mm nozzle machine is shown in Fig.12. The cycle time of  $\phi 4$  mm washing machine, examined by the water jet trace, is shown in Table 2.

The residual concentration is analyzed by gas chromatogram or spectrophotometer or electrical conduction. Using NaCl, the concentration is analyzed by the electrical conduction.

But in the case of low concentration, the ions of tap water affect electrical conduction, it is difficult to analyse the concentration less than about 0.01% of NaCl by electrical conduction.

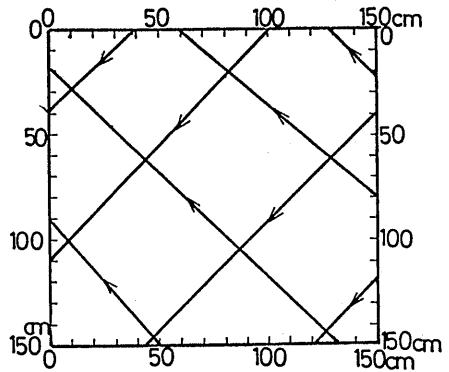
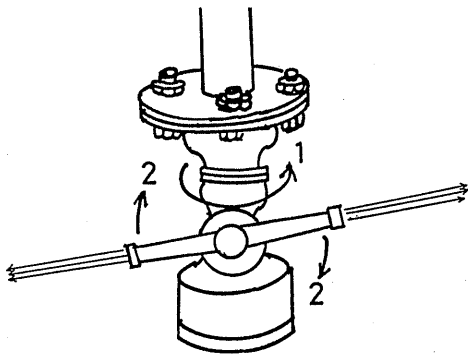


Fig.11 Movement of washing nozzle Fig.12 An Example of the Trace of Jet

(The distance between the nozzle and the test surface is 5 m. The pressure to the washing machine is 98 kpa.)

Table 2 Motion of the washing machines

Water Pressure	4 $\Phi$ Washing Machine				7 $\Phi$ Washing Machine	
	Period of 1 direction	Period of 2 direction	Time of one cycle	Quantity of used water	Period of 1 direction	Period of 2 direction
MPa	Second	Second	Minute	m <sup>3</sup> /M	Second	Second
0.44	9.4	9.1	6.8	0.029	—	—
0.39	10.6	9.7	7.3	0.027	—	—
0.34	10.6	10.5	7.9	0.024	—	—
0.29	12.2	11.5	8.7	0.022	20.8	20.0
0.25	13.9	13.2	9.9	0.020	21.5	21.1
0.20	16.0	15.9	12.0	0.019	23.9	23.5
0.15	17.8	17.2	14.0	0.015	27.6	27.1

### 3.2 The Results of Tank Washing Experiment

Fig. 13 shows the comparison of the tank washing experimental result with  $\phi$  4 mm diameter nozzle and with  $\phi$  7 mm one. By using the small diameter nozzle, necessary washwater can be decreased.

Figs.14-17 show the results of tank washing test with different liquids. There is little difference between water and ethylene glycol concerning tank washing. But there is much difference between glycerin and the liquid with the viscosity less than the viscosity of ethylene glycol. About glycerin, as the viscosity changes much according to the temperature, there is difference between the experiment results of the different season. Fig.18 shows the results of the tank washing test with the liquid adhering to different surfaces and Fig.19 represents the results when the parts where the residue remains are changed. Fig.20 represents the relation between  $Q$  and  $C$  when  $Q$  and  $D$  are changed. The residue in the vicinity of tank well are discharged quickly, and at the later part of the washing, the residue adhering to wall is less discharged than ideal mixing model.

Fig.21 and Fig.22 represent the relation between the washwater quantity and concentration in the effluent when the beginning concentration is changed. Fig.23 represents the relation between the washwater quantity and concentration when the quantity of the residue at the beginning is changed.

In the case that the liquid is insoluble, the cleaning by water jet is difficult. Fig.24 represents the washing result using B heavy oil.

Usually the capacity of pumping out is larger than several times of the one injected by the washing machine. But, during the washing, the remaining water quantity in the tank is small, then the capacity of discharging pump becomes small. Fig.25 is the result of model tank test and Fig.26 is that of the on board test<sup>(6)</sup>. As shown in Fig.26, the ratio of discharged water quantity to injected water quantity becomes about 1.1 on board. Table 2 shows the cycle time about  $\phi$  4 mm nozzle machine examined by the water jet trace.

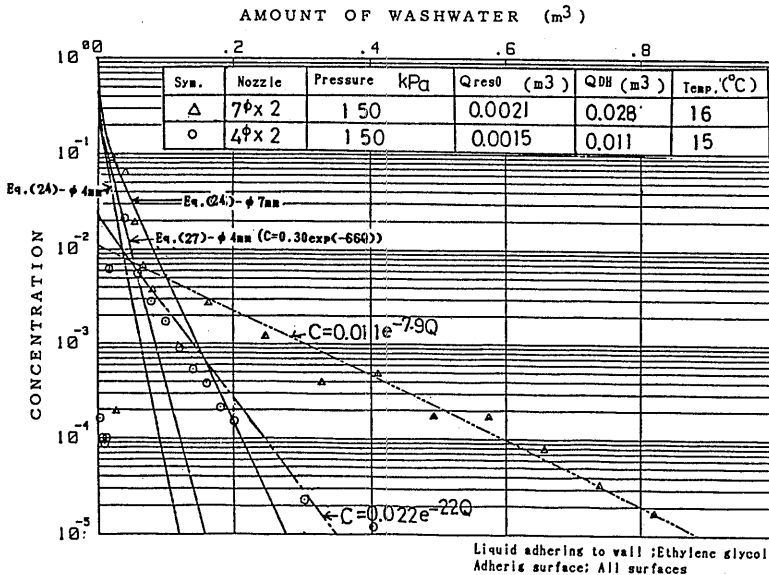


Fig.13 Comparison with Tank Washing between two nozzles



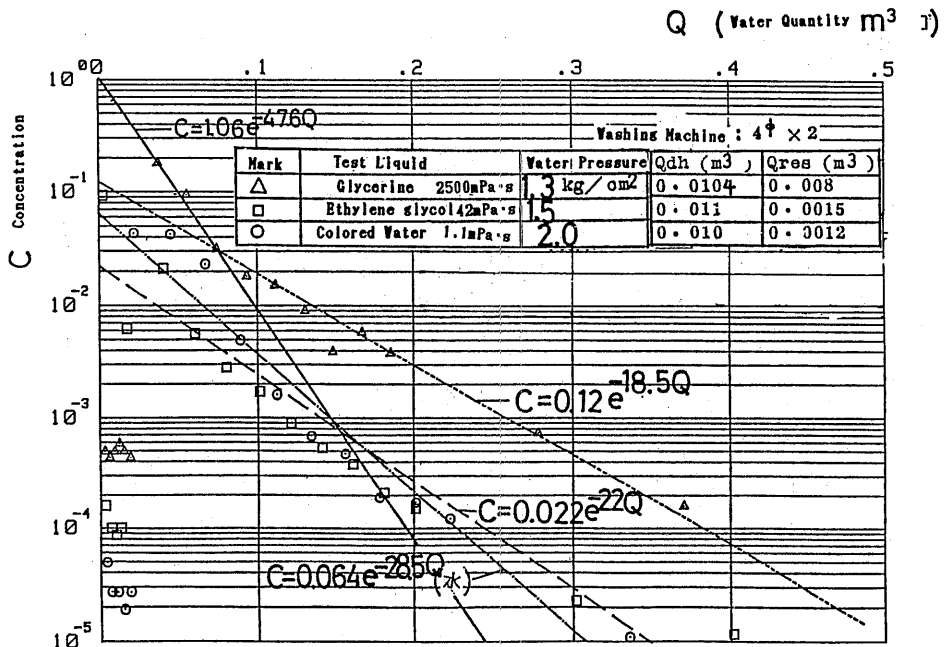


Fig.14 Washing with the test liquids of different viscosity (Liquids adhering to all surfaces in the tank)

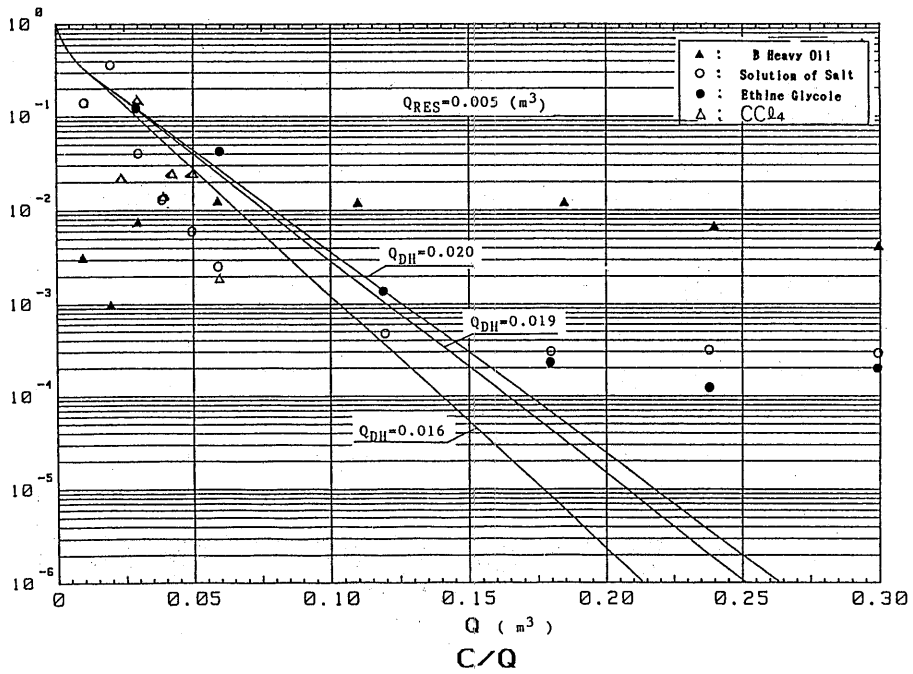


Fig.15 Tank washing result with various kinds of liquid (φ7mm nozzle)

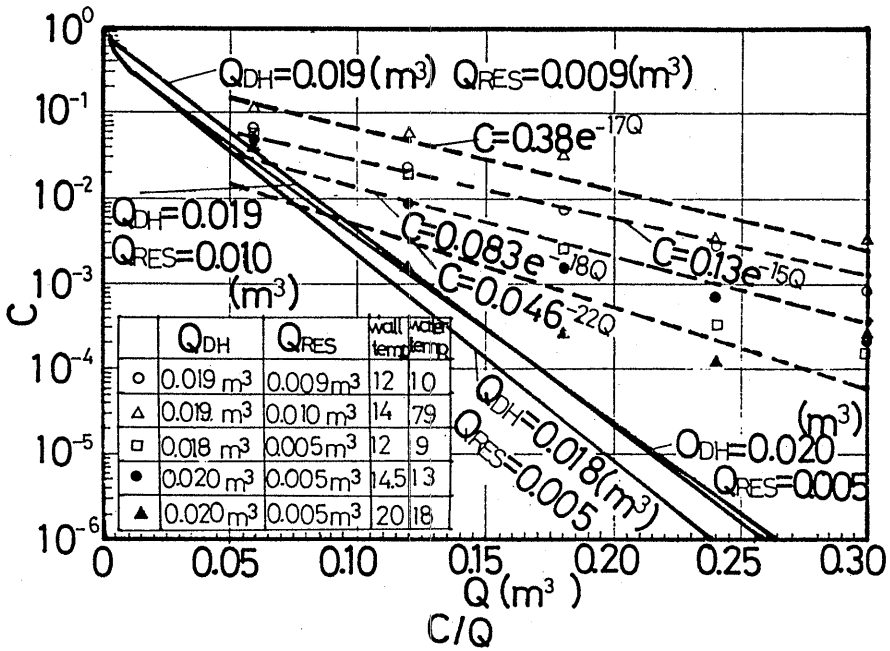


Fig.16 Result of the tank washing test using model tank and glycerin ( $\phi$  7mm nozzle, in autumn)

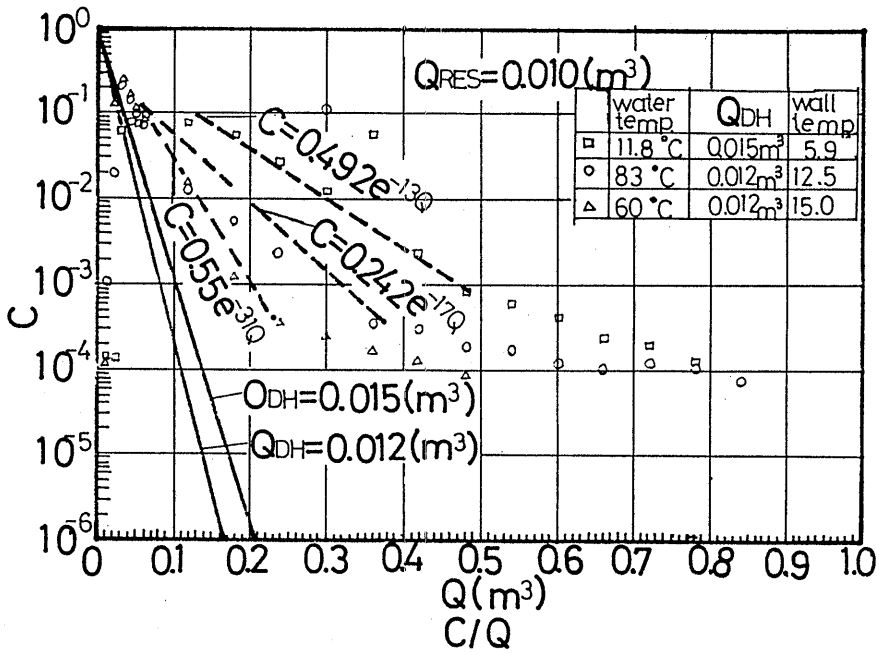


Fig.17 Result of the tank washing test using model tank and glycerin ( $\phi$  7mm nozzle, in winter)

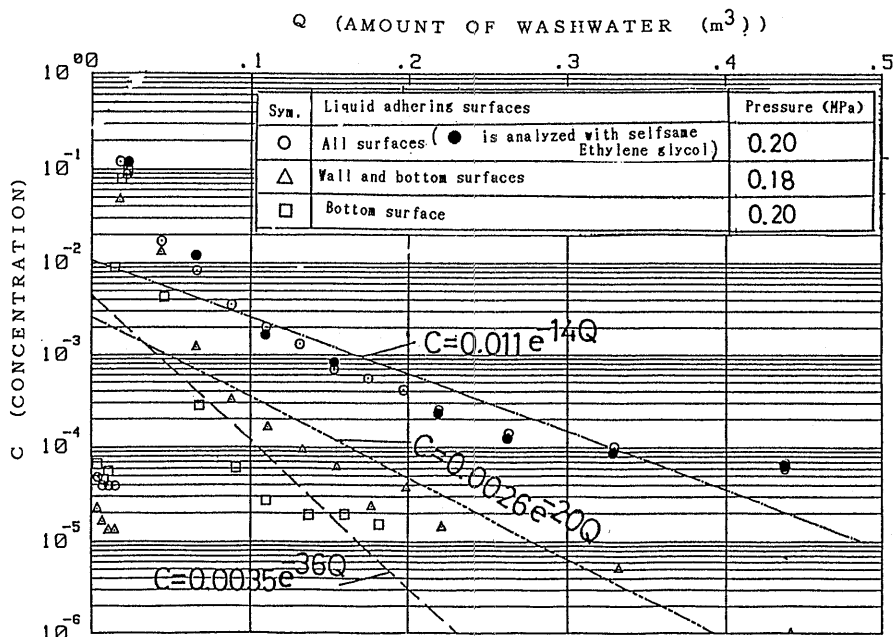


Fig.18 Comparison with Tank Washing among the different Surfaces the liquid adhering to

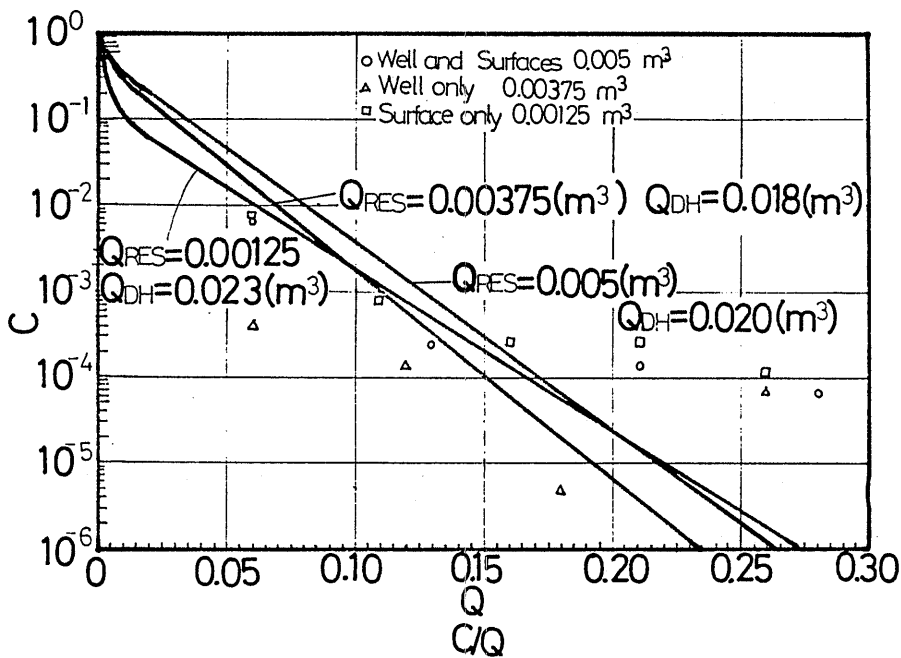


Fig.19 The tank washing result concerning the parts on which the residue remains

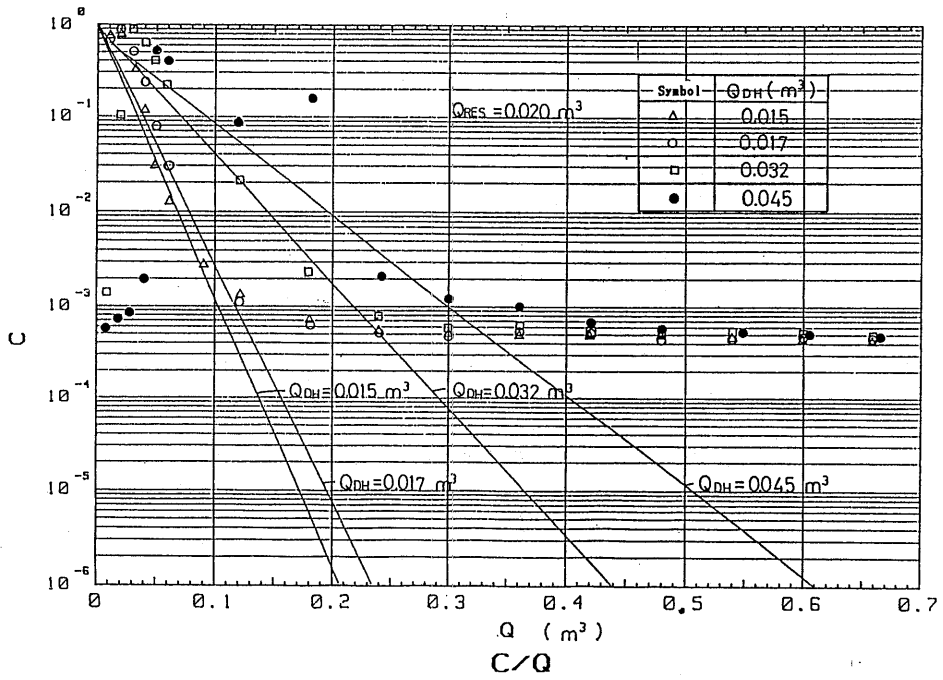


Fig.20 Tank washing test result with QDH (Water viscosity 1.3mPas)

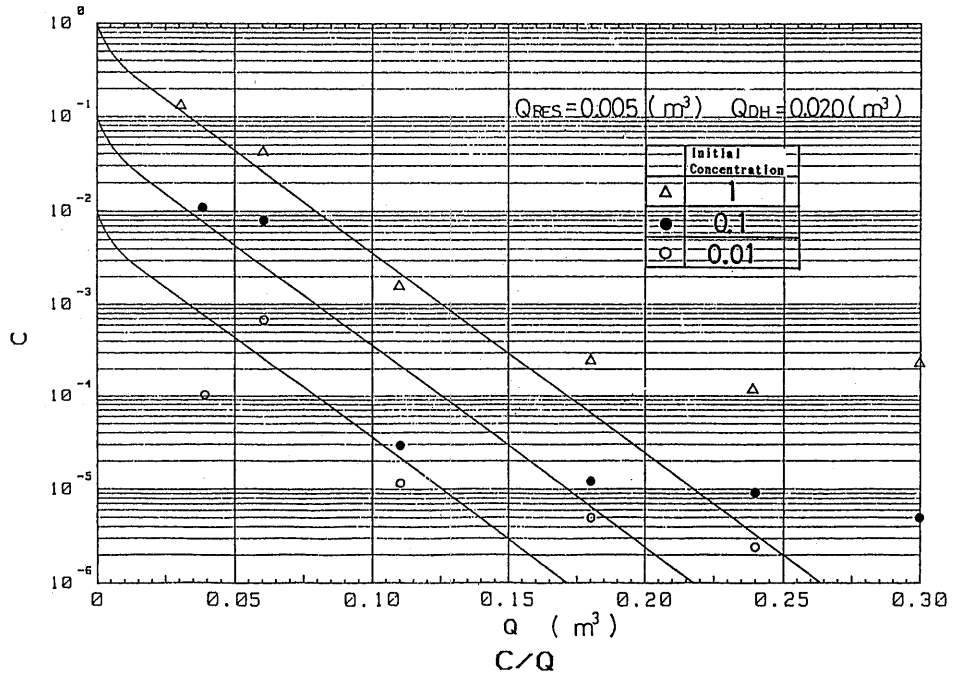


Fig.21 Tank washing when the initial concentration is changed (Test Liquid; Ethylene Glycol)

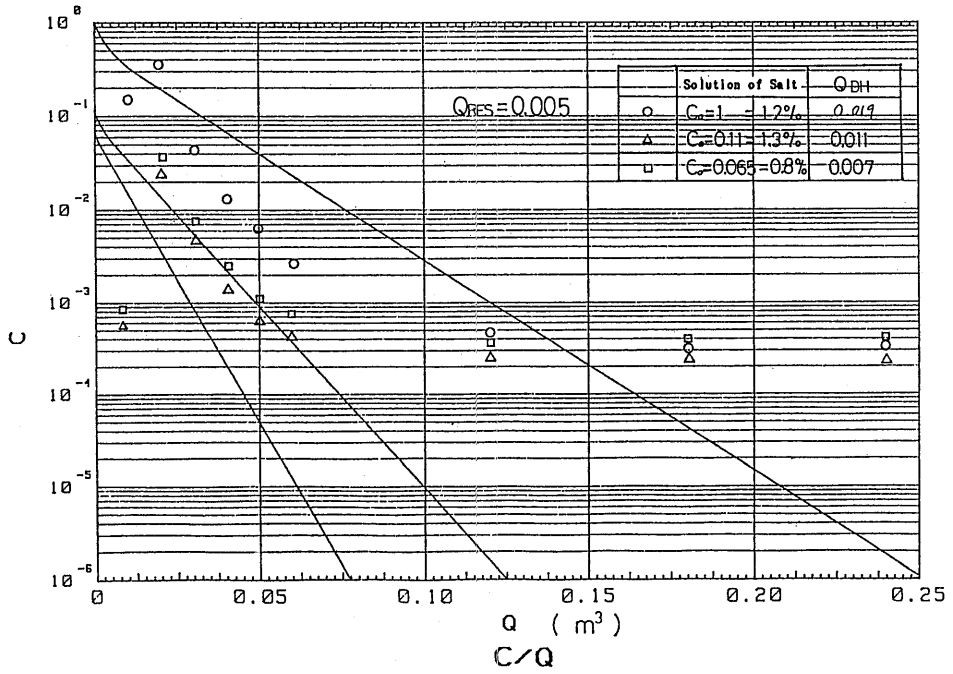


Fig.22 Tank washing when the initial concentration is changed  
(Here  $C=1$  is settled for the 12% Solution of Salt)

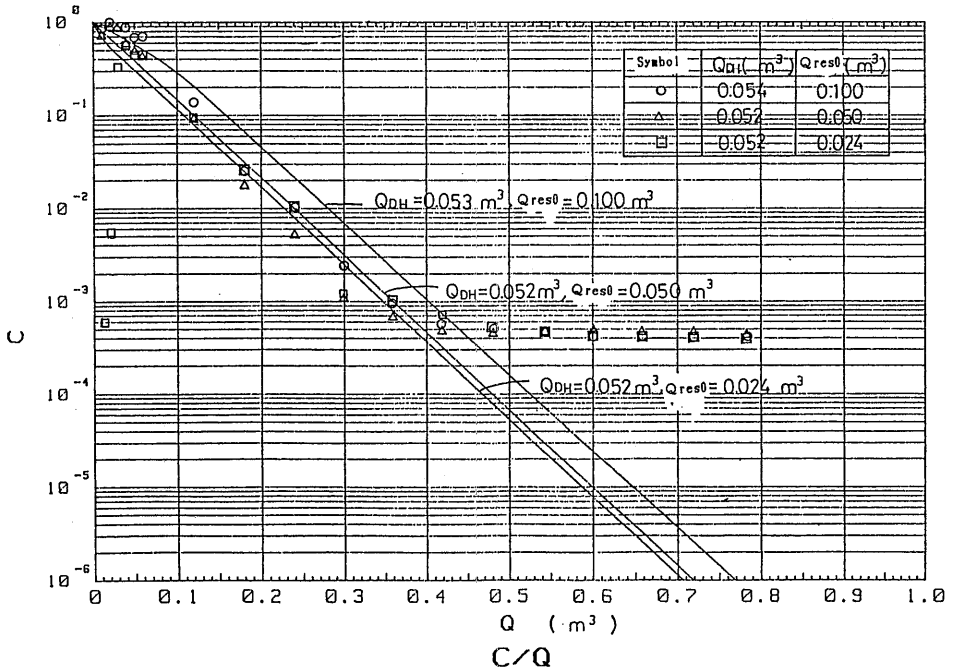


Fig.23 Washing in the case of different  $Q_{res0}$

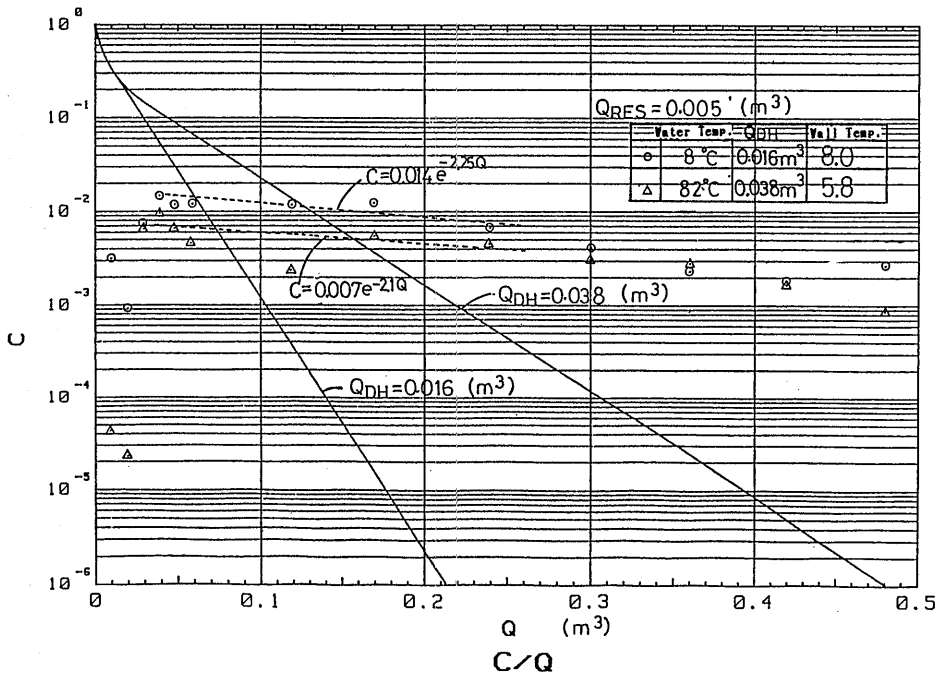


Fig.24 Tank washing test result with insoluble liquid in water (B Heavy oil)

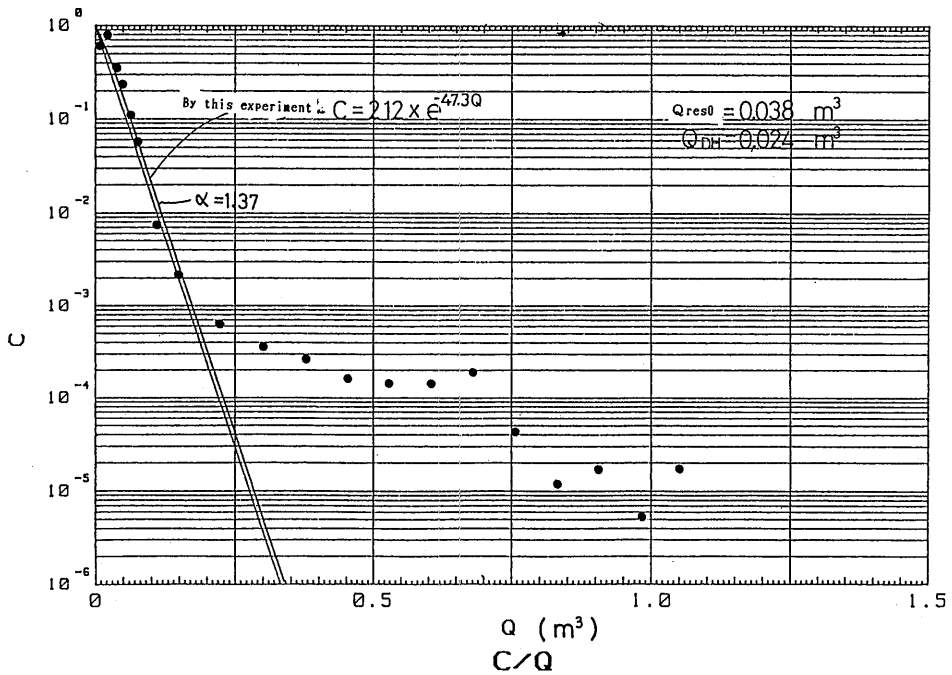


Fig.25 Washing in the case of large  $Q_{res0}$

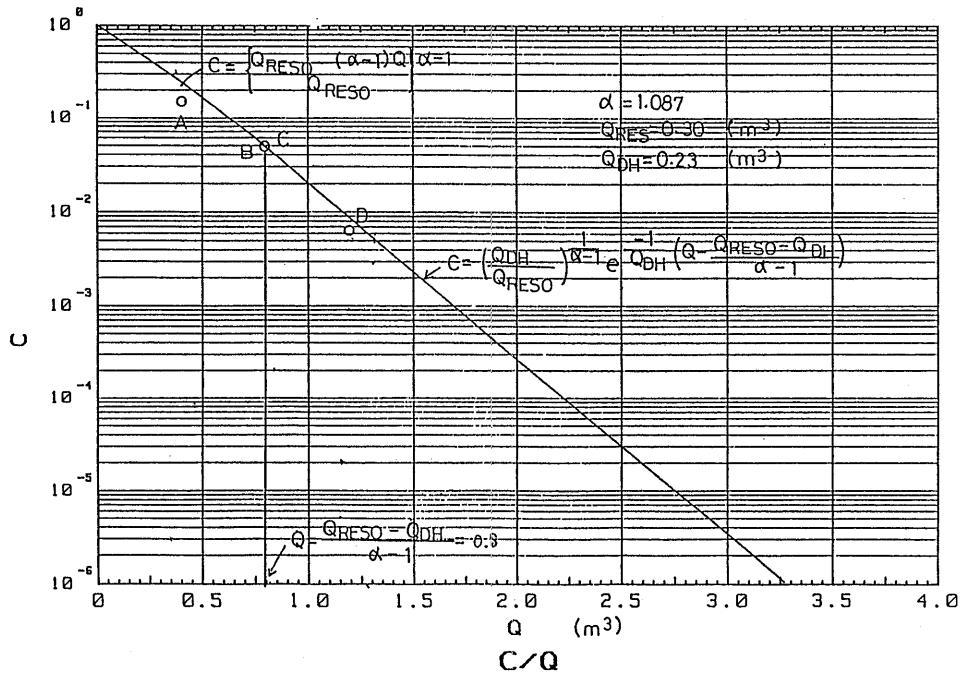


Fig.26 Presumption of  $\alpha$

**3.3 Experiment of the Clingage Residue Adhering to Tank Surfaces**

Fig.27—Fig.29 show the relation between time lapsed and the amount of clingage residues when the liquids are sprinkled to the bottom surface, the bottom and vertical surfaces and the all surfaces respectively with water, ethylene glycol and glycerin. The tank size is 2m×2m×4m as shown in Fig.10.

From these results, the relation between the amount of clingage residues 90 minutes after sprinkling and the viscosity is found in Fig.30. The states of clingage on each surface with each liquids are shown from photo 1 to photo 3. From these experimental results, the clingage residue quantity per unit area on each surface were estimated and are shown in Fig.31. Here, let  $y = a_1 + b_1 \cdot \log x$ , where the quantity of the adhering to the surfaces per unit area is  $y$  and the viscosity is  $x$ . Coefficients  $a_1$  and  $b_1$  are shown in Table 3.

Table 3 Coefficient of the lines in Fig.

Number of lines in Fig. 31	Low viscosity		High viscosity	
	$a_1$	$b_1$	$a_1$	$b_1$
①	0.041	0.086	-4.322	1.779
②	0.029	0.057	-2.812	1.195
③	0.013	0.030	-2.060	0.901
④	0.015	0.018	-0.917	0.362
⑤	0.020	0.007	-0.767	0.295
⑥	0.078	0	-0.938	0.338
⑦	0.091	0.035	-1.141	0.478
⑧	0.047	0.042	-1.155	0.468
⑨	0.029	0.057	-0.912	0.387

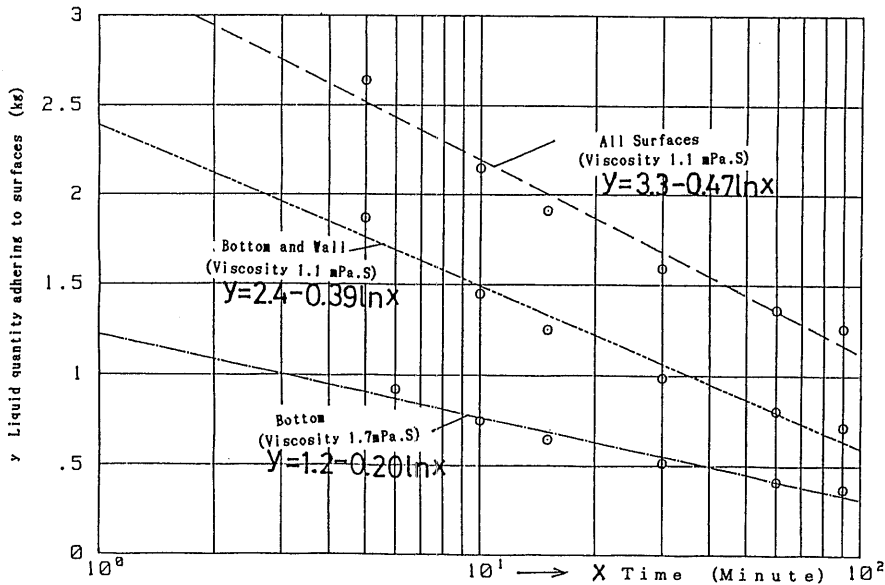


Fig.27 Quantity of water adhering to the surfaces afetr sprinkling

(Trim 2°, List 2°)



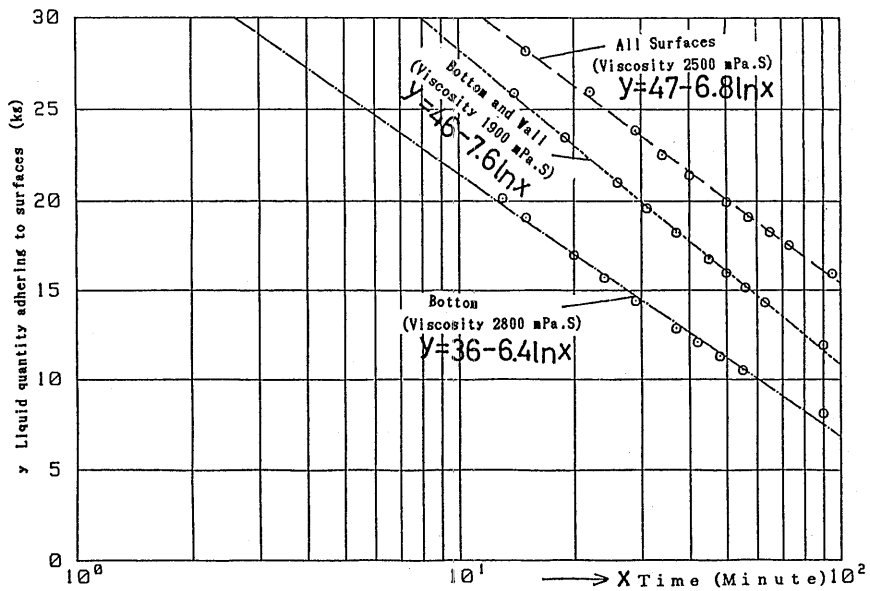


Fig.28 Quantity of glycerin adhering to the surfaces after sprinkling (Trim 2°, List 2°)

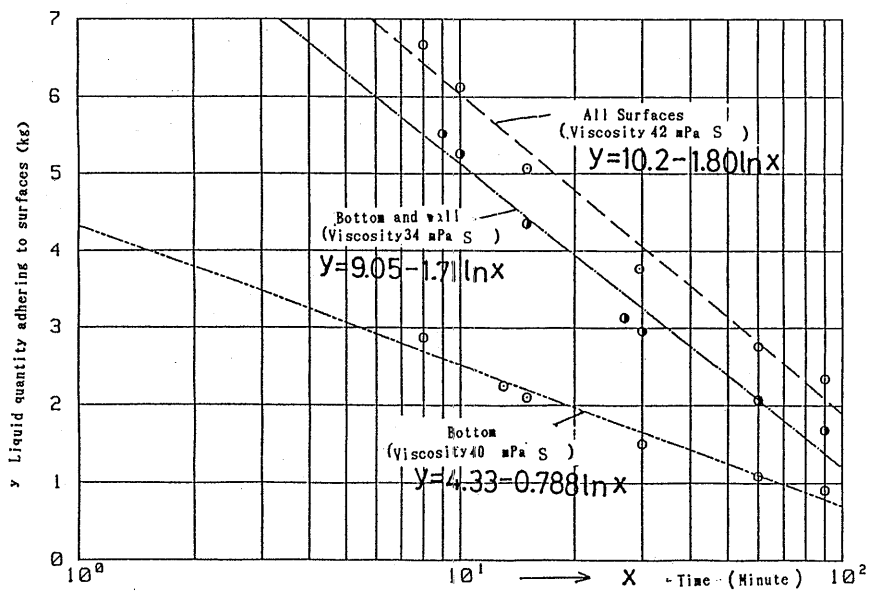


Fig.29 Quantity of Ethylene glycol adhering to the surfaces after sprinkling (Trim 2°, List 2°)

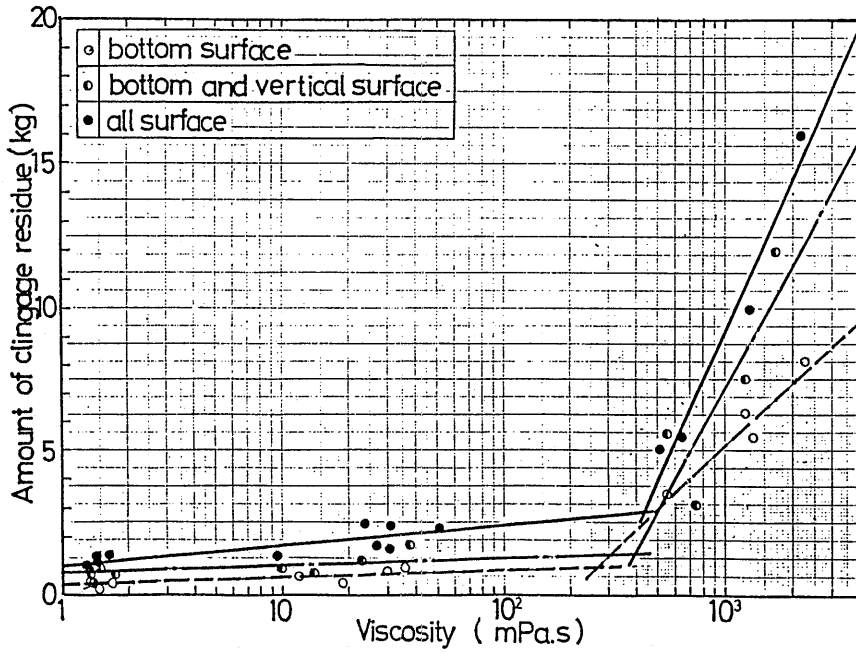


Fig.30 Amount of Clingage residue 90 minutes after sprinkling

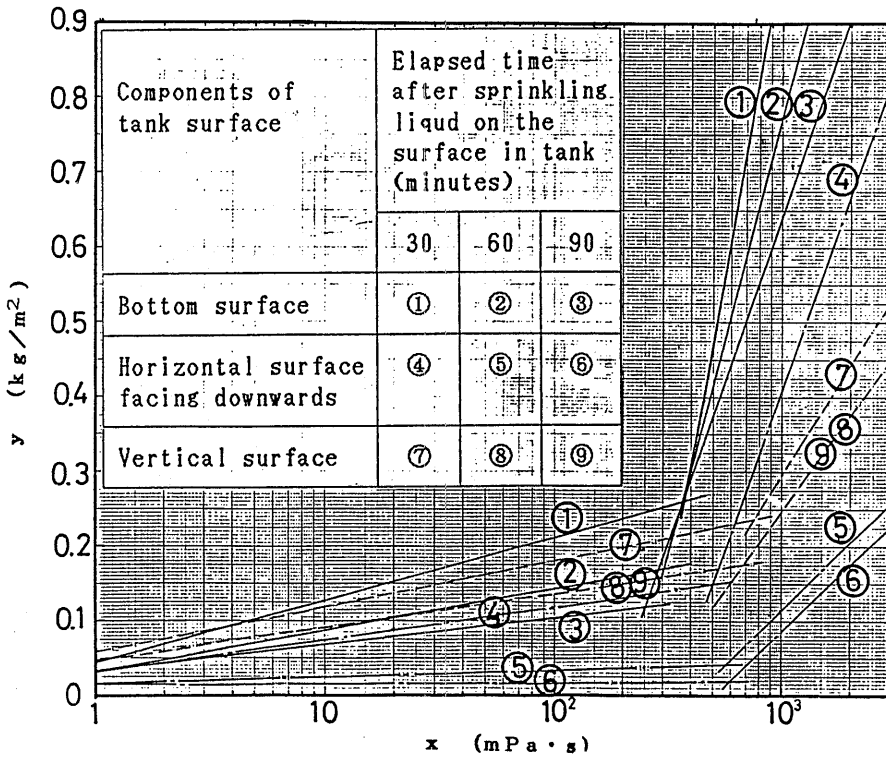
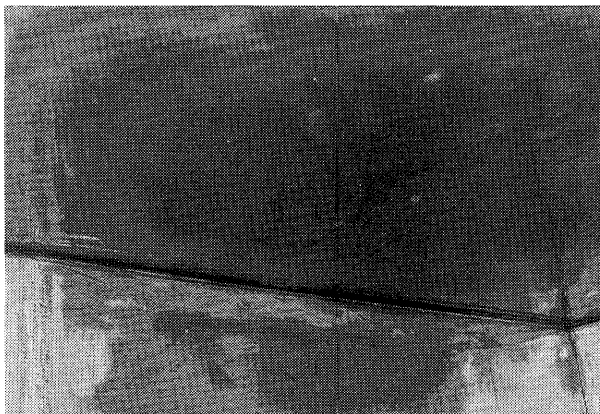
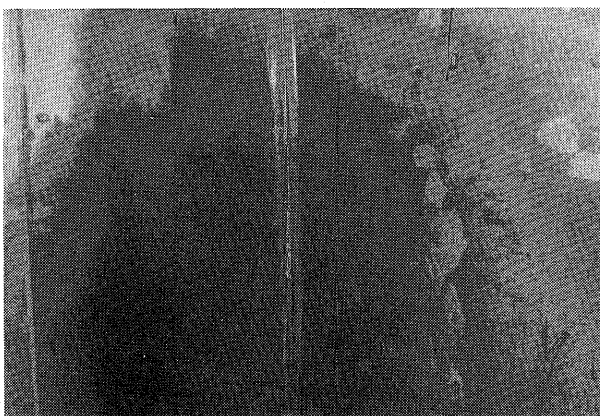


Fig.31 Residual quantity per unit area



Underdeck

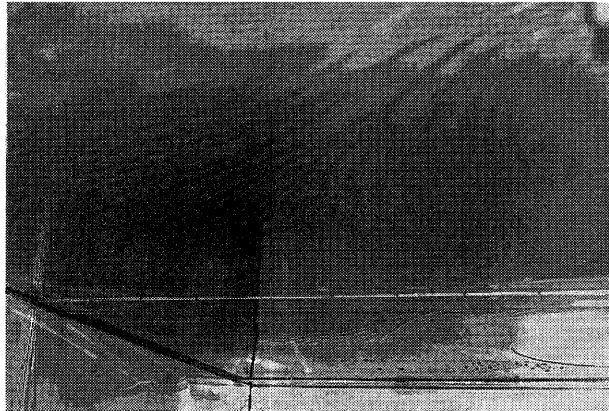


Tank walls

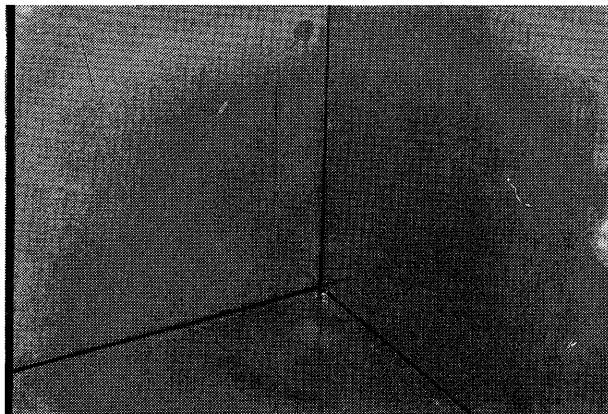


Tank Bottom

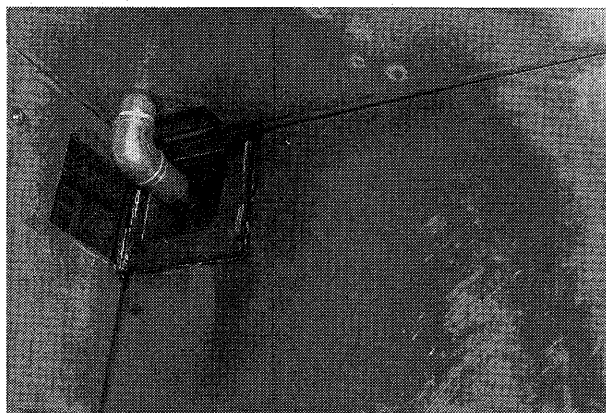
Photo.1 Appearance of the red colored water adhering to the surfaces after 90 minutes from sprinkling



Underdeck

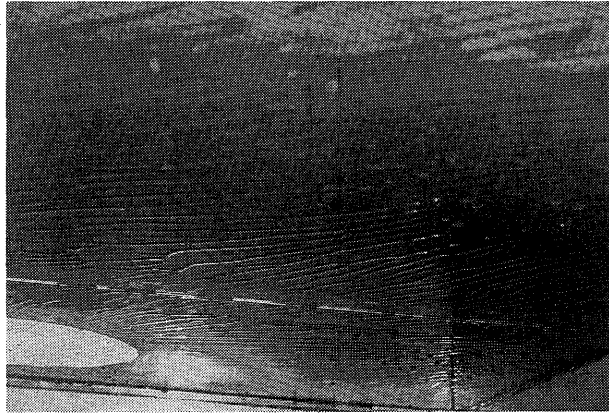


Tank walls

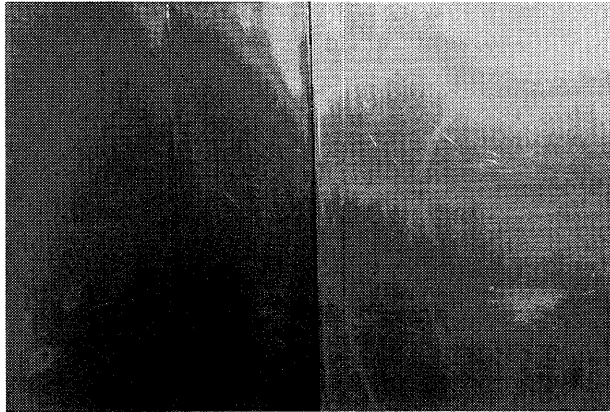


Tank Bottom

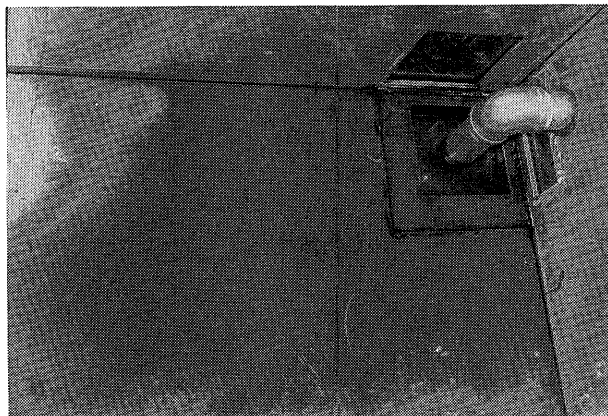
Photo.2 Appearance of the red colored Ethylene glycol adhering to the surfaces after 90 minutes from sprinkling



Underdeck



Tank walls



Tank Bottom

Photo.3 Appearance of the red colored Glycerin adhering to the surfaces after 90 minutes from sprinkling

**3.4 Experiment of the Washings Quantity Remaining in the Tank during washing**

When both the washing pump are discharged pump is stopped at the same time, the water quantity in the tank  $Q_{total}$  is expressed:

$$Q_{total} = Q_0 + Q_1 + Q_2 + Q_{s2} + Q_3 + Q_4$$

In which.  $Q_0$  is the water quantity from the nozzle to the walls,  
 $Q_1$  is the water quantity on the vertical surfaces,  
 $Q_2$  is the water quantity on the bottom surface,  
 $Q_{s2}$  is the remaining water quantity in the vicinity of the tank well,  
 $Q_3$  is the water quantity flows backward from discharged pipe,  
 $Q_4$  is the water quantity flows from washing machine.

$$Q_{DH} = Q_1 + Q_2 + Q_{s2}$$

$$Q_{DH} = Q_{total} - Q_0 - Q_3 - Q_4$$

$Q_{total}$ ,  $Q_3$  and  $Q_4$  are obtained by the experiment.

By the experiment of the model tank test, when the jet velocity is 13 m/s , the average of the water quantities is obtained as following results.

$Q_{total}$  is 0.0225m<sup>3</sup>,  $Q_3$  is 0.0015m<sup>3</sup>,  $Q_4$  is 0.0024m<sup>3</sup>.

$Q_0$  is calculated:

$$Q_0 = \pi/4 \cdot d^2 L = 0.0002 \text{ m}^3$$

Then  $Q_{DH}$  becomes  $18.4 \times 10^{-3} \text{ m}^3$ .

**4. COMPARISON AND DISCUSSION BETWEEN ANALYSIS AND EXPERIMENTAL RESULTS**

**4.1 Comparison between the Ideal Mixing Model and Experimental Results about Tank Washing**

It is compared the difference of tank washing between by the  $\phi$  4 mm nozzle washing machine and by the  $\phi$  7 mm one after the test liquid is made to adhere to all surfaces in tank. The result of the experiment of Fig.13 is considered here.

Let's consider the region of being washed in the case of almost statefully ( $Q > 0.05 \text{ m}^3$ ), for the  $\phi$  7mm $\times$ 2 washing machine, the relation between concentration and water quantity is given by the regression.

$$C = 0.011e^{-7.9Q}$$

C; Concentration in the effluent, Q; Washwater quantity(m<sup>3</sup>)

In the case of  $\phi$  4mm $\times$ 2 and  $Q=0.02 \text{ m}^3$ , it is given as the following

$$C = 0.022e^{-22Q}$$

On the assumption that it is washed homogeneously in the tank, the relation between C and Q is given by Eq.(6). It is rewritten by Eq.(24).

$$C = \frac{Q_{res0}}{Q_{DH}} \cdot \exp \left( - \frac{Q - Q_{DH} + Q_{res0}}{Q_{DH}} \right) \dots\dots\dots(24)$$

$Q_{DH}$ ; Remaining quantity during washing in the tank

$Q_{res0}$ ; Clingage residue at the beginning

In the case of  $Q < 0.05 \text{ m}^3$  with  $\phi$  7 mm nozzle and in the case of  $Q < 0.02 \text{ m}^3$  with  $\phi$  4 mm,