船舶技術研究所報告　第28巻　第３号（平成３年５月）

Tank Washing of Chemical Tanker

By

Koichi Ueda*

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 follwing conclusions are obtained.

(1) At the begining 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 maschine with small diameter nozzles.

---

*Ship Equipment Division

TABLE OF CONTENTS

Chapter

Notations

NOTATIONS

Ab	Area of tank bottom (m^2)
Ad	Horizontal area facing dwon 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 ϕ 7 mm nozzle washing machine
K1	Coefficient of correction for decreasing rate of concentration in the later washing by ϕ 7 mm nozzle washing machine

K2	Coefficient of correction for the beginning by ϕ 4 mm nozzle washing machine
K0s	Coefficient of correction for initial concentration in the later washing by ϕ 4 mm nozzle washing machine
K1s	Cofficient of correction for decreasing rate of concentration in the later washing by ϕ 4 mm nozzle washing machine
K3	Coefficient of correction for washing of high viscosity in the beginning washing by ϕ 4 mm nozzle washing machine
K0sn	Coefficient of correction for initial concentration in the later washing of high viscosity adherings by ϕ 4 mm nozzle washing machine
K1sn	Coefficient of correction for decreasing rate of concentration in the Later washing of high viscosity adherings by ϕ 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)
α	FD/FW (−)
γ	water specific gravity (kg/m^3)
σ_1	Water film thickness along the vertical surface (m)
σ_2	Water film thickness on the bottom during washing (m)
μ	Coefficient of viscosity of water ($kg\ s/m^2$)
ν	Kinematic viscosity of water (m^2/s)
ϕ_1	Angle of the tank wall inclination (°)
ϕ_2	Angle of the tank bottom inclination (°)

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 ϕ 7 mm nozzle and the washing machine with ϕ 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 Qres0 and the amount of the remaining water quantity of the steady state during tank washing QDH 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;

QDH > Qres0

QDH; Remaining water quantity in the tank during washing (m^3)

Qres0; residue in the tank before washing (m^3)

1) In the case of C > Qres0/QDH

C; Concentration of the substance in the effluent

$$C = Qres0/(Q + Qres0) \quad \cdots\cdots\cdots (1)$$

Eq.(1) is rewritten as

$$Q = Qres0/C - Qres0 \quad \cdots\cdots\cdots (1')$$

Q; Quantity of the washwater(m^3)

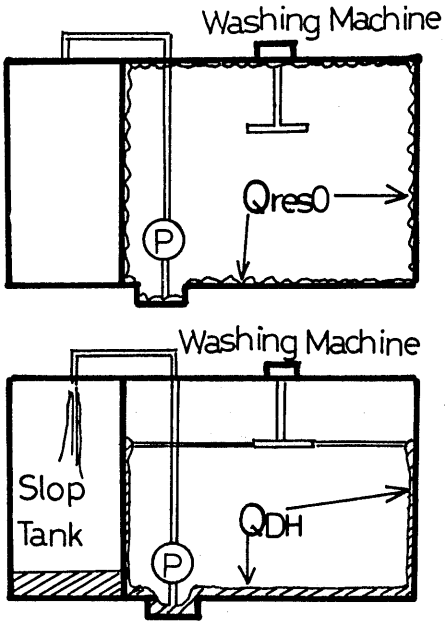
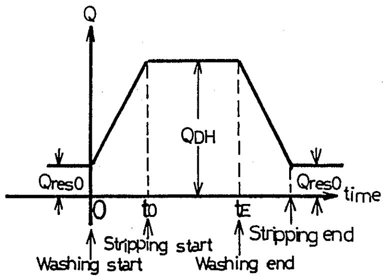
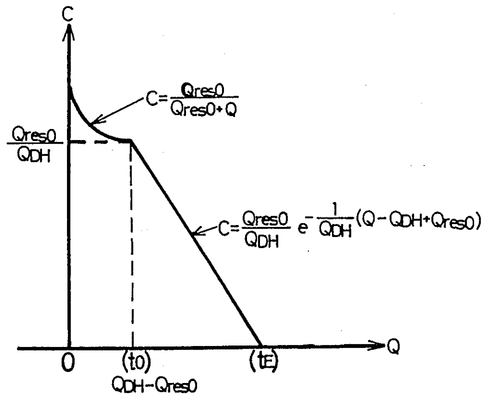


Fig.1 Washing Model



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



(b) Concentration in pumping out

Fig.2 Amount of the remaining water in the tank and the concentration in the pumping out during washing (In the case of remaining water during washing is more than the amount of residue.)

Eq.(1) is indicated from t=0 to t0 in Fig.2.(b). Residue is not discharged and only diluted.
At the steady state; [(1)(2)]

$$\frac{d\,Q_{res}}{d\,t} = \frac{-Q_{res}}{Q_{DH}} \cdot Fw \quad \cdots\cdots\cdots(2)$$

Here Qres is the residue quantity in the tank.

Fw 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;

$$\ln Q_{res} = -\frac{Fw \cdot t}{Q_{DH}} + A1 \quad \cdots\cdots\cdots(3)$$

where Al is an arbitrary constant.
Placing Fw • t=Q, Eq(3) becomes

$$\ln Qres = -Q / QDH + A1 \cdots\cdots\cdots(4)$$

Substituting Q = QDH−Qres0 and Qres = Qres0 as initial condition,

$$Qres = Qres0 \exp\left((Q - (QDH - Qres0)) / QDH \right) \cdots\cdots\cdots(5)$$

or

$$Q = QDH - Qres0 - QDH \cdot \ln\left(\frac{QDH \cdot C}{Qres0} \right) \cdots\cdots\cdots(6)$$

is obtained.

The quantity of the residue Qres and the one of the washwater in the tank QDH are indicated from t0 to tE in Fig.2(a) and the relation between C and Q are indicated from t0 to tE in Fig.2(b). In the most of the case, Eq.(6) is used. To obtain the dimensionless profile variables, Eq(6) divided by Qres0 gives [3];

$$\frac{Q}{Qres0} = \frac{QDH}{Qres0}\left(1 - \ln\left(\frac{QDH \cdot C}{Qres0} \right) \right) - 1 \cdots\cdots\cdots(7)$$

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

(2) In the case that the residue is larger than the remaining washwater quantity in the tank (QDH<Qres0).

1) And in the case of $C > (QDH/Qreso)^{1/(\alpha-1)}$.

$\alpha = FD / FW$ ($\alpha \fallingdotseq 1.1$)

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)

$$\frac{d\,Qres}{dt} = -\frac{Qres}{Qres0-(\alpha-1)Fw \cdot t}\ \alpha \cdot Fw \cdots\cdots\cdots(8)$$

where, Fw is the discharged water quantity Fd.

Eq(8) is transformed and integrated;

$$\ln Qres = \frac{\alpha Fw}{(\alpha-1)Fw} \ln(Qres0-(\alpha-1)Fw \cdot t) + A2$$

where A2 is an arbitrary constant.

Substituting t = 0, Qres = Qres0 as the initial condition;

$$Qres = \frac{(Qres0-(\alpha-1) \cdot Fw \cdot t)^{\frac{\alpha}{\alpha-1}}}{Qres0^{\frac{1}{\alpha-1}}}$$

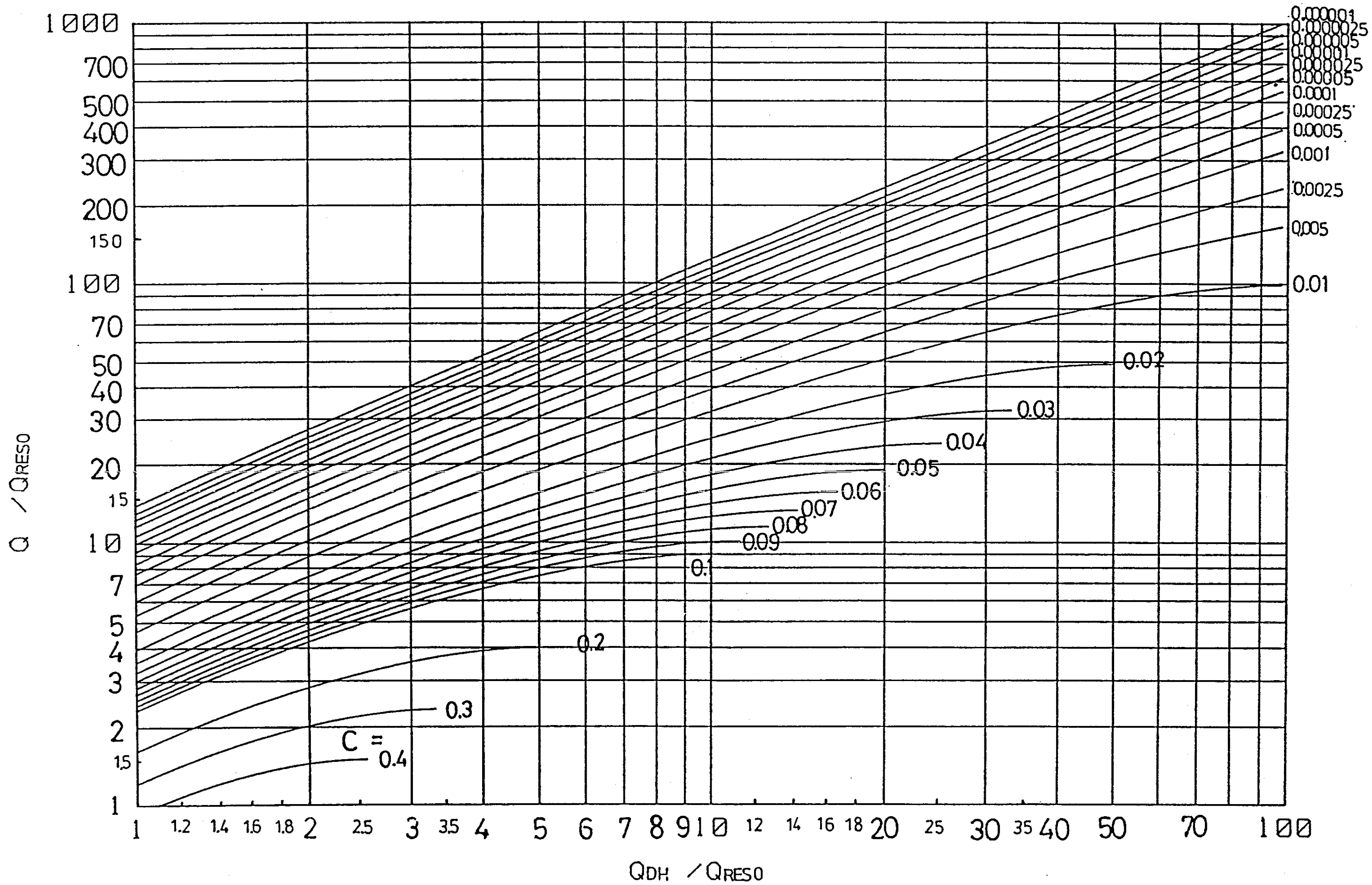


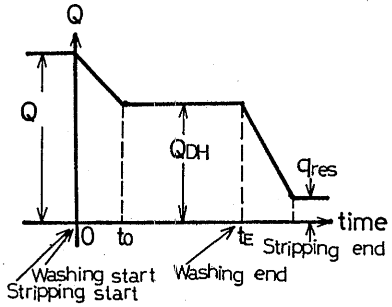
Fig.3 Q/QRESO VS QDH/QRESO

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

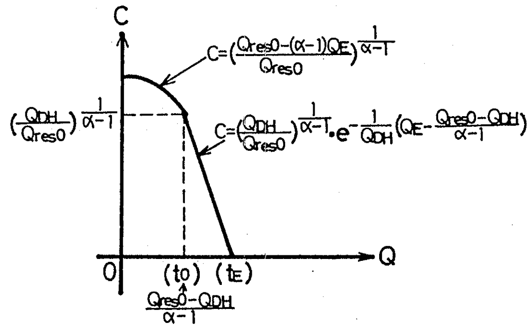
$$C = \left(\frac{Qres0-(\alpha-1)\cdot Fw\cdot t}{Qres0} \right)^{\frac{1}{\alpha-1}} \quad \cdots\cdots\cdots(9)$$

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').

$$Q = \frac{Qres0(1-C^{\alpha-1})}{\alpha-1} \quad \cdots\cdots\cdots(9')$$



(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 QDH<Qres0 and $C<(QDH/Qres0)^{1/(\alpha-1)}$.
At the steady state(in Fig.4, Q is larger than (Qres0−QDH) / (α −1)), Using Eq.(2) and initial conditions;
Q = (−QDH+Qres0)/(α −1) and Qres = QDH,

$$Qres = \frac{QDH^{\frac{\alpha}{\alpha-1}}}{Qres0^{\frac{1}{\alpha-1}}} \exp\left(-\frac{1}{QDH}\left(Q-\frac{Qres0-QDH}{\alpha-1}\right)\right) \quad \cdots\cdots\cdots(10)$$

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

$$C = \frac{Qres}{QDH} = \left(\frac{QDH}{Qres0}\right)^{\frac{1}{\alpha-1.}} \exp\left(-\frac{1}{QDH}\left(Q - \frac{Qres0-QDH}{\alpha-1}\right)\right) \cdots\cdots\cdots(11)$$

or

$$Q = \frac{Qres0-QDH}{\alpha-1} - QDH \ln\left(\frac{C}{\left(\frac{QDH}{Qres0}\right)^{\frac{1}{\alpha-1.}}}\right) \cdots\cdots\cdots(11')$$

In these cases of QDH<Qres0, 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 Qres0 is given by Qres0 = Qres(surf)+Qsl

in which Qres(surf) is a quantity of clingage residue on tank surfaces and Qsl 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

$$Qres(surf) = 1.1x10^{-4}Ad+1.5x10^{-5}Aw+4.5x10^{-4}\ L^{1/2}Ab \cdots\cdots\cdots(12)$$

For substances with viscosities between 5 and 50 mPa.S

$$Qres(surf) = 1.8x10^{-4}Ad+3.5x10^{-5}Aw+1.4x10^{-3}\ L^{1/2}Ab \cdots\cdots\cdots(13)$$

For substances with viscosities greater than 50 mPa.S

$$Qres(surf) = 8.5x10^{-4}Ad+1.1x10^{-4}Aw+4.5x10^{-3}\ L^{1/2}Ab \cdots\cdots\cdots(14)$$

As a general rule, Eq.(12) is used now [5].

Using Eq.(12) and tank shapes represented in Table 1, the relation between Qres(surf) and tank volume V are given by the regression.

$$Qres(surf) = 1.96x10^{-3} \times V^{0.671} \cdots\cdots\cdots(15)$$

Here, the tank shapes are assumed as rectangular parallelepiped.

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

Qsl 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^3)	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 HD
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 Hd
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 Bhd
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	"

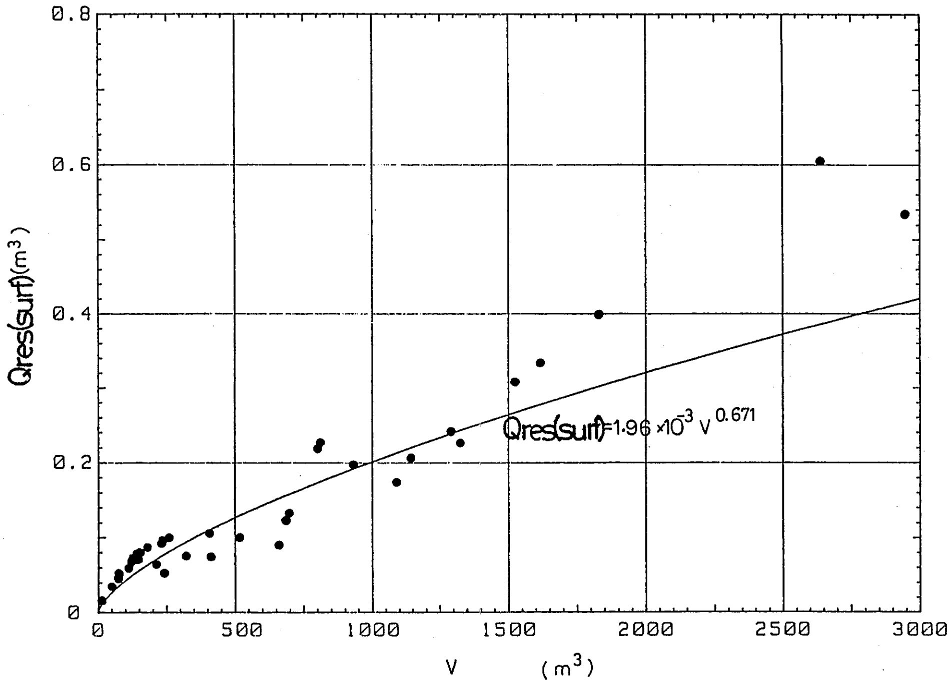


Fig.5 Relation beteen V and Qres(surf)

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.

$$QDH = Q1+Q2+Qs2 \quad \cdots\cdots\cdots(16)$$

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.

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

$\delta 1$ 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.

$$b = 4.3r \quad \cdots\cdots\cdots(18)$$

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.

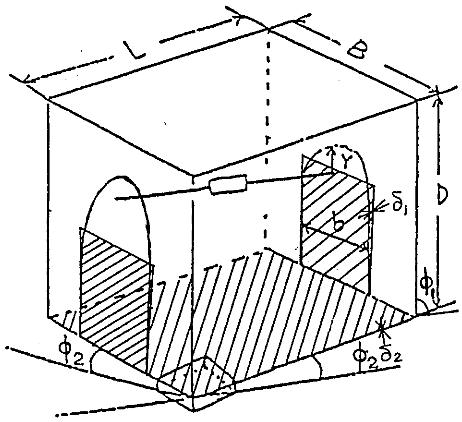


Fig.6 Remaining state on the average during tank washing

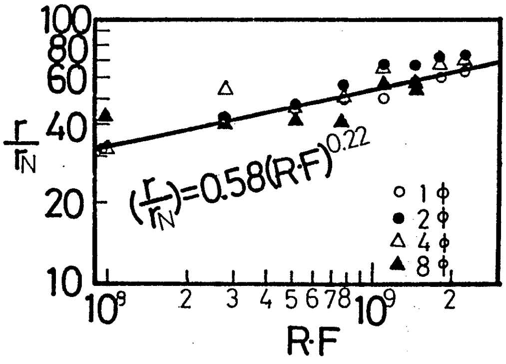


Fig.8 Relation beteen R*F and r/rN

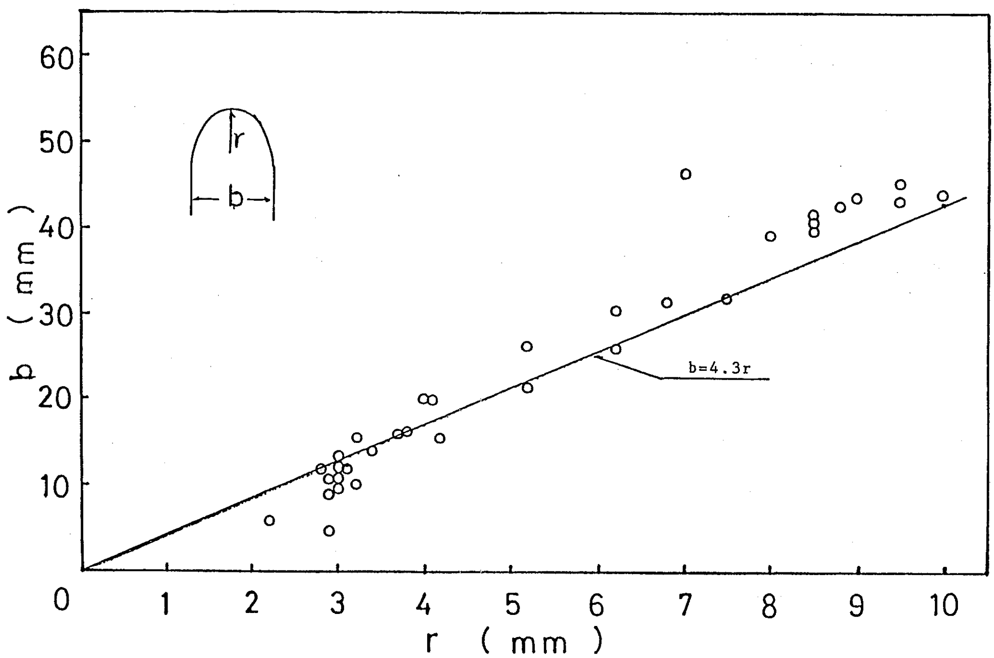


Fig.7 Relation beteen r and b

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

where $R = U \bullet rN/\nu$, $F = U^2/(g \bullet rN)$

Here U is the water jet velocity at the nozzle, rN is the radius of the nozzle, g is the gravity acceleration, and ν is keinematic viscosity of water.

$Q2 = \delta_2 \times B \times L$ ·········(20)

$\delta 2$ is the water film thickness on the tank bottm.

Falling film average thickness δ_1 and δ_2 may give as follows[7];

$$\delta_1 = \sqrt[3]{\frac{3q1 \cdot \mu}{\gamma \cdot \sin \phi_1}} \quad \cdots\cdots\cdots(21)$$

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

where q1 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°, $\delta 1$ is the film thickness by W. Nufelt[8].

Let Q1+Q2 = Q12. The relation between the tank volume V and Q12 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.

$$Q12 = 281 \times 10^{-3} \times V^{0.633} \quad \cdots\cdots\cdots(23)$$

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

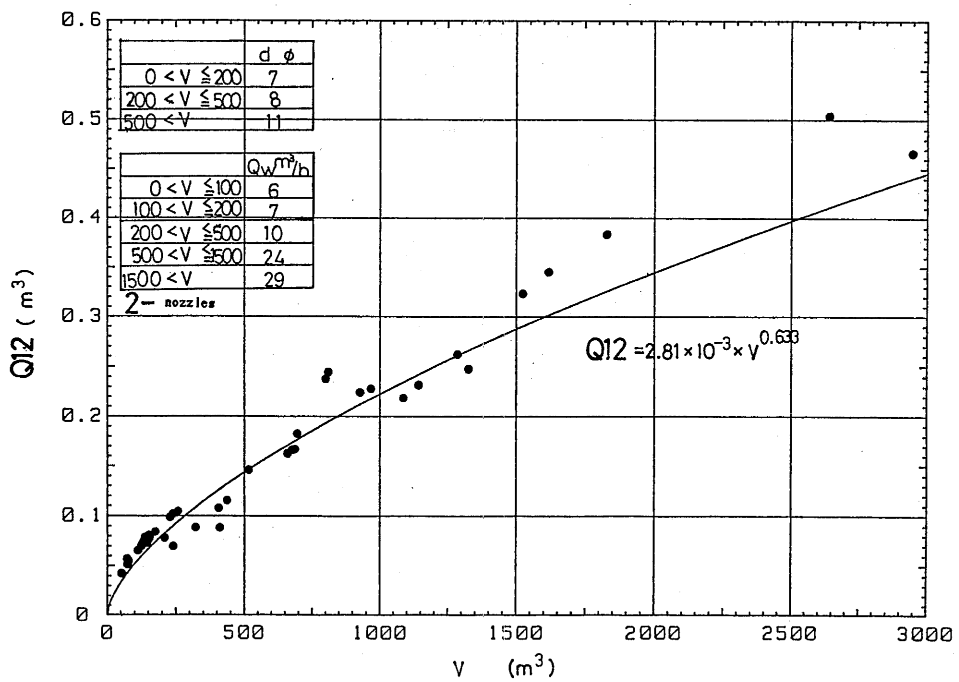


Fig.9 Relation beteen V and Q12

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 clinage 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.

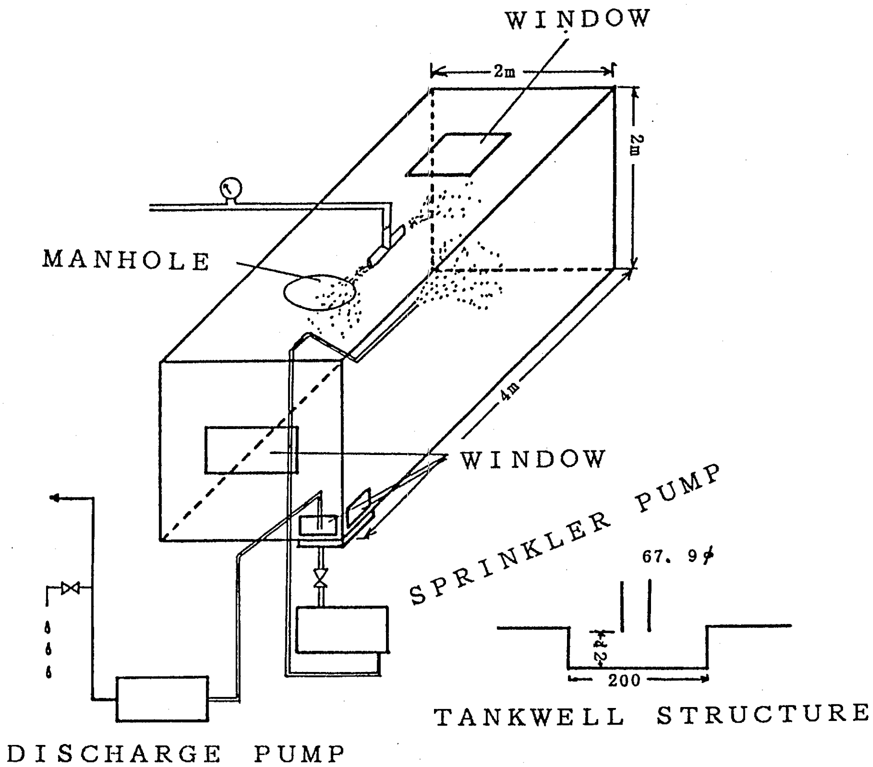


Fig.10 Test Apparatus of the Tank Model

Using the washing machine with ϕ4 mm nozzle and the ϕ7 mm nozzle, tank washing experiments were done and compared. There experiment were done after the weighing of clingage residues.

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

The residual concentration is analyzed by gaschromatogram 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 tab water affect electrical conduction, it is difficult to analyse the concentration less than about 0.01% of NaCl by electrical conduction.

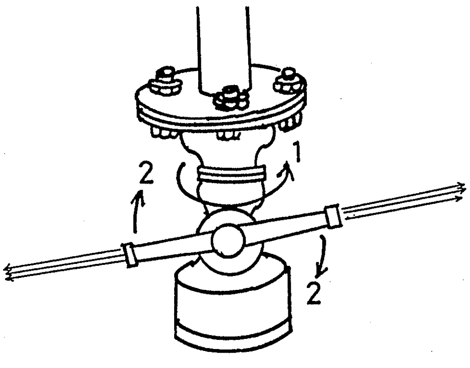


Fig.11 Movement of washing nozzle

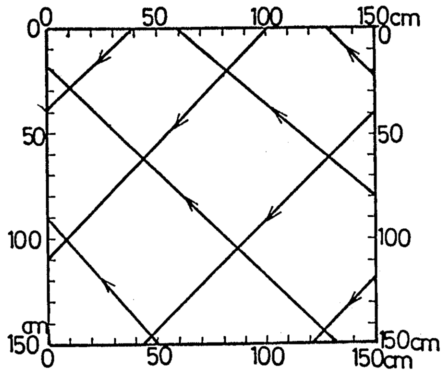


Fig.12 An Example of the Trace of Jet
(The distance between the nozzle and the test surface is 5 m. The pressure to the washing machine is 98 kpa.)

Table 2 Motion of the washing machines

Water Pressure	4 Φ Washing Machine				7Φ Washing Machine	
	Period of 1 direction	Period of 2 ditection	Time of one cycle	Quantity of used water	Period of 1 direction	Period of 2 direction
MPa	Second	Second	Minute	m^3/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 ϕ 4 mm diameter nozzle and with ϕ 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 glycole concerning tank washing. But there is much difference between glycerin and the liquid with the viscosity less than the viscosity of ethylene glycole. 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 QDH are changed. The residue in the visinity 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 begining concentration is changed. Fig.23 represents the relation between the washwater quantity and concentration when the quantity of the residue at the begining 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[6]. 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 ϕ 4 mm nozzle machine examined by the water jet trace.

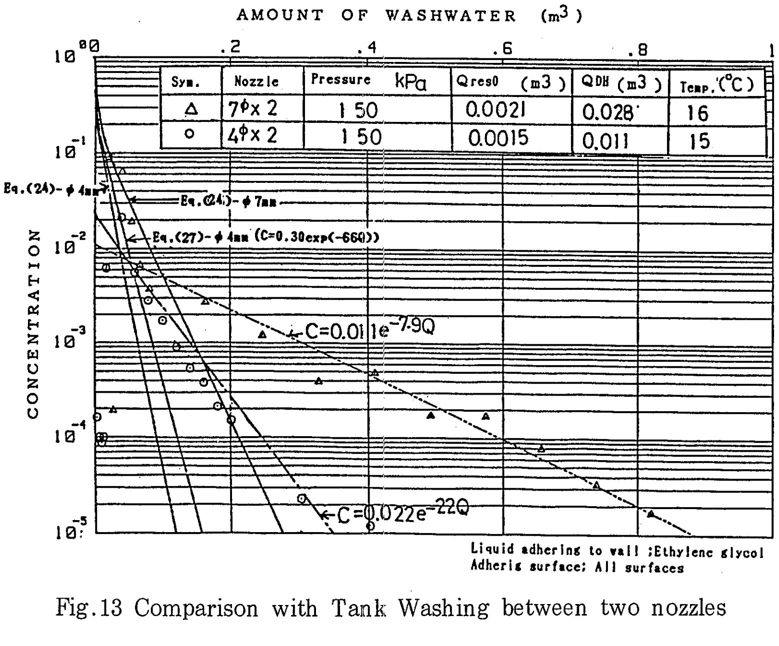


Fig.13 Comparison with Tank Washing between two nozzles

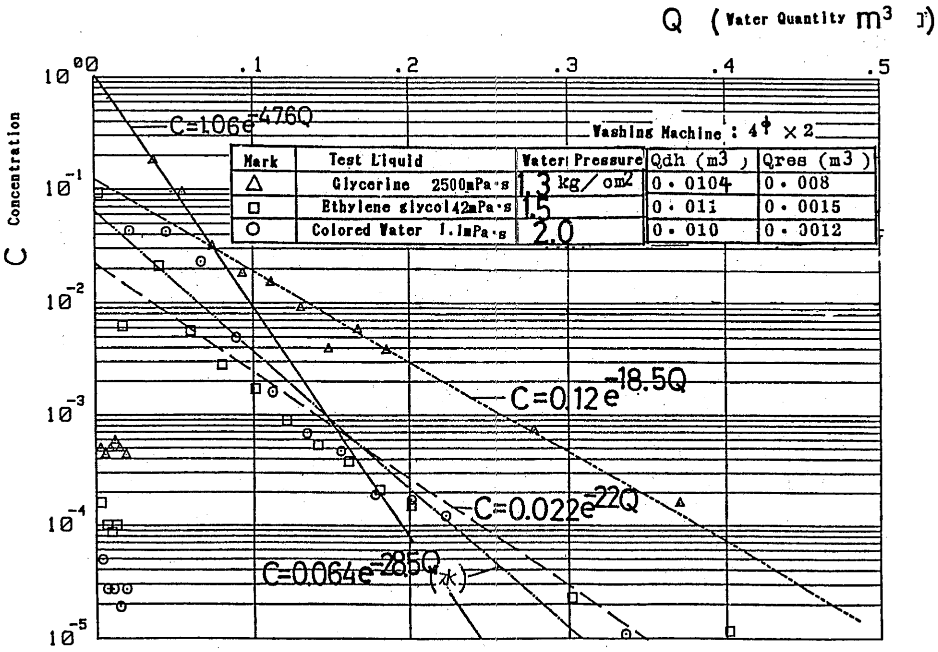


Fig.14 Washing with the test liquids of different viscosity
(Liquids adhering to all surfaces in the tank)

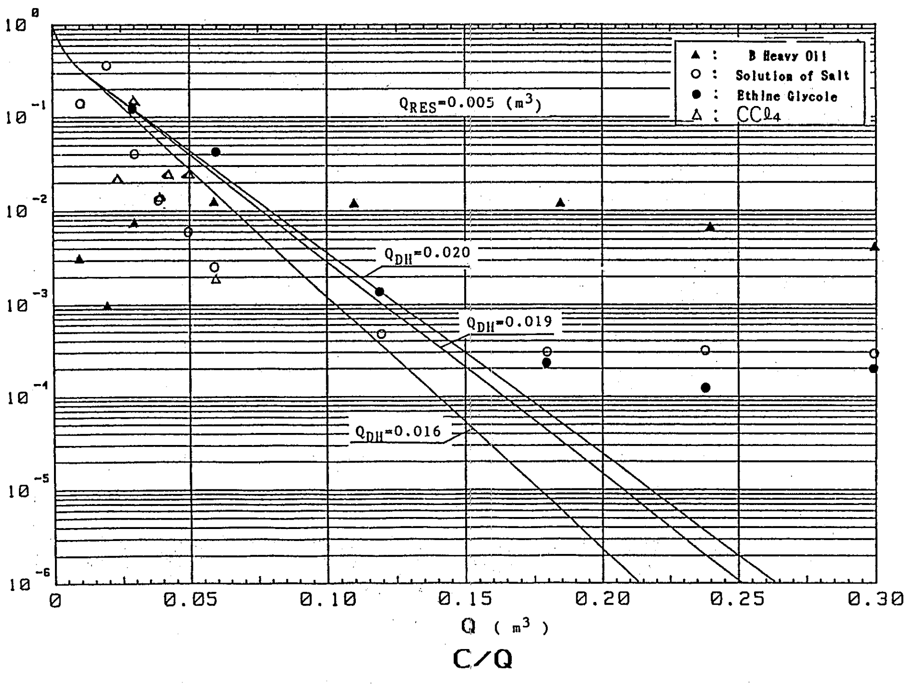


Fig.15 Tank washing result with various kinds of liquid(ϕ 7mm nozzle)

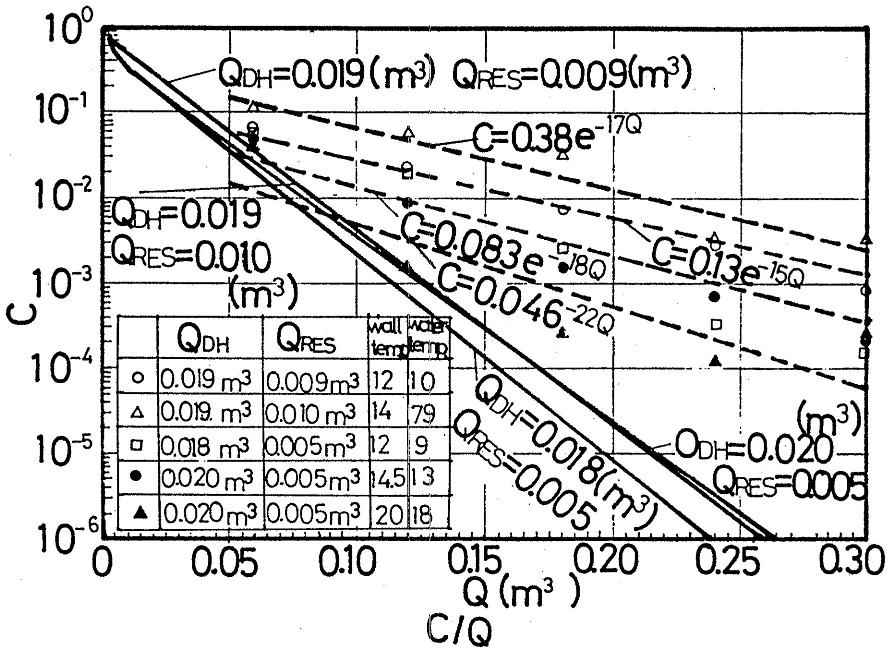


Fig.16 Result of the tank washing test using model tank and glycerin (ϕ7mm nozzle, in autumn)

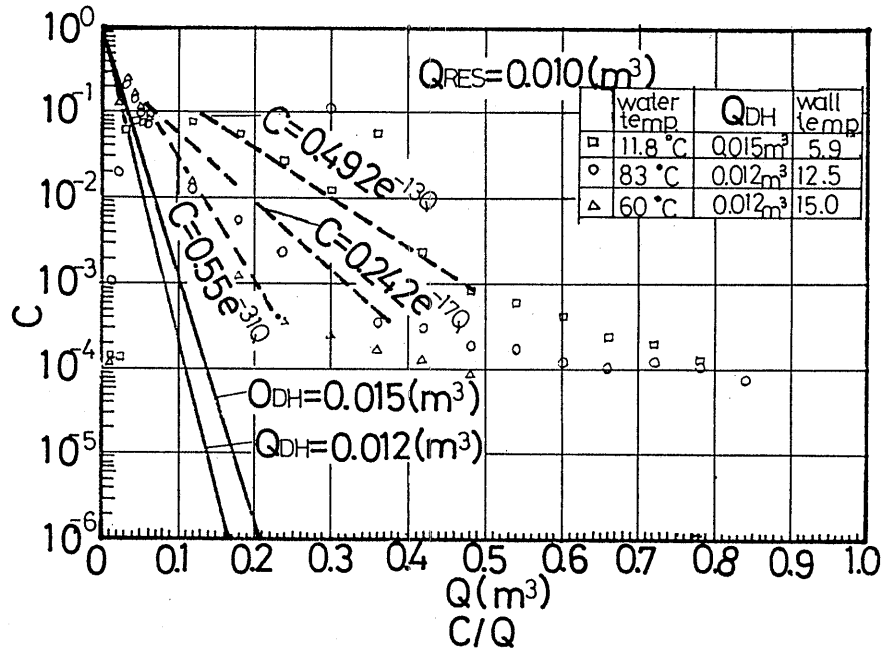


Fig.17 Result of the tank washing test using model tank and glycerin (ϕ7mm nozzle, in winter)

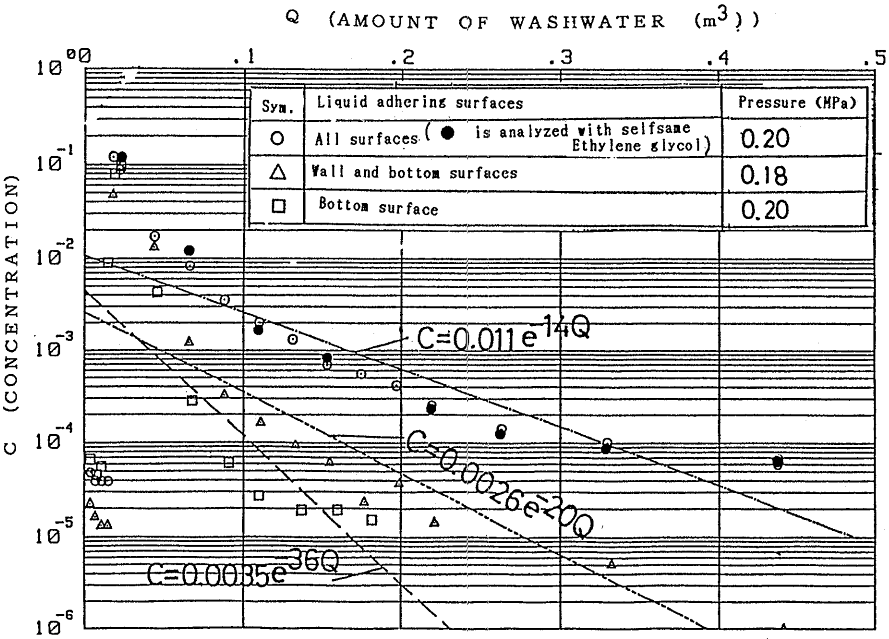


Fig.18 Comparison with Tank Washing among the different Surfaces the liquid adhering to

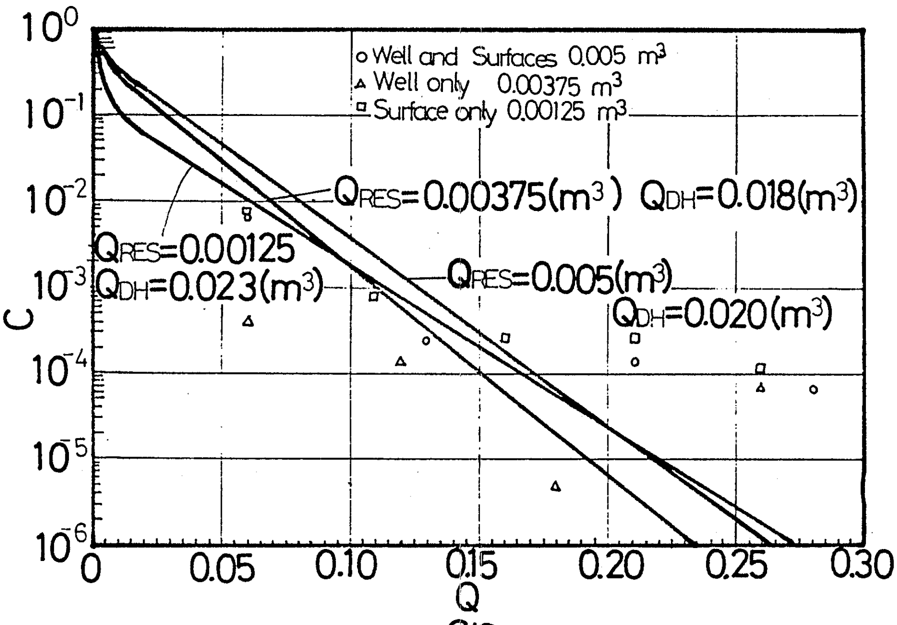


Fig.19 The tank washing result concering the parts on which the residue remains

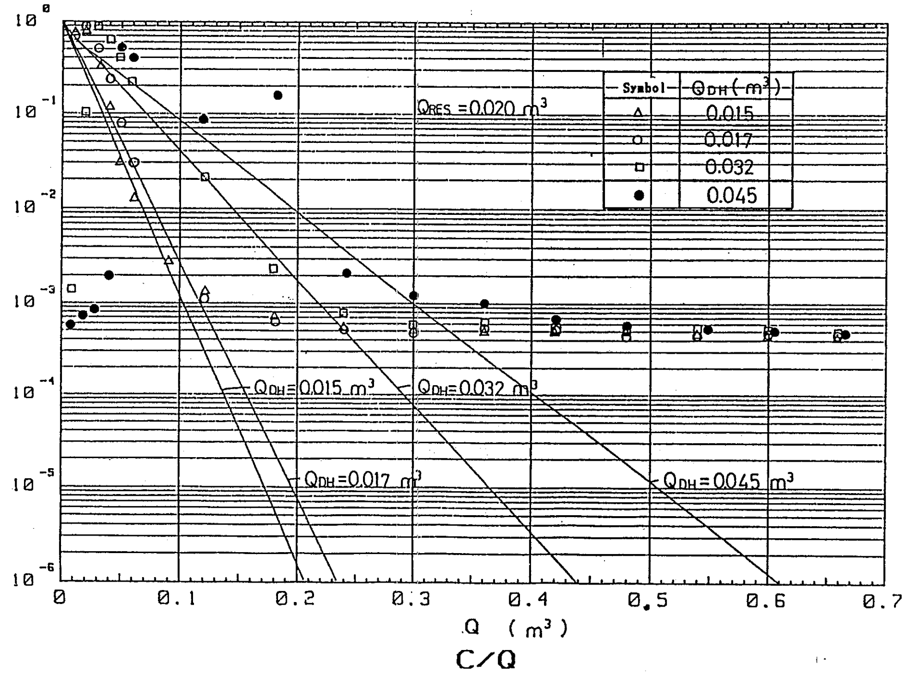


Fig.20 Tank washing test result with QDH (Water viscosity 1.3mPas)

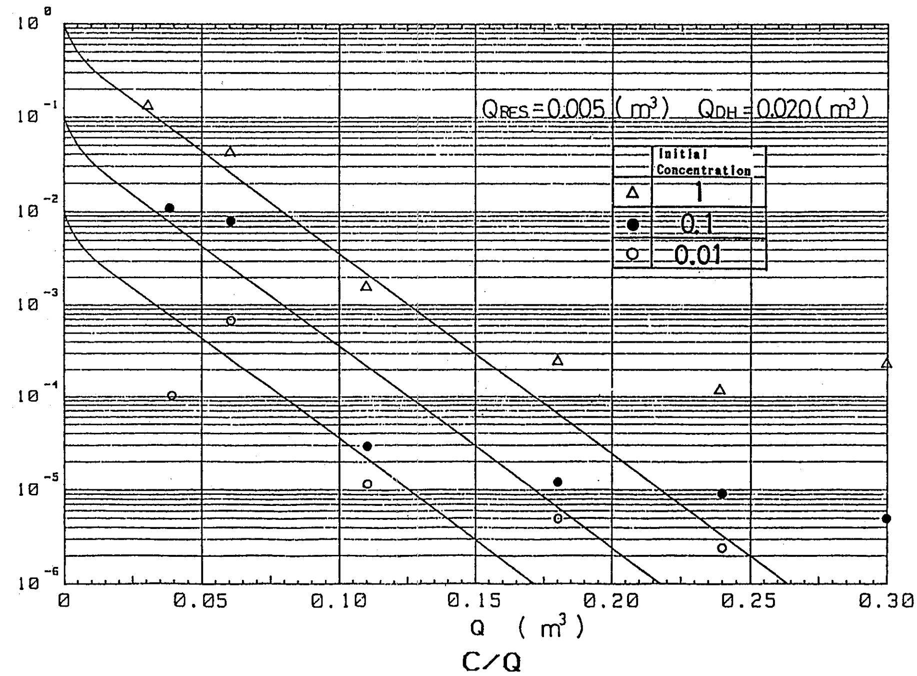


Fig.21 Tank washing when the initial concentration is changed
(Test Liquid;Ethylene Glycole)

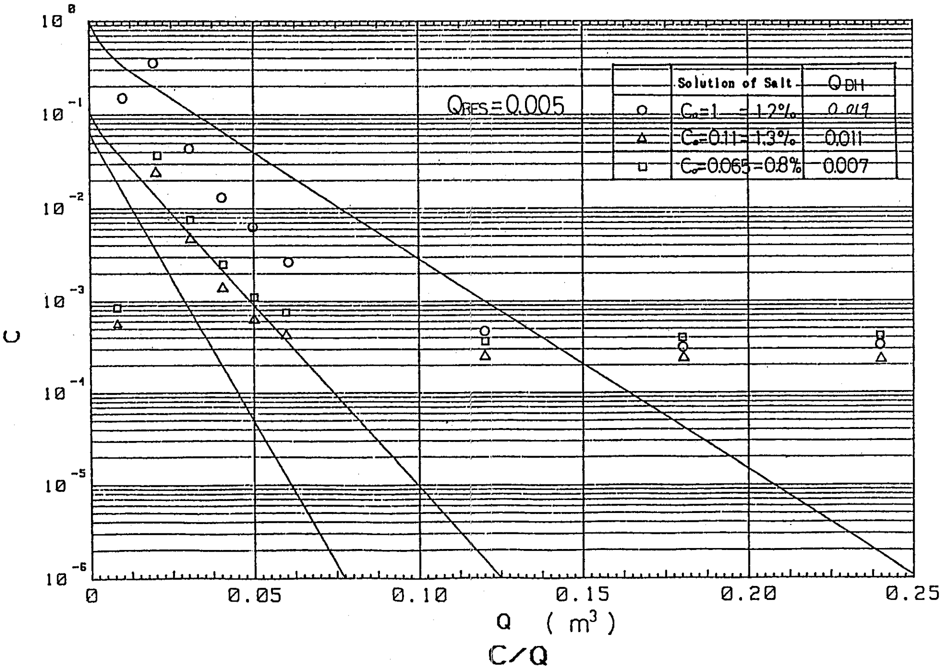


Fig.22 Tank washing when the initial concentration is changed
(Here C=1 is settled for the 12% Solution of Salt)

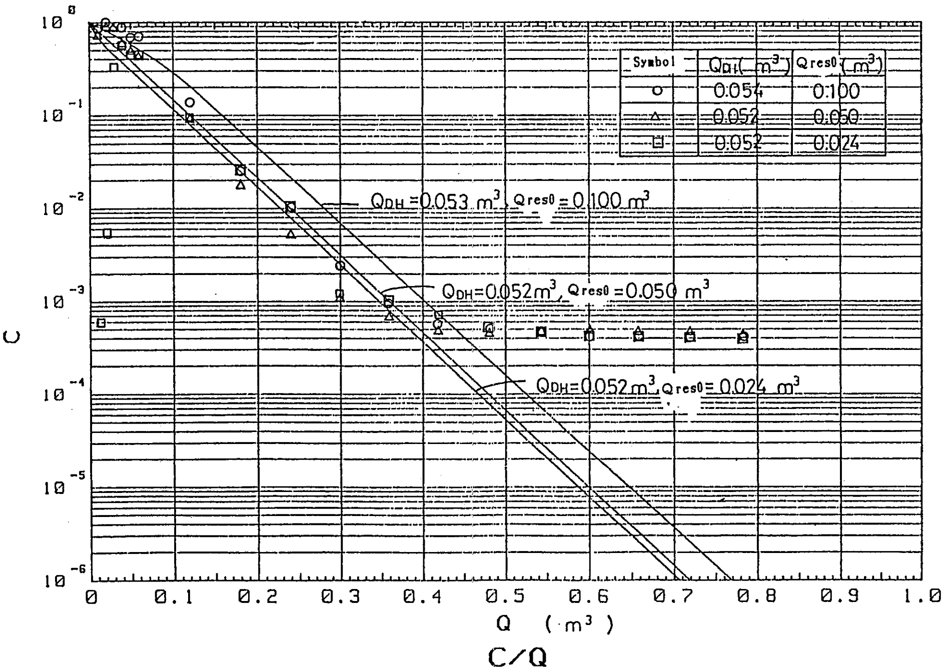


Fig.23 Washing in the case of different Qres0

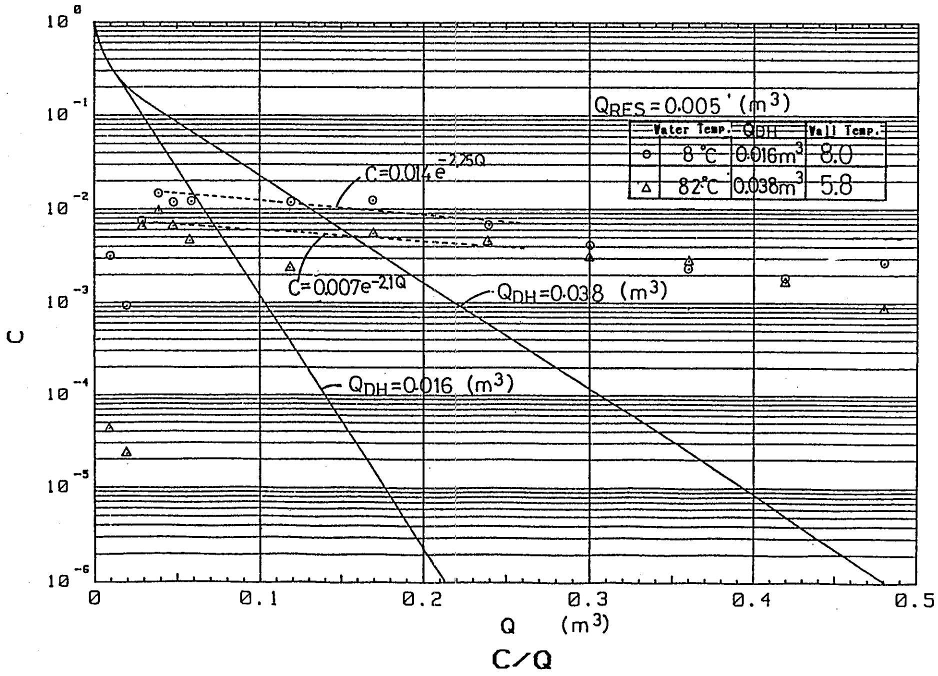


Fig.24 Tank washing test result with insoluble liquid in water (B Heavy oil)

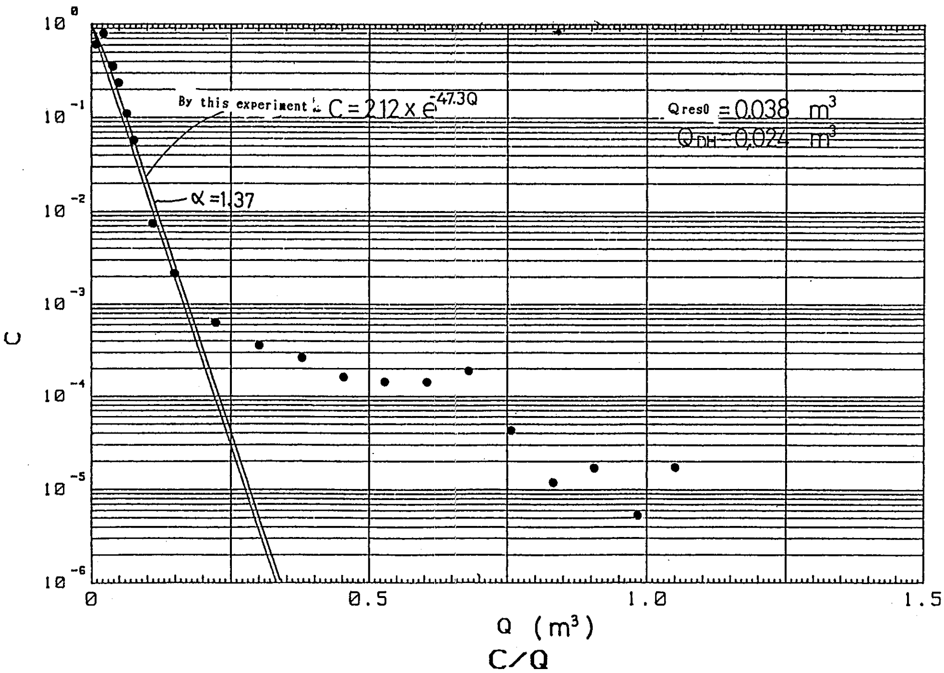


Fig.25 Washing in the case of large Qres0

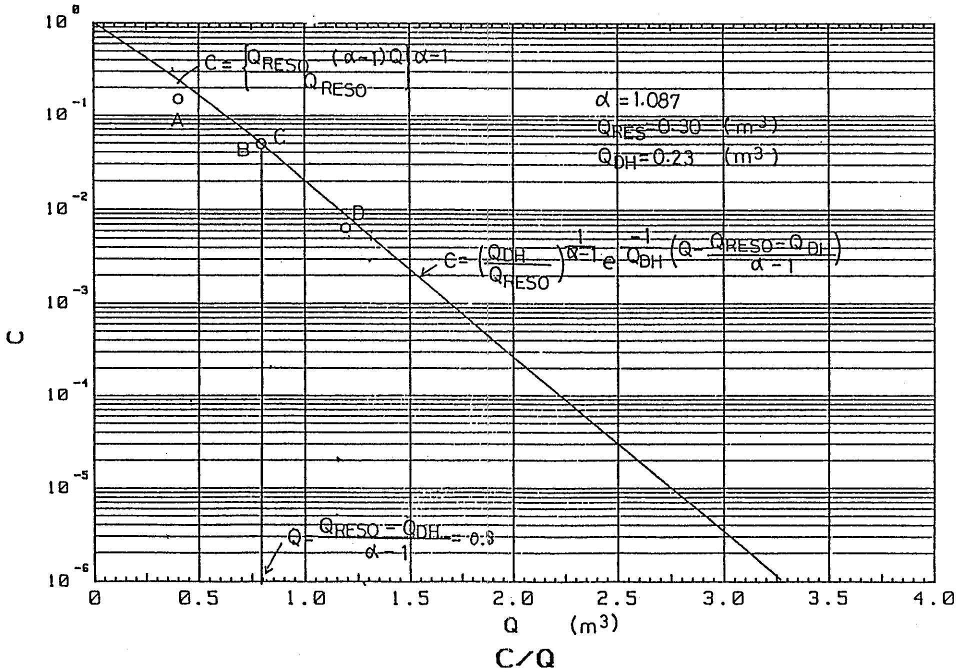


Fig.26 Presumption of α

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 = al+bl・logx , where the quantity of the adhering to the surfaces per unit area is y and the viscosity is x. Coefficients al and bl are shown in Table 3.

Table 3 Coefficient of the lines in Fig.

Number of lines in Fig.31	Low viscosity		High viscosity	
	a]	b]	a]	b]
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

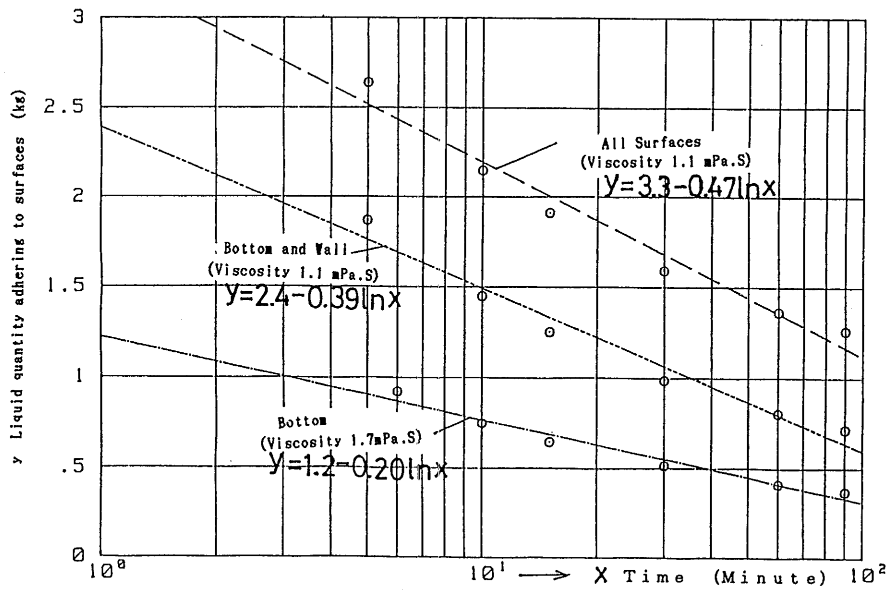


Fig.27 Quantity of water adhering to the surfaces afetr sprinkling (Trim 2°,List 2°)

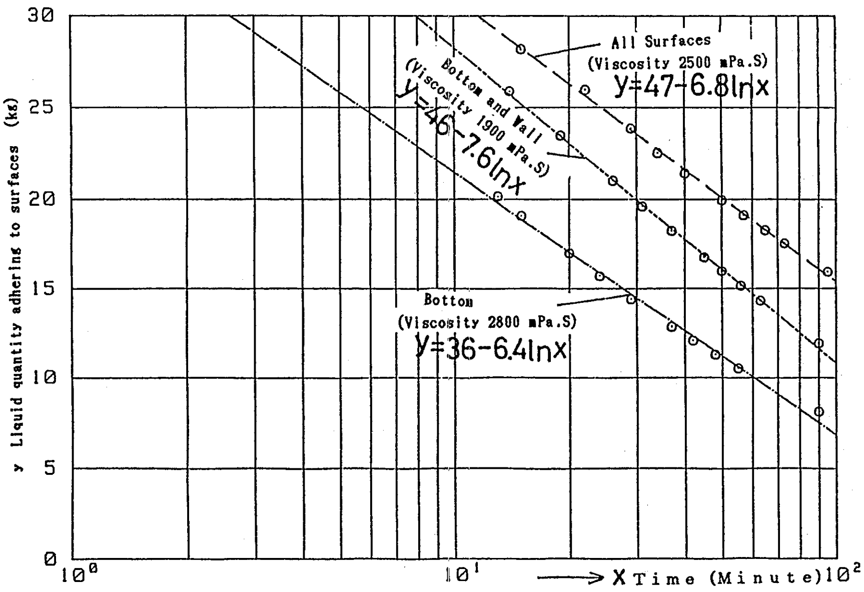


Fig.28 Quantity of glycerin adhering to the surfaces after sprinkling (Trim 2°, List 2°)

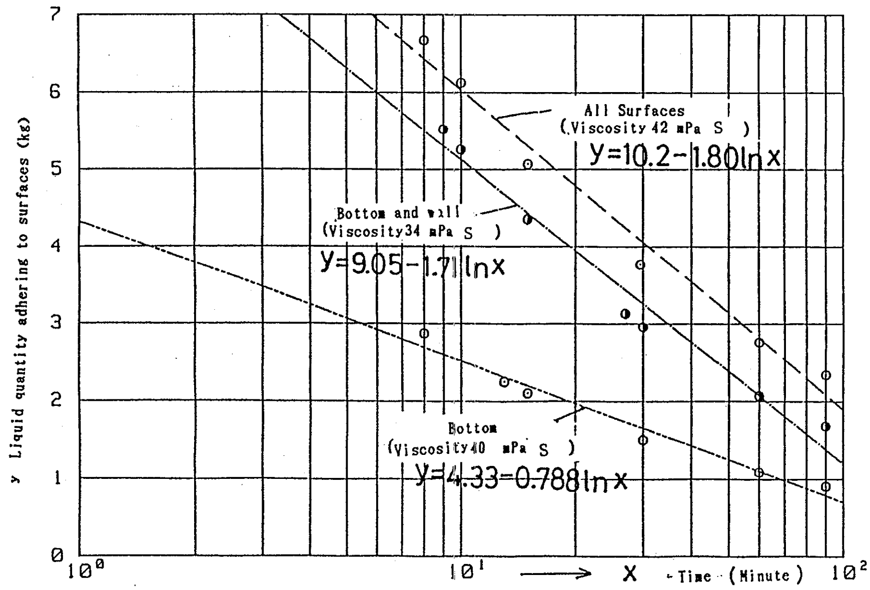


Fig.29 Quantity of Ethylene glycol adhering to the surfaces after sprinkling (Trim 2°, List 2°)

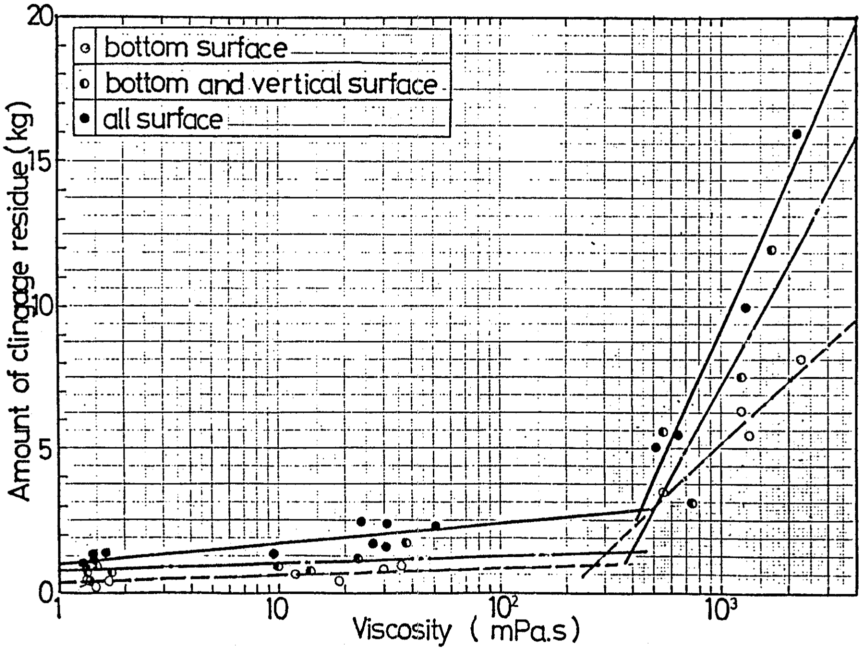


Fig.30 Amount of Clingage residue 90 minutes after sprinkling

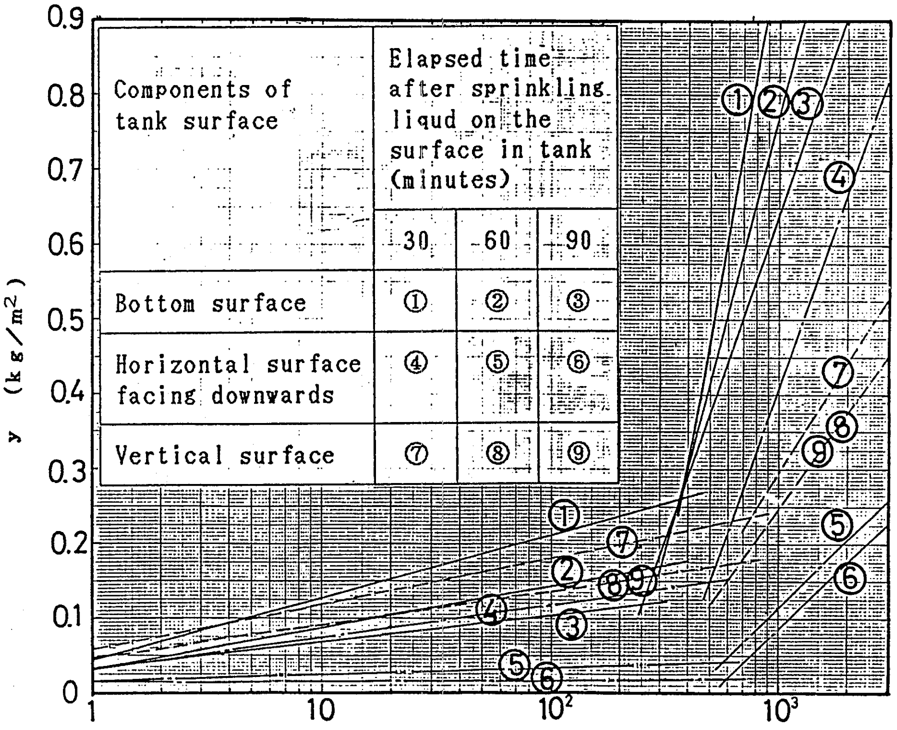
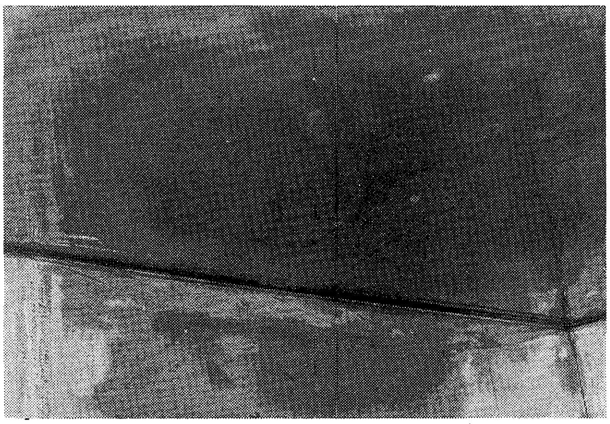
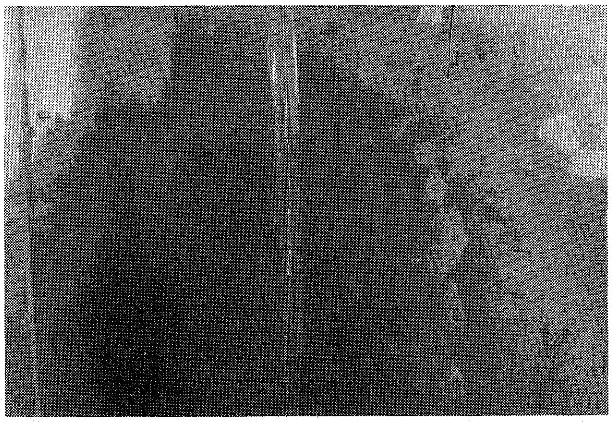


Fig.31 Residual quantity per unit area



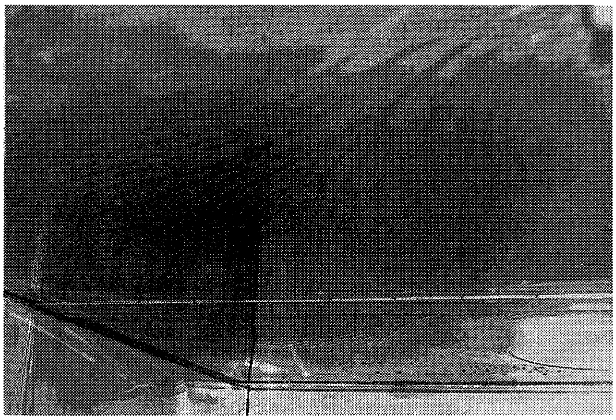
Underdeck



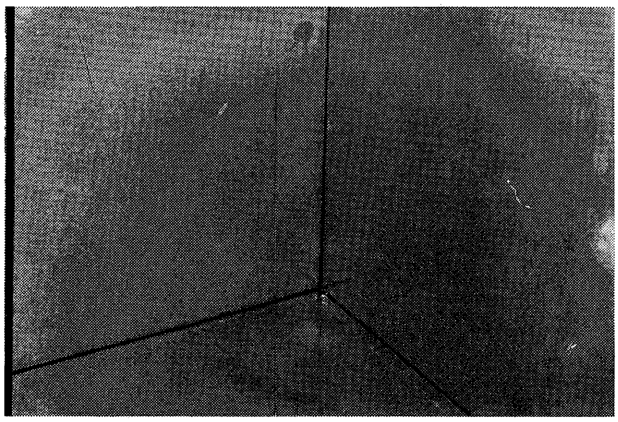
Tank walls

Tank Bottom

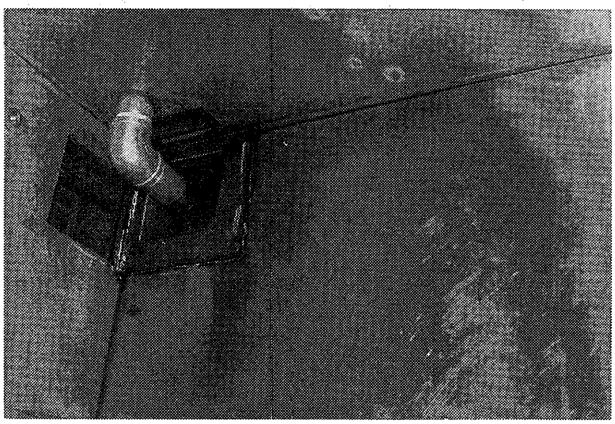
Photo.1 Appearance of the red colored water adhering to the surfaces after 90 minutes from sprinkling



Underdeck

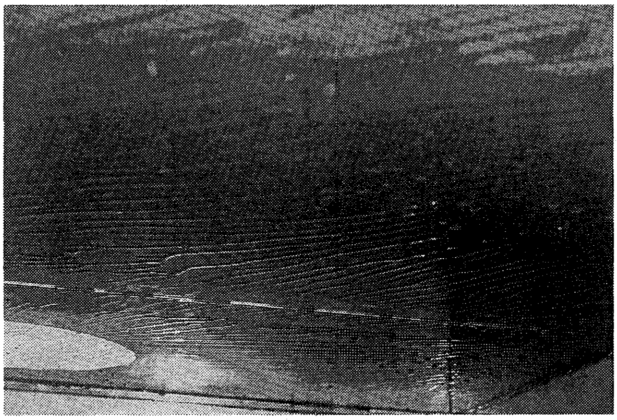


Tank walls

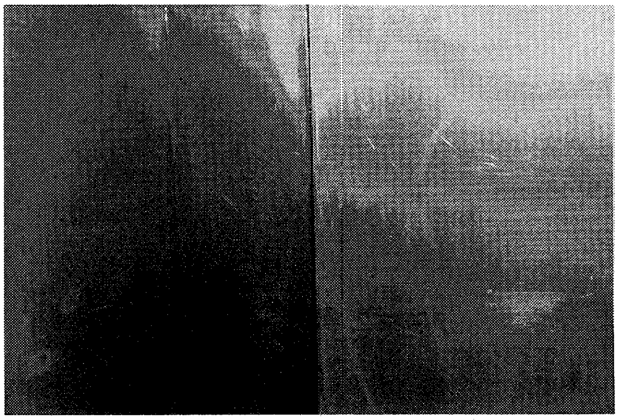


Tank Bottom

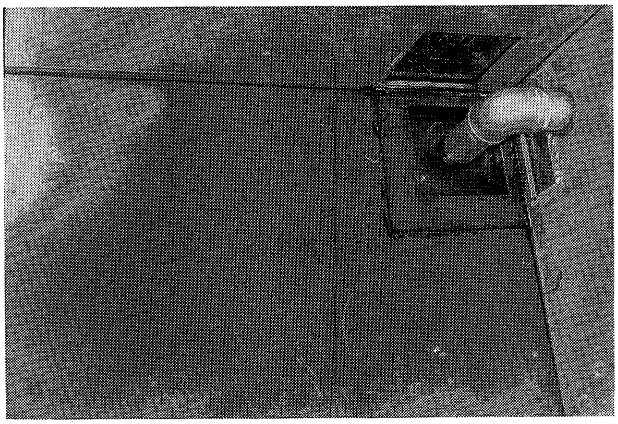
Photo.2 Appearance of the red colored Ethylene glycol adhering to the surfaces after 90 minutes from sprinkling



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 Qtotal is expressed:

Qtotal = Q0+Q1+Q2+Qs2+Q3+Q4

In which. Q0 is the water quantity from the nozzle to the walls,

Q1 is the water quantity on the vertical surfaces,

Q2 is the water quantity on the bottom surface,

Qs2 is the remaining water quantity in the vicinity of the tank well,

Q3 is the water quantity flows backward from discharged pipe,

Q4 is the water quantity flows from washing machine.

QDH = Q1+Q2+Qs2

QDH = Qtotal−Q0−Q3−Q4

Qtotal, Q3 and Q4 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.

Qtotal is 0.0225m^3, Q3 is 0.0015m^3, Q4 is 0.0024m^3.

Q0 is caluculated:

$Q0 = \pi/4 \cdot d^2 L = 0.0002\ m^3$

Then QDH becomes $18.4\times10^{-3}\ m^3$.

4. COMPARISON AND DISCASSION 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 ϕ 4 mm nozzle washing machine and by the ϕ 7 mm one after the test liquid is made to adhere to all surfaces in tank. The result of the ezperiment of Fig.13 is considered here.

Let's consider the region of being washed in the case of almost statecally ($Q>0.05m^3$), for the ϕ 7mm×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^3)

In the case of ϕ 4mm×2 and $Q=0.02m^3$, 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).

$$C = \frac{Qres0}{QDH} \cdot \exp\left(-\frac{Q-QDH+Qres0}{QDH}\right) \quad \cdots\cdots\cdots(24)$$

QDH; Remaining quantity during washing in the tank

Qres0; Clingage residue at the begining

In the case of $Q<0.05\ m^3$ with ϕ 7 mm nozzle and in the case of $Q<0.02\ m^3$ with ϕ 4 mm, Eq(24) agrees with the experimental results. But when C becomes thiner, Eq(24) gets out of the experimental result, In Fig.13, the inclination of the concentration curve of discharged washing water($\triangle \log C/\triangle Q$) is proprotional to $-1/QDH$.

Let's the discrepancy from this inclination be K, and the concentration inclination during washing be 1/(K QDH) and caluculate from the result. In the case of ϕ 7 mm ×2, as QDH is 0.028 m^3;

$1/0.028K = 7.9$

therefore, $K = 4.5$

In the case of ϕ 4 mm ×2, as QDH is 0.011 m^3,

$1/0.011K = 22$

therefore $K = 4.1$

It is considered that washing efficiency decreases as the K incresses. Between ϕ 7 mm and ϕ 4 mm, there is little difference in washing efficency. Although there is much effect with QDH, at the later period of low concentration, the gradient $\frac{\triangle \log C}{\triangle Q}$ of the curve Q−C of the experimental result of ϕ 4 mm is as 2.8 times large as one of ϕ 7 mm. Necessary quantity of washwater decreases with decreasing diameter of washing nozzle. However if the washwater in the same pipe line is used for both the washing and the power to move washing machine, it is difficult to move nozzle smoothly in the case of small diameter nozzle. Because it is insufficiency of the momentum. According to the different viscosety of liquids which adhere to tank surface, from Fig, 14, in the case of glycerin of high viscosity;

$C = 0.12\exp(-18.5Q)$

is given and in the cases of low and middle viscosity,

$C = 0.064\exp(-28.5Q)$

$C = 0.022\exp(-22Q)$

are given respectively. In the case of high viscosity, the efficiency of washing decreases. From the results described above, it is tried to estimate the quantity of necessary water to wash tank. If it is assumed that the water is homogeneously mixed in the tank during tank washing, the concentration in the effluent C is given by the expression.

$C = Qres0/(Q+Qres0)$

When $Q>QDH-Qres0$; Eq.(24) is used.

$$C = \frac{Qres0}{QDH} \cdot \exp\left(-\frac{Q-QDH+Qres0}{QDH}\right) \quad \cdots\cdots\cdots(24)$$

On the other hand, fron the experimental result, in the region almost steady region $C<10^{-2}$, the relation between the concentration and the amount of used water is expressed as

$$C = a2 \cdot \exp(-b2 \cdot Q) \quad \cdots\cdots\cdots(25)$$

then a2 and b2 obtained by the experiment, in the case of ϕ 7 mm washing machine.

$a2 = 0.011, \quad b2 = 7.9$

are given.

Substitution of $QDH = 0.028$ m^3 and $Qres0 = 0.0021$ m^3 of the data of expetiment into Eq.(24) gives

$C = 0.19\exp(-36Q)$

Here, coefficients K0 and K1 are given by

$K0 = a2/(Qres0/QDH \cdot \exp((QDH-Qres0)/QDH)$

$K1 = b2/(1/QDH)$

In the case of ϕ 7 mm washing machine, K0 and K1 becomes

$K0 = 0.058$

$1/K1 = 1/4.6$

In Fig. 13, at the begining region, line Eq.(24)−7 represents the relation between C and Q by Eq.(24) about ϕ 7 mm nozzle washing machine. And for the later half, the relation can be represented by Eq.(25).

Eq.(25) may be modified by the follwing expression,

$$C = K0 \cdot Qres0/QDH \cdot \exp(\ (QDH-Qres0)/QDH) \cdot \exp(-Q/K1 \cdot QDH) \quad \cdots\cdots\cdots(26)$$

The boundary between Eq.(24) and Eq.(26) is given as follows.

$C = Qres0/QDH\ \exp(\ (QDH-Qres0/QDH)\ \exp(-K1 \cdot \ln K0/(1-K1)\ )$

$Q = K1 \cdot QDH \cdot \ln K0/(1-K1)$

Then, the experimental results of the washing machine are considered. When QDH is $0.011m^3$ and Qres0 is $0.0015m^3$, Eq.(24) is plotted by Eq.(24)−4 in Fig.13. It deviates downwards little from the experimental result. From the experimental results,

at the begining region; $C = 0.30\exp(-66Q)$

at the latter region; $C = 0.022\exp(-22Q)$

are given. At the begining region,

$$C = Qres0/(K2 \cdot QDH) \cdot \exp(-(Q-K2 \cdot QDH+Qres0)/K2 \cdot QDH) \cdots\cdots\cdots(27)$$

K2 is the coeffiecient which express the effectiveness of the washing of begining region.

$K2 = (1/QDH)/66 = 1.4$

The plofile calculated by Eq.(27) plotted with Eq.(27)−4 in Fig.13.

At the latter region,

$$C = K0s \cdot Qres0/QDH \cdot \exp((QDH-Qres0)/QDH)\ \exp(-Q/(K1s \cdot QDH)) \quad \cdots\cdots\cdots(28)$$

$K0s = 0.069$

$K1s = 4.1$

are given.

Next, the viscosity of clingage residue is considered here.

From Fig.14, considering the effect of the washing in the care of the different viscosity, there is little difference in it between the ethlene glycole (middle viscosity) and the water (low viscosity), but it becomes lower in the care of the glycerine (high viscosity). The washing about the clingage of different viscosity is considered similary in the care of the comparison of the diameter of the washing nozzle. From the result of washing test about high viscosity glycerin, at the begining washing time,

$C = 1.06\exp(-47.6Q)$

at the later washing time,

$C = 0.12\exp(-18.5Q)$

are given, and it is expressed by the equation, at the beginning region;

$$C = \frac{Qres0}{K3 \cdot QDH} \cdot \exp\left(-\frac{Q - K3 \cdot QDH + Qres0}{K3 \cdot QDH}\right)$$

$K3 = 2.0$

This is considered the product of the factor $K2 = 1.4$ reduced by making the nozzle diameter smaller and the factor 1.4 of the reduced washing efficiency by the viscosity.

At the later part,

$$C = K0sn \cdot \frac{Qres0}{QDH} \cdot \exp\left(\frac{QDH - Qres0}{QDH}\right) \cdot \exp\left(\frac{-Q}{K1sn \cdot QDH}\right)$$

$K0sn = 0.11 \quad K1sn = 5.2$

are given.

In the case of the tank washing by the prevailing washing machine, until about 0.5% residual concentration, the relation between concentration and washwater agrees with the ideal mixing model. But after that, in the case of the concentration less than about 0.5%, the washing efficiency decreases.

Then the recirculation washing is recomended at the later washing.

Here the case of $QDH = 0.085\ m^3$ and $Qres0 = 0.074m^3$ is considered. At first, tank is washed continiously and washwater is discharged until the concentration becomes down to 0.5% After that, recirculation washing is done. In Fig.32, line ABC is for the washing by continiously pumping out slops.

In the case of the tank washing by recirculation, it is more effective if the washwater is stripped in the middle of the washing. If to do so, the C−Q curve becomes CEG. The more time the washwater is stripped completely, the cleaner comes the tank. If the washing is done at the begining as curve ABH shown in Fig.32, it is not so effective compared with the washing by continiously pumping by continiously pumping out slops shown as line ABC.

4.2 Copmarison and Discussion of Results of Clingage Residues.

From Fig.30 the formulas to calculate the clingage residues are obtained concerning the different viscosity. In the cases of 1.5 mPa.s of water for low viscosity, 22 mPas of ethlene glycol for middle viscosity and 1300 mPa.s of glycerin for high viscosity, the amount of clingage residue on tank surfaces are estimated. The amount of clingage residue to each tank surface is obtained as follows.

$Q_d = Q_T - (Q_W + Q_b)$

$Q_W = (Q_W + Q_b) - Q_b$

$Q_b = Q_b$

Q_T: amount of clingage residue to all surface

Q_d: amount of clingage residue to horizontal area facing downwards

Q_W: amount of clingage residue to vertical area of tank

Q_b: amount of clingage residue to area of tank bottom.

Q_T, $(Q_W + Q_b)$ and Q_b are measured.

The formulas corresponding to Eqs.(12),(13),(14) are obtained from the result of the model tank test as follows. In the case of the 90 minutes later after sprinkling;

At 1.5mPa.s;

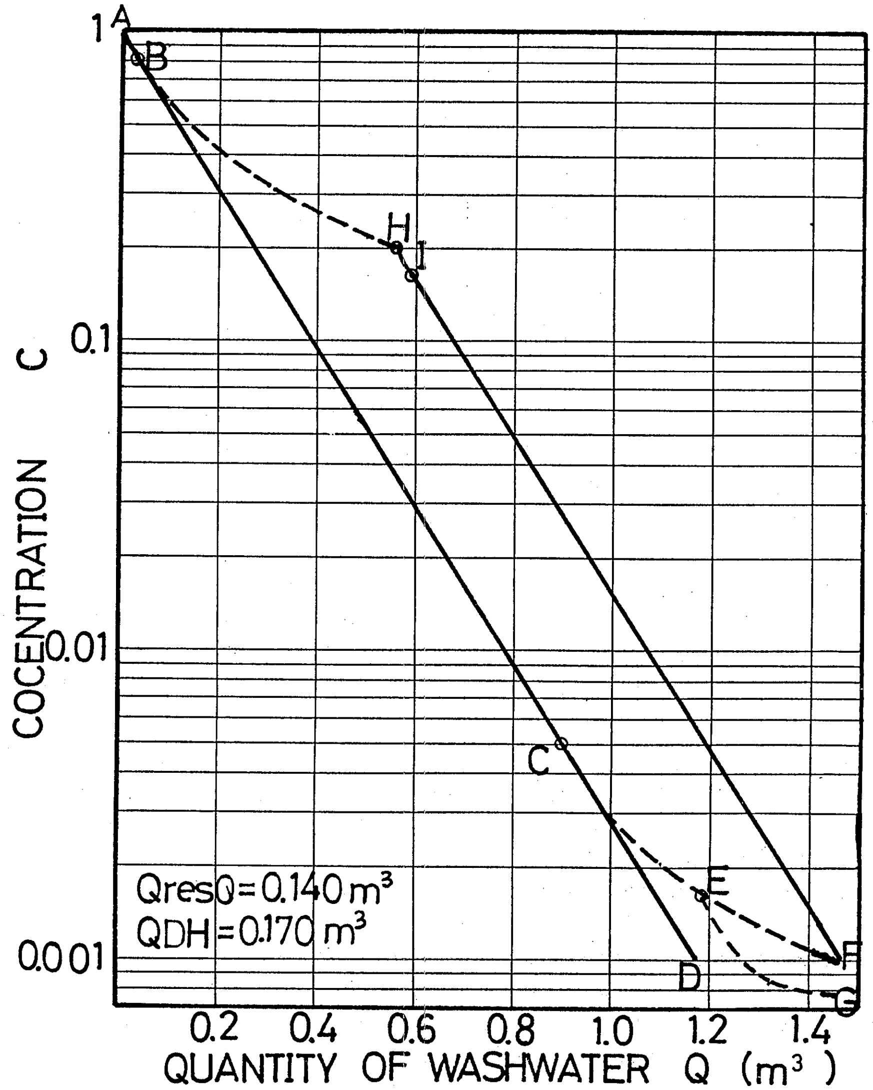


Fig.32 Comparison between continious washing and recirculating washing

Qres(surf) $= 2.5\times10^{-5}$ Ad$+2.1\times10^{-5}$ Aw$+1.9\times10^{-5}$ $L^{1/2}$ Ab ·········(12')

At 22 mPa.s;

Qres(surf) $= 1.1\times10^{-4}$ Ad$+2.9\times10^{-5}$ Aw$+3.1\times10^{-4}$ $L^{1/2}$ Ab ·········(13')

At 1300 mPa.s;

Qres(surf) $= 8.5\times10^{-4}$ Ad$+1.1\times10^{-4}$ Aw$+2.3\times10^{-4}$ $L^{1/2}$ Ab ·········(14')

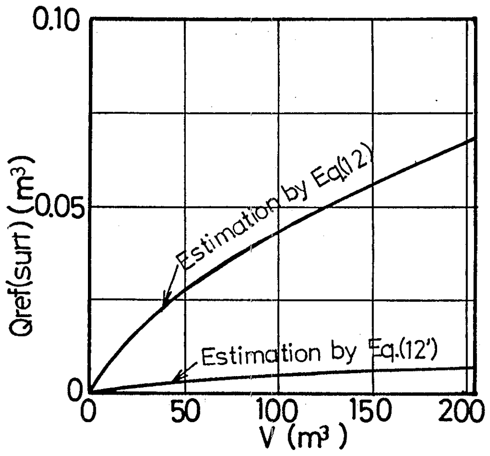


Fig.33 V—Qres(surf)

These equations give smaller Qres(surf) than Eqs. (12),(13),(14).

Fig.33 represents the difference in Qres(surf) between by Eq.(12) and by Eq.(12'). This is estimated using Table 1. V is tank volume. It is necessary to confirm these equations by the board test. However, as the efforts have been made to minimize the residual cargo on board, amount of clingage residues seemes to become less now.

Next, the relation between the temperature of the test liquid and amount of clingage residues was considered. The liquid temperature changed from 6℃ to 38℃ through the year. From Fig.30, the viscosity and the amount of clingage residue per unit area corresponding to these temperatrres are shown in the table 4. Concerning the water of low viscosity and ethylene glycole, the change of the amount of clingage residue by the season is small but concerning the glycerin of high viscosity, the change by season is large.

Table 4 Comparison with the amount of liquid adhering to the tank surfaces between 6℃ and 38 ℃ (Trim=List=2°)

Liquid	Adhering surfaces	6°C	38°C
Water	(Viscosity)	(1.7 mPa S)	(1.1 mPa S)
	Underdeck	0.041 kg/m²	※ 0.031 kg/m²
	Wall	0.018 〃	※ 0.019 〃
	Bottom	0.041 〃	※ 0.038 〃
Ethylene glycol	(Viscosity)	(44 mPa S)	(9.2 mPa S)
	Underdeck	0.061 kg/m²	0.050 kg/m²
	Wall	0.048 〃	0.028 〃
	Bottom	0.094 〃	0.041 〃
Glycerin	(Viscosity)	(3000 mPa S)	(280 mPa S)
	Underdeck	※ 0.55 kg/m²	0.075 kg/m²
	Wall	※ 0.25 〃	0.075 〃
	Bottom	※ 1.2 〃	0.175 〃

(※ is gained by extrapolation)

4.3 Comparison between Estimation and Experimental Result about Washings Quantity Remaining in Tank during Washing

QDH may be estimated by calculation. In the case of the model tank test, QDH is obtained as follows.

Model Tank: Length;4 m, Breadth;2 m, Depth;2 m

Washing Machine: Capacity $Q = 0.001 m^3/sec$, two$-\phi$ 7 mm nozzles

$QDH = Q1+Q2+Qs$ ·········(30)

$Q1$ = Water Quantity on the Vertical Surface(m^3)

$Q2$ = Water Quantity on the Bottom(m^3)

$Qs2$ = Water Quantity in the vicinity of the well (m^3)

$Q1 = \delta_1 \times b \times D/2 \times 2$ ·········(30)

$Q2 = \delta_2 \times B \times L$ ·········(32)

(1) Estimation of Q1

Velocity $U = (1/2 \cdot Q)/(\pi/4 \cdot d^2) = 13.0 (m/s)$

Using Eq.(19);

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

Here,

$R = U \cdot rn/\nu = 4.55 \times 10^4$, ($\nu = 1.0 \times 10^{-6}\ m^2/s$)

$F = U^2/(g \cdot rN) = 4930$

By substituting R and F into Eq.(19);

$r = 0.139 (m)$

Substituting r into Eq.(18);

$b = 4.3r = 0.60 (m)$

Flow rate per Unit Width $ql = q/2b = 8.3 \times 10^{-4}\ (m^2/s)$

Viscosity $\mu = 1.0 \times 10^{-4}\ (kg.s/m^2)$

Water specific gravity $\gamma = 998\ (kg/m^3)$

Then, water Film Thickness along the vertical surface;

$\delta_1 = ((3ql \cdot \mu)/(\gamma \cdot \sin\phi 1))^{1/3} = 0.63 \times 10^{-3}$ (m)

Therefore, from Eq.(17), Q1 is obtained:

$Q1 = 0.77 \times 10^{-3}\ (m^3)$

(2) Estimation of Q2

$\phi 2 = 2^\circ$ By using Eq.(22),

Water Film Thickness on the Bottom $\delta_2 = ((3q \cdot \mu)/(B \cdot \gamma \cdot \sin\ \phi 2))^{1/3} = 1.6 \times 10^{-3} (m)$.

Substituting δ_2 into Eq.(20);

$Q2 = 1.6 \times 10^{-3} \times 2 \times 4 = 1.28 \times 10^{-3}\ (m^3)$

(3) Qs2 is obtained by the washing test with water in this model tank.

$Qs2 = 2.28 \times 10^{-3}\ (m^3)$

(4) QDH = Q1+Q2+Qs = 15.9×10^{-3} (m^3)

By the experimental result of the model tank test, the average of QDH is 18.4×10^{-3} (m^3).

So the estimation by the calculation is not so much deviate from the experiment.

Let Q1+Q2 = Q12. The relation between Q12 and the tank volume V can be estimated statistically in Fig.34.

The tank shapes are considered as rectangular parallelepiped and the dimensions are shown in Table 1.

In Fig.34, Q12 of the prevailing washing machine is compared with Q12 of the one with two ϕ 4 mm nozzles and Q12 of the one with two ϕ 2.5 mm nozzles.

In the cases of ϕ 4 mm nozzle and ϕ 2.5 mm washing machine, the water pressure is 200kPa. Using the washing machine with small diameter nozzle, Q12 can be decreased.

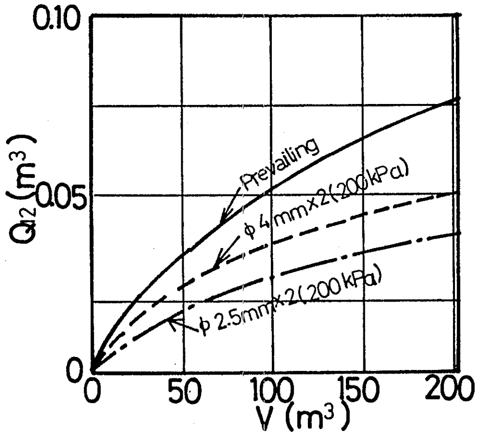


Fig.34 V−Q12

5. CONCLUSION

From the result of the model tank test, the relation between the concentration in discharged water and the water quantity was gained as follows;

(a) At the early washing stage of prevailing washing machine (nozzle diameter is 7 mm) in the case of the model tank, the relation between the concentration of discharged water and the water quantity is given as the following.

$C = Qres0/QDH \cdot \exp(-(Q-QDH+Qres0)/QDH)$

C:concentration, QDH:remaining water in the tank during washing, Qres0:Amount of residue in tank.

(b) At the later washing stage of prevailing washing machine in the case of the model tank, the relation between the concentration and the washing water quantity is given as follow.

$C = K0 \cdot Qres0/QDH \cdot \exp(((QDH-Qres0)/QDH) \cdot \exp(-Q/K1 \cdot QDH)$

K0, K1 are coeficients and k0 = 0.058, K1 = 4.6 respectively.

(c) At the early washing stage of the washing machine with small diameter nozzles (nozzle diameter = 4 mm), the relation between the concentration of discharged water and water quantity for washing is estimated by the following equation.

$$C = Qres0/K2 \cdot QDH \cdot \exp(-(Q - K2 \cdot QDH + Qres0)/K2 \cdot QDH)$$

K2 is coefficient, K2 = 1.4

(d) At the later washing stage of the small diameter washing machine, the relation between the concentration of discharged water and washing water quantity is estimated by the equation.

$$C = K0s \cdot Qres0/QDH \cdot \exp((QDH - Qres0)/QDH) \cdot \exp(-Q/K1s \cdot QDH)$$

K0s and K1s are coefficients, K0s = 0.069, K1s = 4.1

(e) At the early washing stage of high viscosity residue by the small diameter washing machine, the relation between the concentration of discharged water and washing water quantity is estimated by the expression.

$$C = Qres0/K3 \cdot QDH \cdot \exp(-(Q - K3 \cdot QDH - Qres0)/K3 \cdot QDH)$$

K3 is coefficient, K3 = 2.0

(f) At the later washing stage of high viscosity by the small diameter washing machine, the relation between the concentration of discharged water and washing water quantity is estimated by the following equation.

$$C = K0sn \cdot Qres0/QDH \cdot \exp((QDH - Qres0)/QDH) \cdot \exp(-Q/K1sn \cdot QDH)$$

K0sn and K1sn are coefficients, K0sn = 0.11 and K1sn = 5.2 .

These coefficients are obtained only by the model tank experimnt, it is necessary that the coefficients shall be confirmed by the board test.

At the begining time of the tank washing, the estimation of the washwater quantity by the ideal mixing agrees with the experimental result. But at the end of the tank washing, the estimation by the ideal mixing, deviates from the line by the experimental result. At the end of the washing, the residue become hard to remove from the tank surfaces. Therefore, at the begining the tank should be continiously washed and washings should be discharged until the concentration becomes about 0.5%.

After that, the washing should be done by recycling of washing medium.

Residual quantity of the tank surfaces is approximatelly estimated by Eqs.(12'),(13'),(14').

Remaining tank washings quantity in the tank during washing is approximately estimated by Eq.(23) or Fig.34.

Fig.35 represents the comparison of the tank washing by different diameter nozzle. From this, by using small diameter nozzle and reestimation of clingage residue, the necessary water seemes to be decreased.

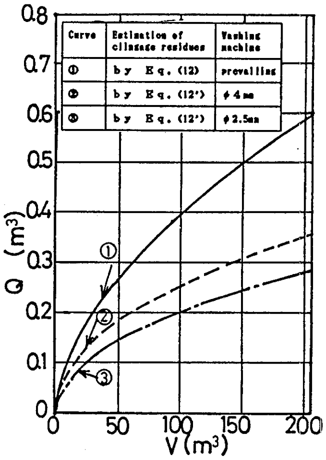


Fig.35 Necessary washwater quantity to wash until the concentration of 1%(estimated by ideal mixing model)

REFERENCES

(1) H.I.A. SCHUURMANS et al., Prewash Procedure for Chemical Tankers, Shell Research B−V − June, 1979

(2) Investigation report of Procedures and arrangements for the discharge of noxious liquid substance, The ship building resarch association of Japan

(3) Investigation report of Procedures and arrangements for the discharge of noxious liquid substance, The ship building resarch association of Japan, 1986, March, 332−337 page (in Japaese)

(4) Investigation report of Procedures and arrangements for the discharge of noxious liquid substance, The ship building resarch association of Japan, 1984, March, 137page(in Japanese)

(5) THE INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS, 1973 AS MODIFIED BY THE PROTOCOL OF 1978 RELATING THERETO (MARPOL 73/78), Kaibundo, 1986

(6) Investigation report of prevention of marine pollution, JAPAN ASSOCIATION FOR PREVENTING MARINE ACCIDENT 1985, March, 98page (in Japanese)

(7) R. Byron Bird. Warren E. Stewart, and Edwin N. Lightfoot, TRANSPORT PHENOMENA, A WILEY INTERNATIONAL EDITION, 40page

(8) WILHELM NUSSELT, Der Warmeaustausch am Berieselungskuhler, Zeitschrift des deutscher Ingeniere, 67−9,1923

ACKNOWLEDGEMENTS

For this investigation, the author would like to thank the comittee concerning procedures and arrangements for the discharge of noxious liquid substance of JAPAN ASSOCIATION FOR PREVENTING MARINE ACCIDENT and THE SHIP BUILDING RESEARCH ASSOCIATION OF JAPAN for giving the auther an amoumt of knowledge through meetings and on board test.

The auther would like to thank Mr. H. KOITABASHI for his assistance in the experiments and the drawings of the figures.