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Liquid Holdup on Rotational-current Tray

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Recently various trays in which mass transfer operations are carried out have been developed, and the authors have designed one of the rotational-current tray which is designed to direct flow of ascending gas horizontally across the tray surface. In this report, as a fundamental study for mass transfer on this tray, flow mechanism and liquid holdup on the tray are considered experimentally. Experiments are carried out by water-air, methanol-water-air and gricerine-water-air systems.

§ 1. Introduction

Studies of liquid holdup on trays are very important to know correlations for predicting tray efficiencies in distillation and absorption columns. For the liquid holdup on the trays of cross-current or counter-current types, some expeimental results have already been reported, but few in Kittel tray[1)] and Jet tray[2)]. The rotational-current tray which has been studied by the present authors[3,4,5,6)] is designed to direct the flow of ascending gas or vapor horizontally across the tray surface, and the contacting mechanism of liquid and gas or vapor on the tray is similar to those of Kittel tray aud Jet tray. Therfore the liquid on the tray is carried along by the gas flow and intimately mixed with it.

In this work, as a fundamental study on the mass transfer in the rotational-current tray, the liquid holdup on the tray were determined experimentally by the water-air, methanol-water-air and gricerine -water-air systems.

§ 2. Experimental apparatus and procedure

The structure of rotational-current tray used in this work is shown in **Fig. 1.** The shape of holes in the tray is a half ellipse.

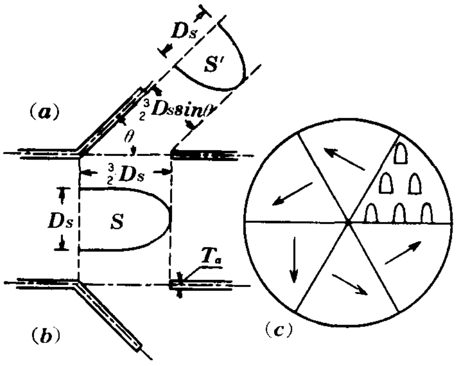

Fig. 1 Structure of tray

Table 1 Dimensions of trays

Trays	θ	D_s	D	n	T_a	T	T/D	A_h/A_c
P- 5	45	0.78	0.72	60	0.16	0.38	0.53	0.172
P- 6	45	0.78	0.72	60	0.08	0.33	0.46	0.172
P- 7	45	0.88	0.82	60	0.08	0.40	0.49	0.223
P- 8	45	1.00	0.92	60	0.08	0.40	0.43	0.281
P-14	45	0.71	0.64	90	0.08	0.30	0.47	0.207
P-15	45	1.10	1.10	36	0.08	0.47	0.43	0.225

The dimensions of trays are shown in **Table 1.** In the table, D and A_h/A_c are obtained from projected area of hole S', and T is given by the following equation,

$$T = (T_a \cdot l + S)/l' \qquad (1)$$

The flowsheet of the experimental apparatus and the structure of column are shown in **Fig.2.** Air from a blower ④ flows into the column ① after passing through a flow meter ③. It then flows through a distributor ⑩ and tray ⑧. On the other hand, liquid is stored in a feed tank ⑥ and pumped from there by a circulation pump ⑤ to a constant head tank ②, from which it is fed to a liquid distributor ⑦, after passing through a flow meter ③. Liquid flowed through the distributor, is stored on the tray, and it forms foaming layer, contacts with air, and then it is purged off from the bottom of the column.

Liquid holdup on the tray h_l is measured by a stopper ⑨ fitted just under the tray; that is, the stopper is closed at the same time that feed liquid and gas are stopped, and some falling liquid which exists between the liquid distributor and the top of foaming layer on the tray, is deducted from liquid volume on the stopper.

Pressure loss of gas through a tray is measur-

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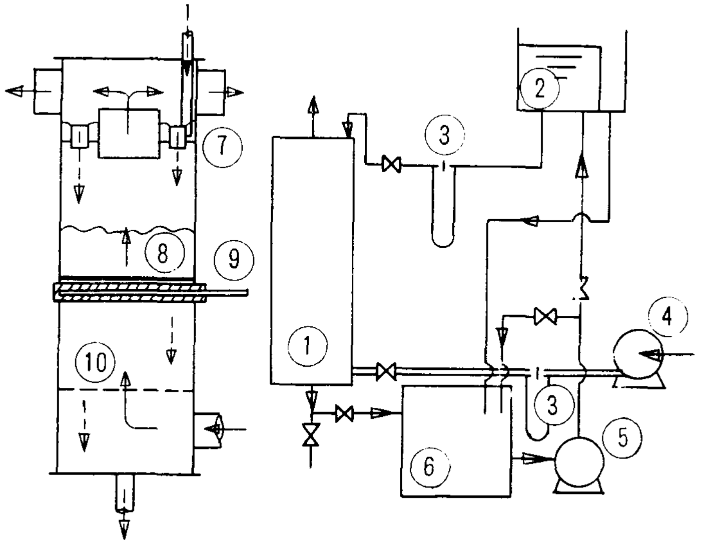

① tower ② head tank ③ flow meter ④ blower
⑤ pump ⑥ feed tank ⑦ liquid distributor ⑧ tray
⑨ stopper ⑩ gas distributor

Fig. 2 Experimental apparatus

ed by the inclined manometer, and height of foaming layer is measured visually. Besides, gas velocity at which liquid begins to be held up on the tray, is determined by experimental results of pressure loss.

The column is 14.6 cm in diameter and is made of transparent vinyl chloride. Therfore the observation of foaming layer from outside is possible. The variables and their ranges investigated are as follows; Reynolds number of gas and liquid phase (Re_G = 800–12,000, Re_L = 50–300), surface tension (σ = 31 – 72 dynes/cm), viscosity (μ_L = 0.8–8.5 c. p.) and density (ρ_L = 0.87–1.0g/cm^3).

§ 3. Experimental results and discussion

1) Visual observation

As an example of the experimental results, **Fig.3** shows the relation between the gas velocity and the liquid holdup on the tray, the pressure loss of gas through a tray, the foam density, respectively, using the velocity of liquid as a parameter. From this figure, three types of bubbling motion on the tray are observed.

When the gas velocity is low, foaming layer is not formed on the tray. In this region, the pressure loss is proportional to a square of the gas velocity. But, as the gas velocity increases, liquid begins to hold up on the tray. This point is *R* in Fig. 3 and is the critical under limit of operation for the tray. The liquid retention point *R* is determined from energy balance of both liquid and gas through holes of tray. As shown in **Fig. 4**, the gas velocity at the point *R* decreases with both liquid flow rate and liquid viscosity increasing, and increases with both liquid surface tension and hole diameters.

Further, at this point *R*, the pressure loss increases extremely and the foaming layer is formed on the tray. The foaming layer in region (*I*) shown in Fig. 3 is comparatively stable because the interactions between bubbles are little, and is rotating slowly on the tray. The liquid holdup and the pressure loss increase rapidly as the gas velocity becomes greater in this region. In region (*II*) shown in Fig. 3, the motion of foaming layer on the tray is complicated; that is, the interactions between bubbles and the rotation of foaming layer are remarkable, and the oscilation of foaming layer begins. Further,

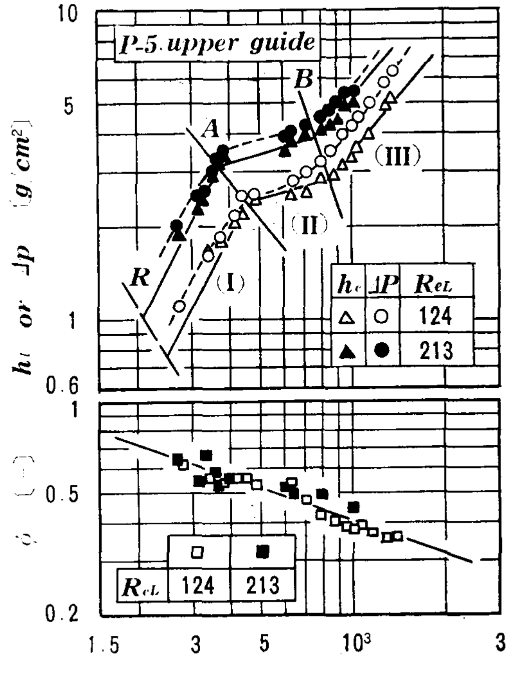

Fig. 3 Liquid holdup, pressure loss and foam density on a test tray

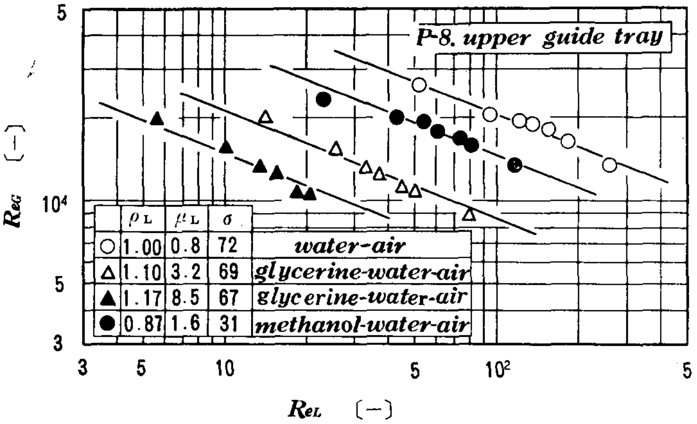

Fig. 4 Liquid retention points

the liquid holdup and the pressure loss increase slowly as the gas velocity becomes greater. In region (*III*), moreover, the height of foaming layer becomes very high and the entrainment from this layer becomes remarkable. The liquid holdup and the pressure loss increase again rapidly. And finally flooding phenomena are observed.

It is found from Fig. 3 that the behavior of liquid holdup on the tray is similar to that of the pressure loss of gas through a tray. And also the liquid holdup and the pressure loss increase with liquid flow rate and they decrease as free area of the tray becomes greater.

Finally as shown in Fig. 3, the foam density is not influenced by liquid flow rate and it decreases with gas velocity through the whole regions.

2) Liquid holdup on the tray

The factors which influence the liquid holdup in each region (*I*), (*II*) and (*III*), and points *A* and *B* in Fig. 3 are the flow rates w_h, u_h, the properties of liquid and gas ρ_L, ρ_G, μ_L, μ_G, σ and tray dimensions D, D_t, A_h, A_c. If arranged in terms of dimensionless groups, points *A* and *B* are presented as

$$(w_h/u_h)=\xi_R Re_L^a (A_h/A_c)^b St_G^c \qquad (2)$$

where Re_L is Reynolds number of liquid phase, $Re_L=\mathrm{D}w_h\rho_L/\mu_L$, and St_G is Stability number, $St_G=\mu_G{}^2/D_t\sigma\rho_G$. Further the liquid holdup on the tray is also presented as

$$(1/Fr)=\xi_L (w_h/u_h)^d Re_L^e (A_h/A_c)^f St_G^g \qquad (3)$$

where Fr is Froude number, $Fr=u_h{}^2\rho_L/h_l g_c$.

Experimental data for points *A* and *B* are arranged by Eq. (2). From these results, coefficient ξ_R and exponents *a*, *b* and *c* for upper and down guide tray become as shown in **Table 2.**

Table 2 Coefficient and exponents of Eq. (2)

Tray \ Critical point		ξ_R	a	b	c
Upper guide tray	A	1.6	1.4	−0.5	0.8
	B	1.1×10^9	1.2	0	1.9
Down guide tray	A	1.6×10^5	1.4	−1.8	1.5
	B	2.4×10^6	1.3	——	1.6

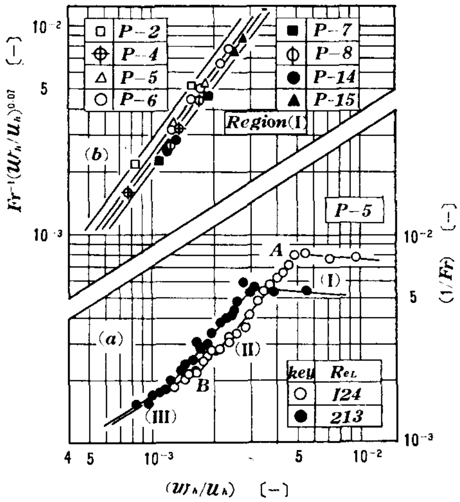

Fig. 5 Liquid holdup on down guide trays

On the other hand, it is clear from **Fig. 5 (a)** that the relation between ratio of flow rates w_h/u_h and Froude number Fr in each region is linear, and that slopes of the lines do not change with liquid flow rates and tray dimensions. Then, the Froude number in the region (*I*) for down guide tray is presented as follows;

$$(1/Fr)\propto(w_h/u_h)^{-0.07} \qquad (4)$$

Further, from the relations in **Fig. 5 (b)** and **Fig. 6 (a)** and (**b**), the liquid holdup in region (*I*) for down guide tray is obtained as

$$(1/Fr)=6.7\times10^{11}(w_h/u_h)^{-0.07} Re_L^{1.3}(A_h/A_c)^{-0.3} St_G^{2.3} \qquad (5)$$

Table 3 Coefficient and exponents of Eq. (3)

Tray	Region	ξ_L	d	e	f	g
Upper guide trays	(I)	3.7×10^{-7}	0.17	0.95	−1.2	−0.26
	(II)	2.0×10^{-7}	1.7	−1.2	−0.36	−1.5
	(III)	2.6×10	0.68	0	−0.34	0.29
Down guide trays	(I)	6.7×10^{11}	−0.07	1.3	−0.3	2.3
	(II)	2.6×10^{57}	$7.5\times10^{6}S_{tG}^{0.9}$	−0.74	0.72	7.3
	(III)	1.9×10^{-2}	0.70	0.20	——	−0.08

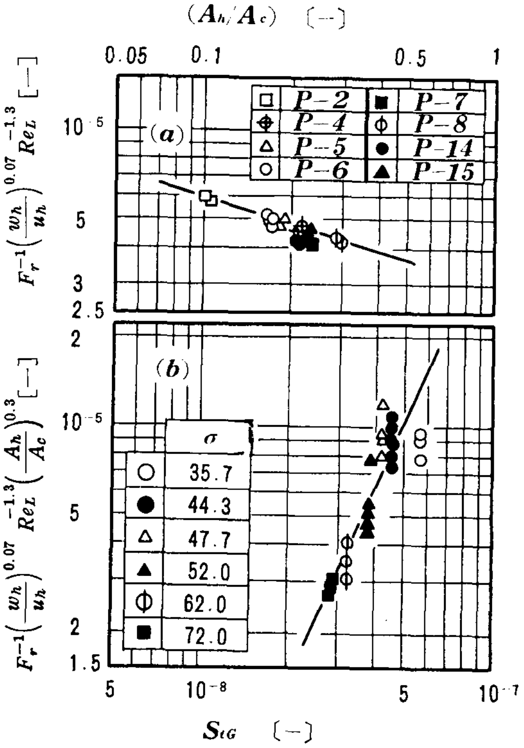

Fig. 6 Liquid holdup on down guide trays in region (*I*)

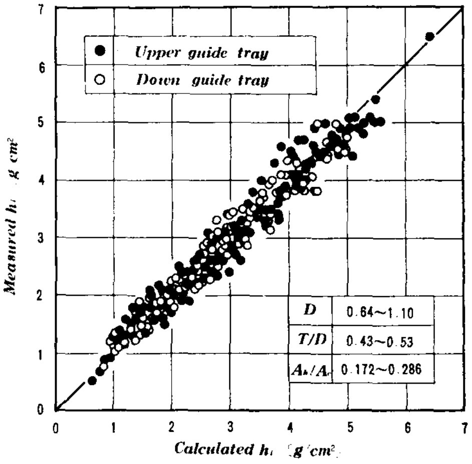

Fig. 7 Comparison between measured and calculated h_l

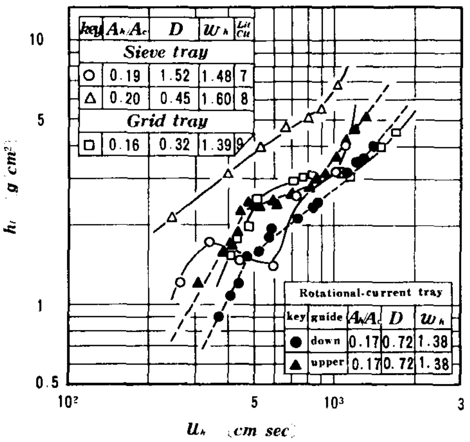

Fig. 8 Comparison of liquid holdup on various counter-current trays

For regions (*II*) and (*III*) of down guide tray, and regions (*I*), (*II*) and (*III*) of upper guide tray, the following general correlations are obtained, that is, coefficient ξ_L and exponents *d*, *e*, *f* and *g* in Eq. (3) become as shown in **Table 3**.

Fig. 7 shows the comparison between the values calculated by Eq. (3) and Table 3 and the measured values of liquid holdup. From this figure, it is recognized that the calculated values agree with the measured values.

In **Fig.** 8, the liquid holdup on trays are compared for the perforated plate of counter-current type[7,8], the grid tray[9] and the rotational-current tray. From this figure it is evident that the liquid holdup on the down guide rotational-current tray is smaller than that of other types. This is probably due to the fact that the falling of liquid through the down guide tray is made easy by the guide.

§ 4. Conclusions

Behaviors of foaming layer on the rotational-current tray in which contacting mechanism of liquid and gas or vapor on tray is similar to that of Kittel tray or Jet tray, have been studied in this work. The results are as follows;

1) Three types of bubbling motion on the tray are observed.

2) The behavior of liquid holdup on the tray is similar to that of the pressure loss of gas through a tray, and the foam density decreases with gas velocity.

3) The critical points *A* and *B* of bubbling motion are obtained from Eq. (2) and Table 2. And the liquid holdup on the tray in each region (*I*), (*II*) and (*III*) is obtained from Eq. (3) and Table 3.

4) It is concluded that the liquid holdup on the down guide rotational-current tray is smaller than that of other counter-current types.

Nomenclature

A_c : cross-sectional area of column [cm^2]
A_h : total hole area [cm^2]
D : $=4S'/l'$, equivalent diameter of hole [cm]
D_s : minor diameter of ellipse, refer to Fig. 1 [cm]
D_t : column diameter [cm]
g_c : conversion factor [g cm/G sec^2]
h_l : liquid holdup on tray [g/cm^2]
h_f : height of foaming layer [cm]
l : a half peripheral length of ellipse, refer to Fig. 1 [cm]
l' : peripheral length of projected hole S', refer to Fig. 1 [cm]
ΔP : pressure loss of gas through a tray [G/cm^2]
S : area of a half ellipse, refer to Fig. 1 [cm^2]
S' : projected hole area, refer to Fig. 1 [cm^2]
T : equivalent thickness of tray, defined by Eq. (1) [cm]
T_a : tray thickness [cm]
u_h : gas velocity based on hole area S' [cm/sec]
w_h : liquid velocity based on hole area S' [cm/sec]
Fr : $=u_h^2\rho_L/h_l g_c$, Froude number [——]
Re_G : $=Du_h\rho_G/\mu_G$, Reynolds number of gas phase [——]
Re_L : $=Dw_h\rho_L/\mu_L$, Reynolds number of liquid phase [——]
St_G : $=(We/Re_G^2)=\mu_G^2/D_t\sigma\rho_G$, Stability number [——]
We : $u_h^2 D_t\rho_G/\sigma$, Weber number [——]
θ : angle, refer to Fig. 1 [rad.]
μ_G, μ_L: viscosity of gas and liquid phase [c. p.]
ρ_G, ρ_L: density of gas and liquid phase [g/cm^3]
σ : surface tension [dynes/cm]
ξ_R, ξ_L : coefficients in Eqs. (2) and (3) [——]
ϕ : $=h_l/h_f\rho_L$, foam density [——]

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