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Hydraulic Properties of Froth Layer on a Perforated Plate

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Synopsis

This paper deals with the comparison of gas-liquid holdup and froth height on a perforated plate under various operational conditions such as liquid stagnant, cocurrent, countercurrent and crosscurrent gas-liquid flow system.

Tendency to foam is remarkable in countercurrent and crosscurrent flow system. The crosscurrent flow system is suitable for the operation of mass transfer from the point of view of gas-liquid holdup.

Introduction

The dispersion of gas through a perforated plate is of interest in the design of various plate columns and bubble columns employed in operations involving distillation, absorption, stripping and other separations. The efficiency of contact related to mass transfer between gas and liquid is affected by operational conditions such as liquid stagnant, cocurrent, countercurrent and crosscurrent gas-liquid flow system. Therefore, gas-liquid holdup and froth height on a plate in these flow systems are very important factors. The authors have investigated these properties on a perforated plate under different contact systems between gas and liquid(1-7).

This paper concerns the comparison of the difference between the

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above properties under each flow system.

1. Summary of Previous Work

1.1 Liquid Holdup

Few researches have been reported about liquid holdup on a perforated plate in cocurrent flow system.

Hiratsuka et al.(9) have proposed the relationships predicting liquid holdup in countercurrent flow system. The correlations contain a function of gas-liquid mass flow rate ratio and gas velocity through hole, whereas the effect of physical properties of liquid was not found.

Kamei et al.(10) have proposed the following equation in relation to froth height in crosscurrent flow system:

$$H/h_f = 0.053\{U_{gc}\rho_g/(U_{\ell c}\rho_\ell)\}^{-0.6}\rho_\ell, \qquad (1 - 1)$$

Smith et al.(11) have given accounting for weir height,

$$H = 0.725H_w - 1.84\times10^{-8}H_w U_{gc}\sqrt{\rho_g} + 9.3\times10^{-8}Q/B + 0.0061, \qquad (1 - 2)$$

and Shono et al.(12) have given the following equation:

$$H = (0.333H_w + d + 0.002 + 2U_{\ell c})\,\ell og(1000U_{\ell c}/U_{gc}). \qquad (1 - 3)$$

$F = 0.06\text{-}0.09$, $d = 0.005\text{-}0.015$ m, $H_w = 0.03\text{-}0.09$ m
$U_{\ell c} = 0.0033\text{-}0.0088$ m/s, $U_{gc} = 0\text{-}1.38$ m/s

The above each relationship contains the effect of weir height, while the effect of physical properties of liquid is not noticed.

1.2 Gas Holdup

The effect of gas distributor on gas holdup under liquid stagnant flow system has been reported by Houghton et al.(13) as follows: gas holdup was affected by geometry of plate. On the other hand, Shulman et al.(14) has reported that gas holdup was not affected by geometry of porous plate.

For bubble column, where a deep pool of liquid is commonly used, Akita et al.(15) proposed the following equation:

$$(1 - \Psi)/\Psi^4 = 0.2(gD^2\rho_\ell/\sigma)^{1/8}(gD^3/\nu_\ell{}^2)^{1/12}(U_{gc}/\sqrt{gD}). \quad (1 - 4)$$

Kato(8) has shown the gas holdup for bubble column with both cocurrent and countercurrent gas-liquid flow. However, little has been found about gas holdup in crosscurrent flow system.

1.3 Froth Height

Only a few studies have been made of froth height on a perforated plate. Azbel(16) has analyzed theoretically the froth height with no liquid flow and given the following equation:

$$h_f = H(1 + \sqrt{Fr}). \quad (1 - 5)$$

However, few studies on froth height have been carried out for different gas-liquid flow systems.

2. Hydraulic Properties of Froth Layer on a Perforated Plate

As shown in Fig.1, when gas is dispersed through a perforated plate

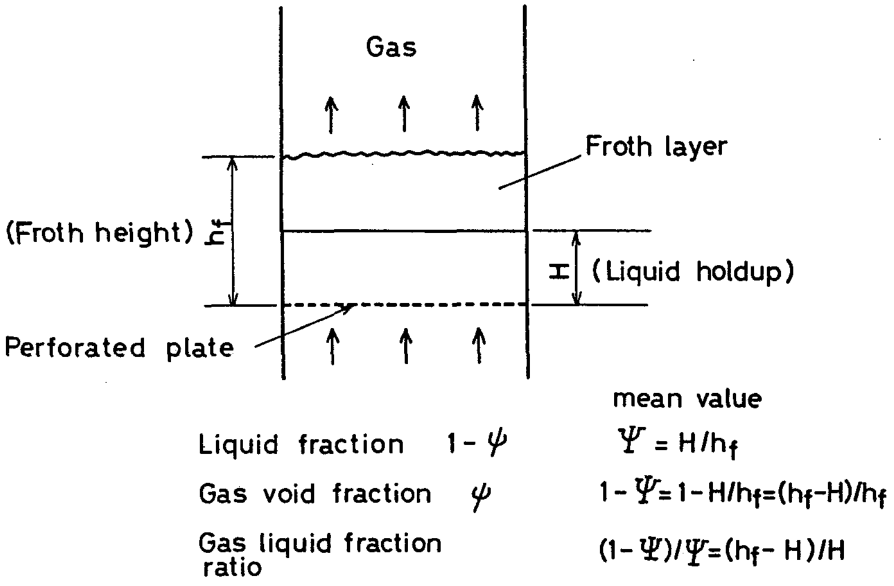


Fig.1 Definition of gas-liquid fraction

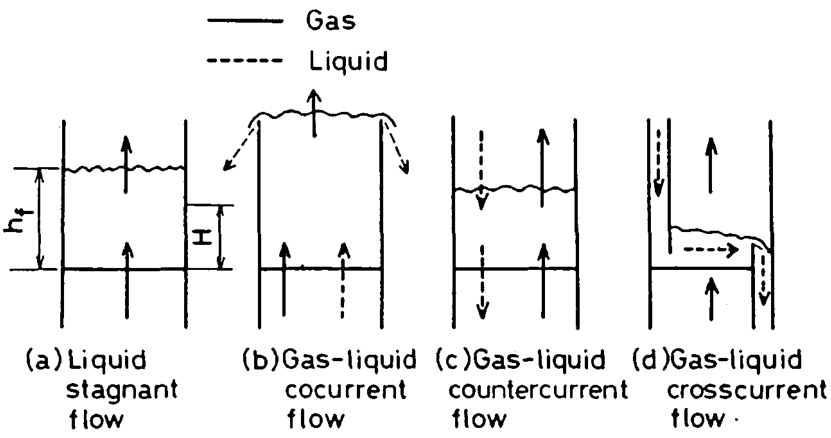


Fig.2 Froth layer on a perforated plate

into liquid, its liquid depth being H, froth, with the height of h_f, is formed. Gas holdup in the froth, ψ, has a profile over a plate, and the integration of ψ from the plate to the top of the froth height gives mean gas holdup,$1-\Psi$.

Figure 2 shows various flow systems. Characteristics of froth on a plate are as follows: (a)Liquid depth, H, becomes froth height, h_f, by the contact between gas and liquid. (b)Froth breaks down at the top of the column, and liquid flows over a weir. (c)Liquid depth can be determined mainly by gas flow rate, and liquid holds up on a plate. (d)Properties of froth are affected by weir height.

Liquid depth for liquid stagnant flow system(a) is determined spontaneously. Bubbles formed from a perforated plate are accompanied by wakes on the rear sides. The wakes cause a circulation of liquid in froth. The liquid depth in the froth shown in Fig.2 (b), (c) and (d) is determined by operational conditions. h_f, ψ and $1-\Psi$ for each flow system have inherent values respectively.

Table 1 shows the operational conditions and the dimensions of the apparatus employed in the previous work(1,2,4-7) briefly.

3. Liquid Holdup

Table 2 shows the comparison of some empirical equations predicting liquid holdup obtained by the authors(1,2,5,7).

H in liquid stagnant flow system is determined spontaneously.

Table 1 Experimental conditions

Flow system	Column diameter D[m]	Hole diameter d[m]	Plate perforation ratio F[-]	Gas velocity U_{gc}[m/s]	Liquid velocity $U_{\ell c}$[m/s]	References
Liquid stagnant	0.04∿0.15	0.00071∿ 0.00306	0.0011∿ 0.0623	0 ∿ 1		4,7)
Cocurrent	0.06∿0.15	0.00071∿ 0.00306	0.0017∿ 0.0535	0 ∿ 1.16	0 ∿ 0.35	5,7)
Counter-current	0.06∿0.15	0.00073∿ 0.0062	0.0071∿ 0.508	0 ∿ 6	0 ∿ 0.09	1,2,5)
Cross-current	B=0.08∿0.15m L=0.1∿0.3m	0.00073∿ 0.0027	0.0044∿ 0.1087	0 ∿ 1	$Q=20\times10^{-6}$∿900×10^{-6} m^3/s	6,7)

Table 2 Liquid holdup,H

a Liquid stagnsnt

H is determined spontaneously (2-1)

b Cocurrent[7)]

$$H/L_T=\{1 + 0.065(Fr_g^{1/2}/Fr_{\ell c}^{1/6})^{0.85}\}^{-1} \qquad (2\text{-}2)$$

$$Fr_g=U_{gc}^2/(gd),\ Fr_{\ell c}=U_{\ell c}^2/(gL_T)$$

c Countercurrent[1,2)]

$$H\rho_\ell=(\frac{1}{\beta-\zeta_h})\{\frac{\zeta_d}{2g}(\frac{U_{gh}}{1-\tau})^2\rho_g+\zeta_\sigma\frac{4\sigma}{dg} + (1-\zeta_h\tau)\frac{\zeta_\ell}{2g}(\frac{U_{\ell h}}{\tau})^2\rho_\ell\} \qquad (2\text{-}3)$$

$$k\rho_g U_{gh}^2\{\tau/(1-\tau)\}^3\{3-2.4F(1-\tau)\}=2.2\rho_\ell(2-\zeta_h\tau)U_{\ell h}^2+8.68\times10^3(0.0316d^{-3/4}-0.87)$$
$$\times(1000\sigma-28.7)\mu_\ell^{1/4}\rho_\ell^{-1}\zeta_h\tau^3$$

$$\zeta_\ell=2.2+\{8.68\times10^3(0.0316d^{-3/4}-0.87)(1000\sigma-28.7)\mu_\ell^{1/4}\rho_\ell^{-2}/(U_{\ell h}/\tau)^2\},\zeta_h=1,\ \zeta_\sigma=0.34$$

$$\beta=1.34(t^2/U_{\ell c})^{1/25}\sigma^{1/20}\mu_\ell^{-1/25}+9.15\times10^{-9}\{U_{gc}/(U_{\ell c}^{1/2}Ft^{1/4}\mu_\ell^{1/5})\}^2\ ;\ F=0.05\sim0.2$$

$$\beta=0.326\{F^{1/5}/(U_{\ell c}^{1/12}t^{1/15})\}\sigma^{-2/9}\mu_\ell^{-1/50}+1.18\times10^{-4}\{U_{gc}/(U_{\ell c}^{1/3}t^{1/5})\}^2\ ;\ F=0.2\sim0.5$$

$\zeta_d=k[\{1-F(1-\tau)\}^2+0.4\{1.25-F(1-\tau)\}]$, k is a function of t/d (obtained by McAllister et al.[17)])

d Crosscurrent[7)]

$$H/H_w=[\sqrt{1.4}\{(Fr_g^{1/2}/Fr_\ell^{1/4})\}^{-0.15}]^n \qquad (2\text{-}4)$$

$$(Fr_g^{1/2}/Fr_\ell^{1/4})\ \leqq 3,\ n=1$$
$$> 3,\ n=2$$

$$Fr_g=U_{gc}^2/(gd),\ Fr_\ell=\{Q/(BL)\}^2/(gH_w)$$

However, the effect of physical properties of liquid is noticed in countercurrent flow system. Column height for cocurrent, weir height for crosscurrent and perforation ratio and hole diameter for countercurrent are main factors controlling liquid holdup on a perforated plate.

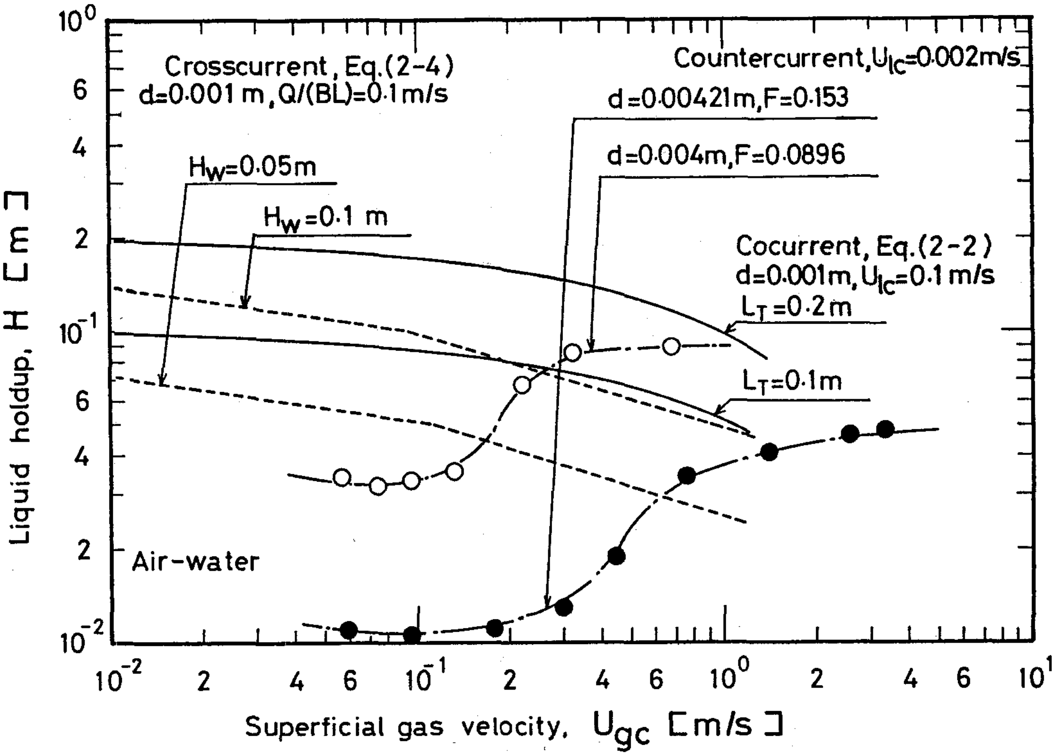


Fig.3 Liquid holdup for each flow system

Figure 3 illustrates an example of the comparison of liquid holdup for each flow system. The effects of column height in cocurrent and weir height in crosscurrent are remarkable, and liquid holdup increases with increasing column height or weir height, respectively. Liquid holdup in cocurrent and crosscurrent decreases with increase of gas velocity, while that in countercurrent increases, and decreases with perforation ratio. These could be interpreted due to the simultaneous passage of gas and liquid through holes of a perforated plate.

4. Gas Holdup

Gas holdup shows a profile over a plate. Figure 4 represents vertical profiles of liquid fraction on a perforated plate obtained by means of γ-ray technique in liquid stagnant flow system. From this chart, the vertical profile is divided into three regions.

i) Bubble formation region

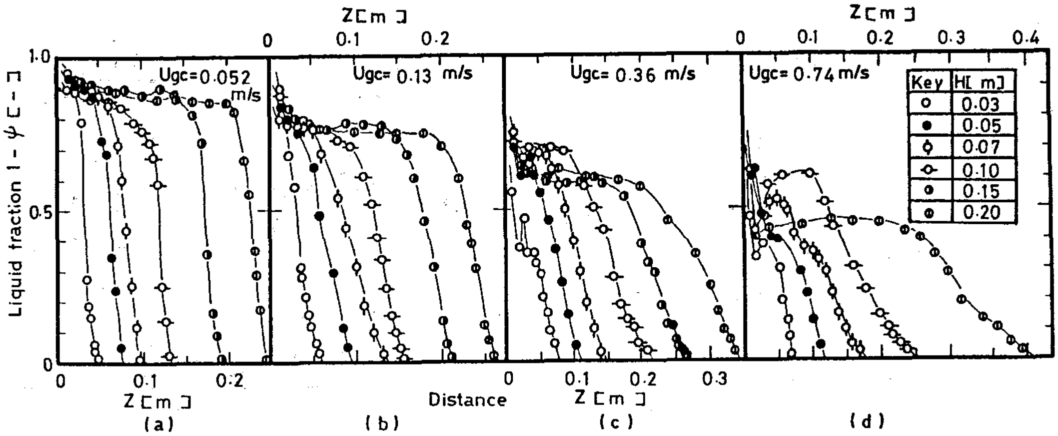
In this region, bubbles are formed at the surface of the plate and stagnant near here as dependent on the growing velocity. Liquid fraction decreases abruptly. This is remarkable at high gas velocity.

ii) Middle region

This is observed remarkably at high liquid depth and a constant liquid fraction is found.

iii) Foam layer region

This region, which is found at the upper section of the froth layer, shows an abrupt decrease of liquid fraction, and an increase of this region is noticeable at higher gas velocity, while bubble formation region decreases.



d = 0.0008 m , m = 974 , t/d = 1 , F = 0.0623 , D = 0.1 m

Air - water

Fig.4 Vertical profile of liquid fraction on a perforated plate

Each flow system shown in Fig.2(b), (c) and (d) has a similar tendency.

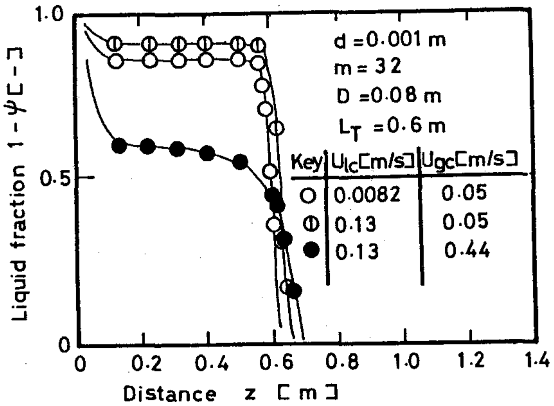
Figure 5 shows an example of vertical profile of liquid fraction in cocurrent and crosscurrent flow system. In cocurrent flow system(a), vertical profile has a similar tendency to the case of liquid stagnant flow system, while profile in crosscurrent flow system is affected by weir height. Vertical profile of liquid fraction in countercurrent flow system is not shown here because of the difficulty of the measurement by means of γ-ray technique for very low froth height.

Table 3 includes the relationships of mean gas-liquid fraction ratio, $(1-\Psi)/\Psi$, obtained by the authors previously with each flow system.

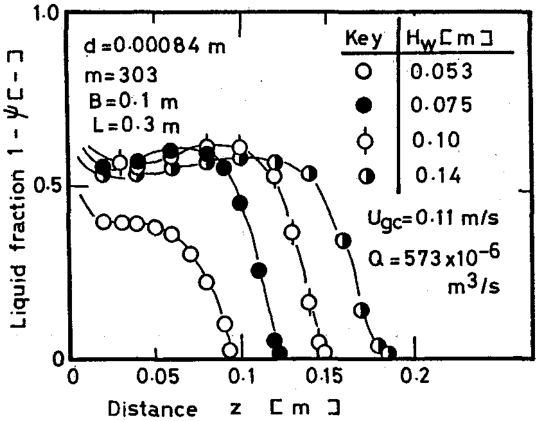
Mean gas holdup decreases with increasing stream velocity in cocurrent flow, whereas that in countercurrent flow increases. No significant effect of liquid flow is found in crosscurrent, although that of perforation ratio is noticed. In each flow system, mean gas holdup increases with gas velocity.

$(1-\Psi)/\Psi$ for each flow system is illustrated in Fig.6. In this chart, $(1-\Psi)/\Psi$ is plotted against $Fr(=U_{gc}^2/(gH))$ which is the Froude number based on liquid depth. $(1-\Psi)/\Psi$ for cocurrent flow is smaller than that for liquid stagnant flow, while that for countercurrent flow is larger. $(1-\Psi)/\Psi$ for crosscurrent flow is also larger. We can find transitional points in liquid stagnant, cocurrent and countercurrent flow system at about $Fr=8.5\times10^{-4}$. On the other hand, the transitional Froude number in crosscurrent flow decreases with perforation ratio, F, and $(1-\Psi)/\Psi$ exhibits the effect of F.

Further, gas holdup shows a different behavior dependent on whether liquid is foaming material or not. The above results are those for non-foaming materials.



(a) Cocurrent
Air-water



(b) Crosscurrent
Air-water

Fig.5 Vertical profile of liquid fraction on a perforated plate

5. Froth Height

Froth height can be calculated from the relationships of gas holdup and liquid holdup. According to the analysis of Azbel(16) and the results of the authors, it is found that froth height becomes a function of the Froude number, Fr based on liquid depth.

Table 3 Gas liquid fraction ratio, $(1-\Psi)/\Psi=(h_f-H)/H$

a	Liquid stagnant[4,7]		
	$(1-\Psi)/\Psi=6.5\sqrt{Fr}$	$;\ Fr\leqq 8.5\times10^{-4}$	(3-1)
	$(1-\Psi)/\Psi=2\ \sqrt[3]{Fr}$	$;\ Fr>8.5\times10^{-4}$	
b	Cocurrent[5]		
	$(1-\Psi)/\Psi=6.5\sqrt{Fr}/\{1+6.5\sqrt{Fr}(U_{\ell c}/U_{gc})\}$	$;\ Fr\leqq 8.5\times10^{-4}$	(3-2)
	$(1-\Psi)/\Psi=2\ \sqrt[3]{Fr}/\{1+2\ \sqrt[3]{Fr}(U_{\ell c}/U_{gc})\}$	$;\ Fr>8.5\times10^{-4}$	
c	Countercurrent[5]		
	$(1-\Psi)/\Psi=6.5\sqrt{Fr}/\{1-6.5\sqrt{Fr}(U_{\ell c}/U_{gc})\}$	$;\ Fr\leqq 8.5\times10^{-4}$	(3-4)
	$(1-\Psi)/\Psi=2\ \sqrt[3]{Fr}/\{1-2\ \sqrt[3]{Fr}(U_{\ell c}/U_{gc})\}$	$;\ Fr>8.5\times10^{-4}$	
d	Crosscurrent[6]		
	$(1-\Psi)/\Psi=8.5\sqrt{Fr}$	$;\ Fr\leqq 4.68\times10^{-4}F^{-0.56}$	(3-4)
	$(1-\Psi)/\Psi=1.25Fr^{1/4}F^{-0.14}$	$;\ Fr>4.68\times10^{-4}F^{-0.56}$	

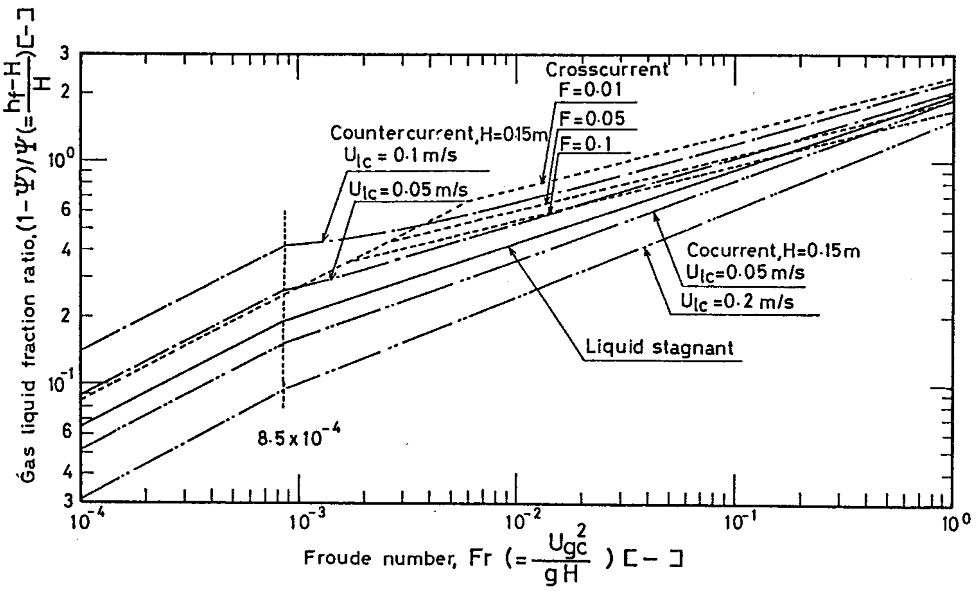


Fig.6 Mean gas liquid fraction ratio for each flow system

Table 4 Froth height, h_f

	Equation	Condition	No.
a Liquid stagnant[4,7]			
	$h_f=H(1+6.5\sqrt{Fr})$	$Fr\leqq 8.5\times10^{-4}$	(4-1)
	$h_f=H(1+2\sqrt[3]{Fr})$	$Fr>8.5\times10^{-4}$	
b Cocurrent[5]			
	$h_f=H[1+6.5\sqrt{Fr}/\{1+6.5\sqrt{Fr}(U_{\ell c}/U_{gc})\}]$	$Fr\leqq 8.5\times10^{-4}$	(4-2)
	$h_f=H[1+2\sqrt[3]{Fr}/\{1+2\sqrt[3]{Fr}(U_{\ell c}/U_{gc})\}]$	$Fr>8.5\times10^{-4}$	
c Countercurrent[5]			
	$h_f=H[1+6.5\sqrt{Fr}/\{1-6.5\sqrt{Fr}(U_{\ell c}/U_{gc})\}]$	$Fr\leqq 8.5\times10^{-4}$	(4-3)
	$h_f=H[1+2\sqrt[3]{Fr}/\{1-2\sqrt[3]{Fr}(U_{\ell c}/U_{gc})\}]$	$Fr>8.5\times10^{-4}$	
d Crosscurrent[6,7]			
	$h_f=H(1+8.5\sqrt{Fr})$	$Fr\leqq 4.68\times10^{-4}F^{-0.56}$	(4-4)
	$h_f=H(1+1.25Fr^{1/4}F^{-0.14})$	$Fr>4.68\times10^{-4}F^{-0.56}$	

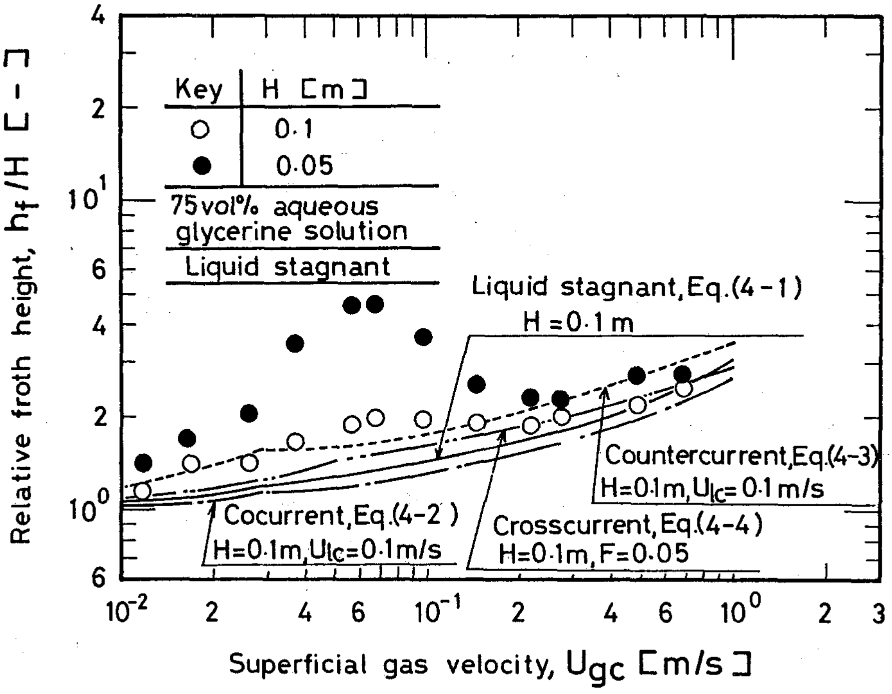


Fig.7 Relative froth height for each flow system

In any flow systems, froth height increases with gas velocity.

Table 4 shows the relationships of froth height obtained from the results of liquid holdup shown in Table 2 and those of gas holdup shown in Table 3. The transitional Froude number, Fr, is found in each flow system. This is probably due to the transition from bubble to froth flow systems.

Figure 7 compares the relative froth height, h_f/H, against gas velocity in each flow system. From this figure, it is found that the tendency to foam is remarkable in countercurrent and crosscurrent flow system. As liquid holdup increases with gas velocity in countercurrent as shown in Fig.3, it is considered that the crosscurrent flow system is most effective for the operation of mass transfer. The results of aqueous glycerine solution, which is a foaming material, under liquid stagnant flow are plotted in Fig.7. At small gas velocity, h_f/H shows the maximum and becomes independent of species of liquids at higher gas velocity. At that point, we can notice a cellular foam, though the phenomenon could not be explained by static properties of liquid such as density, viscosity and surface tension. This is perhaps due to dynamic properties such as surface tension gradient and surface viscosity.

Conclusions

1) Liquid holdup in cocurrent and crosscurrent gas-liquid flow system decreases with gas velocity, whereas that in countercurrent increases.
2) Mean gas liquid fraction ratio in each flow system is correlated well with the Froude number based on liquid depth. Mean gas holdup decreases with liquid velocity in cocurrent and increases in countercurrent, while that in crosscurrent is not affected by liquid flow.
3) Froth height in each flow system increases with gas velocity, and can be determined mainly by liquid holdup and the Froude number based on liquid depth.
4) Tendency to foam is remarkable in countercurrent and crosscurrent flow system.
5) Crosscurrent flow system is suitable for the operation of mass transfer.

Nomenclature

B = weir width [m]
D = column diameter [m]
d = hole diameter [m]
F = perforation ratio [-]
Fr = Froude number $(=U_{gc}^2/(gH))$ [-]
Fr_g = Froude number $(=U_{gc}^2/(gd))$ [-]
Fr_ℓ = Froude number $(=\{Q/(BL)\}^2/(gH_w))$ [-]
$Fr_{\ell c}$ = Froude number $(=U_{\ell c}^2/(gL_T))$ [-]
g = gravitational acceleration [m/s^2]
H = liquid holdup [m]
H_w = weir height [m]
h_f = froth height [m]
k = coefficient [-]
L = liquid flow path length [m]
L_T = column height [m]
ℓ = plate thickness [m]
m = hole number [-]
Q = liquid flow rate [m^3/s]
U_{gc} = superficial gas velocity [m/s]
U_{gh} = gas velocity through hole [m/s]
$U_{\ell c}$ = superficial liquid velocity [m/s]
$U_{\ell h}$ = liquid velocity through hole [m/s]
β = aeration factor [-]
$\zeta_d, \zeta_\ell, \zeta_\sigma, \zeta_h$ = resistance coefficients due to gas, liquid, surface tension and liquid holdup [-]
ρ_g, ρ_ℓ = density of gas and liquid [kg/m^3]
σ = surface tension [N/m]
τ = ratio of hole area of dropping liquid flow per total hole area of a perforated plate [-]
μ_ℓ = viscosity of liquid [Pa.s]
ν_ℓ = kinematic viscosity [m^2/s]
ψ = gas holdup [-]
Ψ = mean liquid holdup [-]

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