

# A Correlation of Flooding Velocities in Countercurrent Gas-Liquid Contactor of Column Type

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In this report, the analogies of the maximum allowable liquid and gas velocities in various countercurrent gas-liquid contactors of column type are considered analytically.

That is, by plotting the flooding points of various columns in a gas-liquid separated coordinates, the similar curves have been obtained in each column. Because the difference of these curves is due to the shape of each column, the difference of each shape must be corrected and evaluated as a shape factor. Then, by containing this factor in coordinate variables, various flooding points in each column may be correlated by a single curve.

If this correlation curve is used, the flooding velocity can be estimated easily, and the maximum allowable liquid and gas velocities in these countercurrent contactors of column type can be compared.

## § 1. Introduction

In recent years, considerable works have been done to determine the operating capacity of a countercurrent gas-liquid contactor. Each investigator has generally correlated his own data and compared his results with that of other investigators without attempting a general correlation of all the existing data. Furthermore, there is no study on the analogies of maximum allowable liquid and gas velocities in these contactors of countercurrent type.

In this work, the upper limit of operating regions, which corresponds with the flooding velocity in the countercurrent contactor of column type, will be compared with each column (packed column, wetted wall column, bubble cap column, perforated plate column, and turbo grid column). Moreover, the correlations among these flooding velocities are discussed, in order to obtain the analogies of these columns.

## § 2. Definition of flooding velocity

As the flow mechanisms of flooding phenomenon are quite different in each column, it is difficult to strictly define the flooding phenomenon and to determine the true flooding point experimentally.

For a packed column or a wetted wall column,

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the flooding point has been defined in general as the upper break point on a log-log plot of pressure drop vs. gas velocity, as shown in Fig. 1.

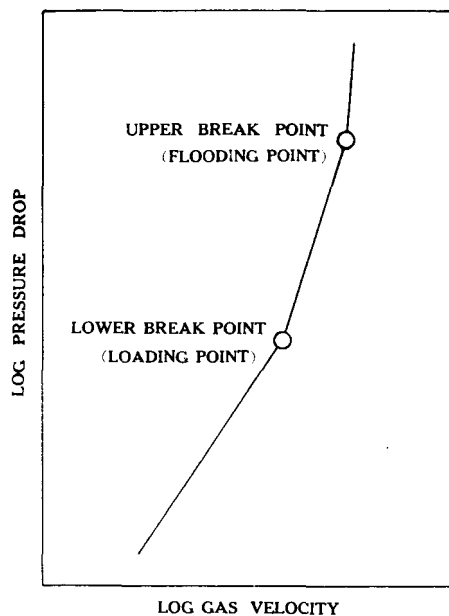


Fig. 1 Typical pressure drop curve in packed column

The visual flooding point is caused by the gas velocity for a given liquid velocity at which the liquid begins to spray out of the top of a column and is mechanically carried up out of the packing by the gas stream.

For plate columns, the flooding can be divided to the following two phenomena generally.

- (i) Owing to excessive entrainment, the aerated froth reaches the above tray.
- (ii) Liquid back up in the downcomer.

The flooding caused by (i) is usually synonymous with the condition which is a sharp increase in pressure drop, as that of a packed column. The flooding caused by (ii) can be prevented by the proper design of the downcomer size. But, few investigations have been done about the relation between (i) and (ii).

As to plate columns, after a strict consideration about bubble cap or perforated plate columns, the tray with downcomer is not counter-current but rather crosscurrent. But, considering from the view point of the operations of these columns, the flooding velocity corresponds with the upper limit in operating. In other words, the flow mechanism of crosscurrent type in the flooding state is approximate to counter-current type. According to this reason, we include in this work the bubble cap column and the perforated plate column with downcomer.

Concerning plate columns, a turbo grid column, as well as a perforated plate column without downcomer, is quite different in flow mechanisms from other bubble cap or perforated plate columns with downcomer. A turbo grid column shows the same curve as a packed column, which

breaks at two points in the log-log plot of pressure drop vs. gas velocity, as shown in Fig. 1. For this reason, the flooding point in a turbo grid column has been defined as the upper break point in the plot mentioned above.

### § 3. Previous work

#### 1) Packed column

In the classical study on the flooding of a packed column, there is a correlation by Sherwood, Shipley, and Holloway<sup>1)</sup>. They presented the correlation curve by plotting previous experimental data in the following log-log coordinates.

$$Y = \frac{w_g^2}{g} \frac{a}{\varepsilon^3} \frac{\rho_g}{\rho_l} \mu^{0.2}, \quad X = \frac{w_l}{w_g} \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \quad (1)$$

However, their available correlation data were obtained through the experiments in which they mainly used raschig rings in varying size from 12.7 to 35 mm, and its deviation gave 29.8%.

In 1945, Lobo, Friend, and Zenz<sup>2)</sup>, investigated the various packing characteristics, improved on the above work of Sherwood et al., and summarized experimental data with an accuracy of 11.5%. Their correlation curve shows Fig. 2.

Recently, Eckert<sup>3)</sup>, by means of correcting the geometrical difference of various packings, has investigated experimentally  $a/\varepsilon^3$  as packing factor and tabulated. (See Table 1)

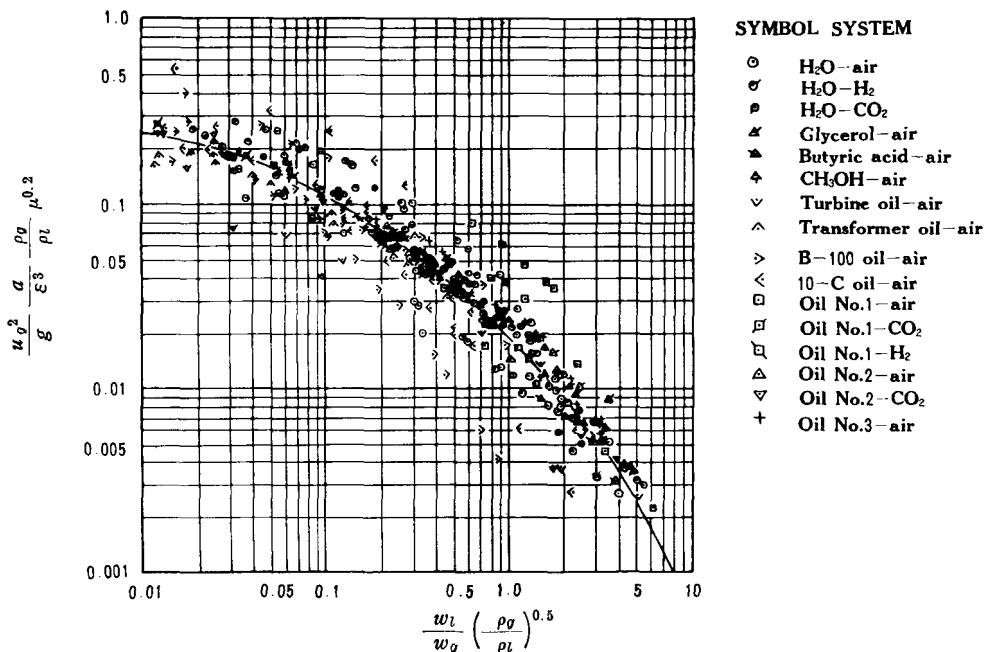


Fig. 2 Correlation of flooding velocity in packed column by Lobo et al<sup>2)</sup>.

Table 1, Packing factor

Type of packing	Materials	Nominal packing size, in.									
		1/4	3/8	1/2	5/8	3/4	1	1 1/4	1 1/2	2	3
Raschig rings	Ceramic	4600	3280	2100	1250	840	525	410	312	214	121
" 1/32-in. wall	Metal	2300		985	850	608	378				
" 1/16-in. wall	Metal			1120	955	755	477	361	272	187	105
" 1/8-in. wall	Metal										125
Intalox saddles	Ceramic	1970		660		477	322		170	131	
Barl saddles	Ceramic	2950		790		560	361		214	148	
Pall rings	Plastic					318	170		105	82	
Pall rings	Metal					233	157		92	66	

Concerning the effect of liquid physical properties on flooding phenomenon, Sherwood et al. showed liquid surface tension had a negligible effect on flooding velocities within the range of 26 to 73 dynes/cm, but Newton, Mason, Metcalfe, and Summers<sup>4)</sup>, using surface active agents, showed the effect of surface tension experimentally: they corrected the original correlation by introducing the term of  $(\sigma_w/\sigma)^3$  as a factor into the abscissa in the original relation (1).

For the reason of above different results, it may be considered that the foaminess of liquid is the factor which affects the flooding velocities.

The original correlation curve shown in Fig. 2 has been represented in a mathematical equation by various investigators. But, because of its complexities, solution for design purpose requires computers.

In 1961, Zenz and Eckert<sup>5)</sup> showed the new chart. They rearranged analytically the original coordinates (1) of Sherwood et al., as follows;

$$Y = \left( \frac{u_g^2}{g} \frac{a}{\epsilon^3} \frac{\rho_g}{\rho_l} \mu^{0.2} \right)^{0.5}$$

$$X = \left[ \frac{w_l}{w_g} \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \right] \left[ \frac{u_g^2}{g} \frac{a}{\epsilon^3} \frac{\rho_g}{\rho_l} \mu^{0.2} \right]^{0.5}$$

that is,

$$\left. \begin{aligned} Y &= u_g \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \left( \frac{a}{\epsilon^3} \frac{\mu^{0.2}}{g} \right)^{0.5} \\ X &= u_l \left( \frac{a}{\epsilon^3} \frac{\mu^{0.2}}{g} \right)^{0.5} \end{aligned} \right\} \quad (2)$$

This correlation shows Fig. 3.

The correlation of (2) means essentially a plot of gas velocity vs. liquid velocity. Fortunately, this simplified flooding correlation eliminates the next tedious manipulation: it requires a trial and error to desire the gas velocity for a known

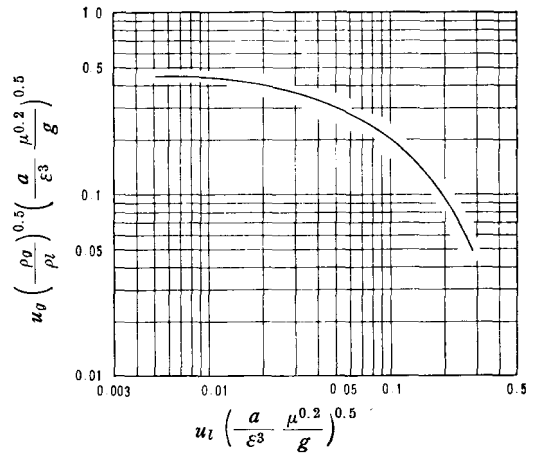


Fig. 3 Correlation of flooding velocity in packed column by Zenz and Eckert<sup>5)</sup>

diameter of the column, because the original correlation has terms of gas velocity in both coordinates.

2) Wetted wall column

Few investigations on the flooding of a wetted wall column have been done, in spite of its being a matter of great importance to industrial operation. Comparison of any flooding correlations shown by various investigators gives quite different result. Perhaps, this may be considered to be due to the difference of various experimental mechanisms by each investigator.

In the flooding correlations of a wetted wall column, Koyanagi and Katayama<sup>6)</sup> investigated experimentally, using the steel pipes of length from 100 to 500 mm, and inner diameter from 12.6 to 60 mm, with air-water, machine oil (viscosity  $18 \pm 2$  c. p.), and heavy oil ( $360 \pm 30$  c. p.), plotted the experimental result in the coordinates (1) of a packed column, and gave the same tendency as that of a packed column. In this

case, they theoretically converted  $a/\varepsilon^3$  in the original coordinates (1) into  $4/D$ , that is,

$$Y = \frac{u_g^2}{g} \frac{4}{D} \frac{\rho_g}{\rho_l} \mu^{0.2}, \quad X = \frac{w_l}{w_g} \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \quad (3)$$

Moreover, they represented the correlation curve in the following mathematical equation.

$$\frac{u_g^2}{g} \frac{4}{D} \frac{\rho_g}{\rho_l} \mu^{0.2} = 1.58 \times \exp \left[ -3.55 \left\{ \left( \frac{w_l}{w_g} \right) \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \right\}^{1/4} \right] \quad (4)$$

### 3) Bubble cap column and perforated plate column with downcomer

For a bubble cap column, Fair and Matthews<sup>7)</sup>, in 1958, presented the generalized correlation by plotting the data of several investigators in the following log-log coordinates.

$$Y = u_g \left( \frac{\rho_g}{\rho_l - \rho_g} \right)^{0.5}, \quad X = \frac{w_l}{w_g} \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \quad (5)$$

Their correlation curve is shown in Fig. 4. This correlation contains the tray spacing as a parameter. This means that, so far as a tray column is concerned, the height of the aerated froth formed on a tray influences flooding dominantly.

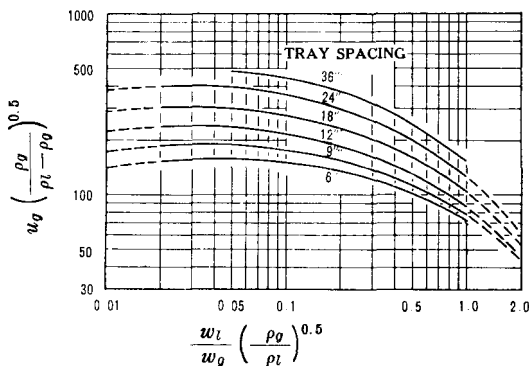


Fig. 4 Correlation of flooding velocity in bubble cap column<sup>7)</sup> and perforated plate column<sup>8)</sup> by Fair and Matthews

The correlation shown in Fig. 4 has the following limitations in designing.

- (i) System is low to non-foaming
- (ii) Weir height is less than 15% of a tray spacing
- (iii) Bubbling area occupies most of area between weirs

For a perforated plate column, in 1961, Fair<sup>8)</sup> showed the same correlation as that of bubble cap column (relation (5) and Fig. 4).

However, this correlation, he had described,

should be used with the following restrictions.

- (i) Surface tension  $\sigma$  is 20 dynes/cm. For  $\sigma \neq 20$  dynes/cm, use (ordinate)  $(\sigma/20)^{0.2}$
- (ii) Weir height is less than 15% of a tray spacing
- (iii) System is low to non-foaming
- (iv) Holes are evenly distributed, and occupied at least 10% of the area between weirs
- (v) Hole sizes in the 1/16 to 1/4 in. range

Moreover, the correlation of Fair is valid for commercial columns having diameter of 18 to 24 in. and larger, and, for the small column, conservative results have been given.

Since 1961, no investigation has been yet presented which was considered effects of hole size, column diameter and other liquid physical properties on flooding. Especially, on a perforated plate column without downcomer, it has not been investigated at all.

### 4) Turbo grid column

In the flooding correlations of a turbo grid column, Kasatkin, Ditnierskii, and Umarov<sup>9)</sup> showed the following equation, which was obtained from their own experimental data.

$$\frac{u_g^2}{g d F^2} \frac{\rho_g}{\rho_l} \mu^{0.16} = 10 \times \exp \left\{ -4 \left( \frac{w_l}{w_g} \right)^{1/4} \left( \frac{\rho_g}{\rho_l} \right)^{1/8} \right\} \quad (6)$$

The form of the above equation is very similar to the packed column correlation (1) of Sherwood et al.

Földes<sup>10)</sup> has mentioned that equation (6) put too much emphasis on the effect of the allowable gas velocity on slot width, because the velocity was directly proportional to the square root of the slot width, and that the data of other investigators were considerably different from the values by the equation (6), especially, in the case of the wider slot than the width from 3.0 to 4.2 mm of Kasatkin et al.

Because of a few studies on flooding of a turbo grid column, no flooding correlation has been yet obtained, which takes into account other physical properties and tray factors.

## § 4. Discussion

As mentioned before, it is clear that various correlations of the flooding velocities in each countercurrent gas-liquid contactor of column type have similar functional forms, except a

bubble cap column and a perforated plate column. From this, in order to compare each correlation as a countercurrent type, it is convenient in general to use the gas-liquid separated coordinates (2) of Zenz and Eckert for a packed column.

For a wetted wall column, the correlation (3) of Koyanagi and Katayama, as well as the rearrangement of Zenz and Eckert, can be rearranged as follows;

$$Y = \left( \frac{u_g^2}{g} \frac{4}{D} \frac{\rho_g}{\rho_l} \mu^{0.2} \right)^{0.5}$$

$$X = \left[ \frac{w_l}{w_g} \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \right] \left[ \frac{u_g^2}{g} \frac{4}{D} \frac{\rho_g}{\rho_l} \mu^{0.2} \right]^{0.5}$$

that is,

$$\left. \begin{aligned} Y &= u_g \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \left( \frac{4}{D} \frac{\mu^{0.2}}{g} \right)^{0.5} \\ X &= u_l \left( \frac{4}{D} \frac{\mu^{0.2}}{g} \right)^{0.5} \end{aligned} \right\} \quad (7)$$

By replotting the original correlation curve (4) in the above log-log coordinates (7), **Fig. 5** can be obtained.

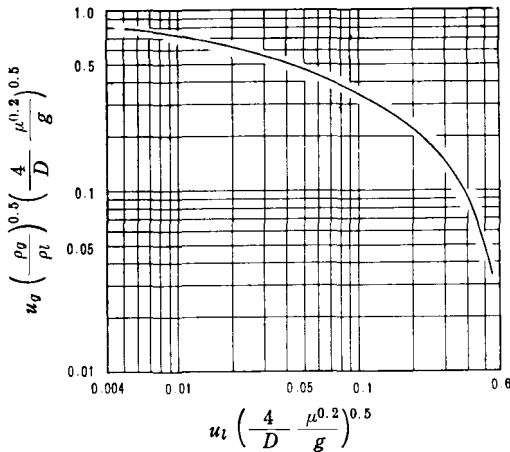


Fig. 5 Correlation of flooding velocity in wetted wall column by (7)

The correlation curve of a wetted wall column shown in Fig. 5 is presented larger by factor 1.4 than that of a packed column in Fig. 3. This is apparently due to the difference caused by assuming  $a/\varepsilon^3$  to be  $4/D$ . In this case, however, provided  $4/D$  to be  $4/D \times (1.4)^2 = 2/D$ , each correlation of a wetted wall column and a packed column may be shown by the same curve.

For a bubble cap column and a perforated plate column, the correlation coordinates (5) of Fair et al. can be converted as follows;

To begin with, using  $\rho_g/(\rho_l - \rho_g) = \rho_g/\rho_l$  for  $\rho_l \gg \rho_g$

$$Y = u_g \left( \frac{\rho_g}{\rho_l} \right)^{0.5}$$

$$X = \left[ u_g \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \right] \left[ \frac{w_l}{w_g} \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \right]$$

that is,

$$Y = u_g \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \quad X = u_l \quad (8)$$

then, provided the variation in  $\mu^{0.2}$  of liquid viscosity (c. p.) is enough small, multiplying (8) by  $(\mu^{0.2}/g)^{0.5}$  gives,

$$Y = u_g \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \left( \frac{\mu^{0.2}}{g} \right)^{0.5} \quad X = u_l \left( \frac{\mu^{0.2}}{g} \right)^{0.5} \quad (9)$$

Apparently, the form of coordinates (9) is similar to the coordinates (2) of a packed column. By replotting the original correlation curve shown in Fig. 4 in above coordinates, **Fig. 6** is obtained.

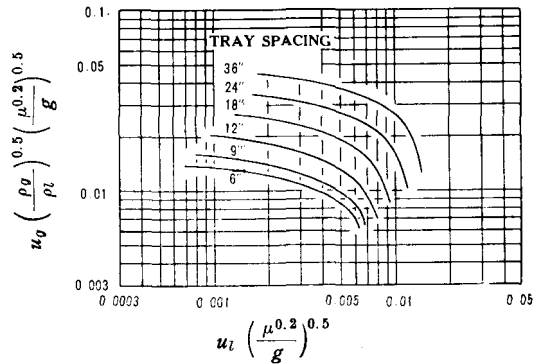


Fig. 6 Correlation of flooding velocity in bubble cap column and perforated plate column by (9)

In Fig. 6, each curve, whose parameter is tray spacing, is similar in general. According to this, by means of neglecting some deviations, and, then, containing tray spacing in coordinate variables, these curves can be represented by a single curve. In this case, the coordinates (9) becomes following.

$$\left. \begin{aligned} Y &= u_g \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \left( \frac{\mu^{0.2}}{g} \right)^{0.5} H^{-0.7} \\ X &= u_l \left( \frac{\mu^{0.2}}{g} \right)^{0.5} H^{-0.7} \end{aligned} \right\} \quad (10)$$

The turbo grid column correlation of Kasatkin et al., as well as a packed column, can be also converted to the following log-log coordinates.

$$\left. \begin{aligned} Y &= u_o \left( \frac{\rho_o}{\rho_l} \right)^{0.5} \left( \frac{1}{dF^2} \frac{\mu^{0.2}}{g} \right)^{0.5} \\ X &= u_l \left( \frac{1}{dF^2} \frac{\mu^{0.2}}{g} \right)^{0.5} \end{aligned} \right\} \quad (11)$$

If the original equation (6) is replotted in the above new coordinates, Fig. 7 is obtained.

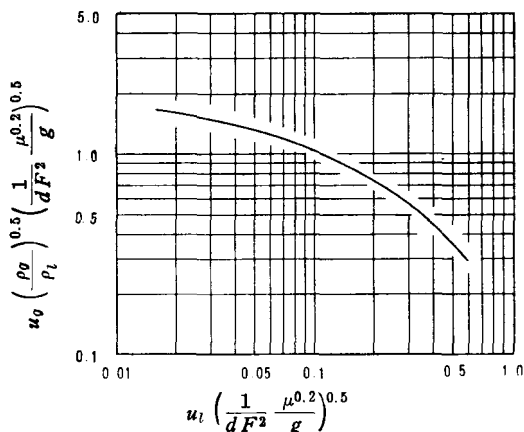


Fig. 7 Correlation of flooding velocity in turbo grid column by (11)

In comparison with various correlation curves (Fig. 3, 5, 6, and 7), these curves show to be similar to each other, and, apparently, the difference of these curves is due to the shape of each column. That is, by estimating the difference of these curves, each column may be compared as countercurrent type.

Next, on the basis of the correlation coordinates (2) of a packed column, by shifting each correlation curve along the coordinates in order to coincide with that of a packed column, Fig. 8 can be obtained.

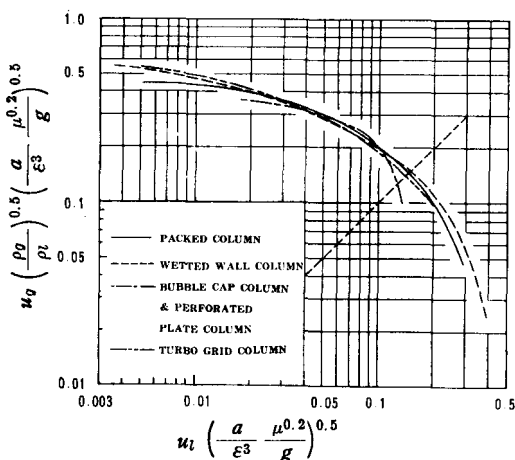


Fig. 8 Generalized correlation of flooding velocity in countercurrent contactor

In Fig. 8, the term corresponding with  $a/\epsilon^3$  in the original coordinates, is as follows;

For wetted wall column,  $2/D$

For bubble cap column and perforated plate column,  $64/H^{1.4}$

For turbo grid column,  $1/9dF^2$

Each correlation curve in Fig. 8 has the same tendency to each other. Considering the scatters on the occasion that each investigator plotted experimental data in the original coordinates, these curves may be shown by a single curve.

As the difference of packing shape may be corrected by packing factor instead of  $a/\epsilon^3$  for a packed column; by assuming the term corresponding with  $a/\epsilon^3$  as a shape factor and then evaluating even the shape factors in each columns, the flooding velocity can be estimated by the single correlation curve, as mentioned above.

Moreover, the correlation curve in Fig. 8 is, apparently, symmetrical against the dotted line in the figure.

This means that the correlation is valid for even when the liquid velocity and the gas velocity are exchanged on the coordinates, i. e., an exchangeability of liquid-gas. For this reason, flooding phenomenon may be considered to be explained analytically.

But, only a few investigations on flooding have been presented. Even for the previous study on a perforated plate column, because the experimental results have neglected the effects of hole size et al., it is necessary to consider the shape factor.

In addition to this, it is necessary to investigate on the effects of liquid surface tension and column diameter which may be considered to affect flooding phenomenon.

## § 5. Conclusion

In the countercurrent gas-liquid contactor of column type, the upper limit of operating regions corresponds with the flooding velocities. That is, on the basis of flooding point, we tried to show the analogy of each column.

For the countercurrent contactor, the flooding point may be defined in general as the upper break point where the log-log curve of pressure drop vs. gas velocity deviates almost vertically upward.

By means of plotting the flooding points of each column (packed column, wetted wall column, bubble cap column, perforated plate column, and turbo grid column) in the following

gas-liquid separated log-log coordinates, these flooding points can be correlated by a single curve.

$$Y = u_g \left( \frac{\rho_g}{\rho_l} \right)^{0.5} \left( S \cdot \frac{l^{0.2}}{g} \right)^{0.5}$$

$$X = u_l \left( S \cdot \frac{l^{0.2}}{g} \right)^{0.5}$$

$\varepsilon$ : fractional voids [—]  
 $\mu$ : liquid viscosity [c. p.]  
 $\sigma$ : liquid surface tension [dynes/cm]  
 $\rho$ : density [Kg/m<sup>3</sup>]  
 subscripts  
 $g$ : gas  
 $l$ : liquid  
 $w$ : water

where  $S$  represents the shape factor correcting the difference due to the shape of each column, as follows;

for packed column, packing factor,  $a/\varepsilon^3$

for wetted wall column,  $2/D$

for bubble cap column and perforated plate column,  $64/H^{1.4}$

for turbo grid column,  $1/9dF^2$

Flooding velocity can be estimated easily by using above correlation curve, and the limits of operation can be compared in each column.

### Nomenclature

$a$ : surface area of packing [m<sup>2</sup>/m<sup>3</sup>]  
 $D$ : column diameter [m]  
 $d$ : slot width [m]  
 $F$ : total slot area to column area ratio [—]  
 $g$ : gravitational acceleration [m/hr<sup>2</sup>]  
 $H$ : tray spacing [m]  
 $u$ : velocity [m<sup>3</sup>/m<sup>2</sup>hr]  
 $w$ : mass velocity [Kg/m<sup>2</sup>hr]

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