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A NEW MODE OF COUNTERCURRENT GAS-LIQUID FLOW IN PACKED COLUMNS

by

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S U M M A R Y

Equations presented in our previous papers (ref. 1,2) for gas-liquid flow in packed columns are used to show that at a given set of gas-liquid rates below flooding rates in countercurrent flow, two types of operation are possible. These are (i) normal operation characterized by stability, low holdup and low pressure gradient; and (ii) incipient flooding operation characterized by instability, high holdup and high pressure gradient. Methods for stabilizing operation in the incipient flooding mode of operation are described. Measurements of flowrates, pressure drop and liquid holdup in a 10cm diameter 1.5m high packed column operating in the normal mode and the incipient flooding mode are reported. The results are in reasonable agreement with predictions from our equations. The equations correctly predict the observed decrease in holdup with increase in gas flowrate at a fixed liquid flowrate in the incipient flooding mode. We suggest that this mode of operation provides a convenient and inexpensive route of increasing separation efficiency and capacity of existing packed columns.

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NOMENCLATURE

a_v = packing area per unit volume of bed (m^{-1})
c = volume of packing pieces per unit volume of bed
g = gravitational acceleration ($m\ s^{-2}$)
G = gas superficial velocity ($m\ s^{-1}$)
h = liquid holdup, i.e. volume of liquid per unit volume of bed
K = apparent volume fraction of dead space
l = packing size (m)
L = liquid superficial velocity ($m\ s^{-1}$)
ρ = density ($kg\ m^{-3}$)
μ = viscosity ($kg\ m^{-1}\ s^{-1}$)
S' = packing factor defined by Buchanan
Subscripts: g - gas
l - liquid
$\frac{dp}{dz}$ = pressure gradient in column (z positive in vertical downward direction) $N\ m^{-3}$

1. INTRODUCTION

Gas liquid contacting in the process industries, such as for gas absorption, stripping and distillation, is often carried out in packed towers in which gas flows upwards against downflow of liquid. In normal operation liquid holdup and pressure gradient are low (below 10% and 2 inches water per foot of column respectively) and the operating flowrates are restricted to below the flooding flowrates. In this paper we show that at the same gas and liquid flowrates a second mode of operation with higher liquid holdup, higher pressure gradient and higher mass transfer coefficient, is possible. This mode of operation, named here as the incipient flooding mode, is unstable, but can be stabilized by simply controlling the pressure gradient in the column with either the liquid or the gas flowrate. We suggest that the incipient flooding mode of operation provides an inexpensive route for increasing separation efficiency in a packed column.

2. THE MODEL FOR TWO PHASE FLOW IN PACKED COLUMNS

In previous papers (ref. 1,2) we showed that for two phase flow in a packed column, liquid holdup, h, and pressure gradient, $(\frac{dp}{dz})$, for a given system can be expressed by

$$h = h(L, \frac{dp}{dz}) \qquad \ldots (1)$$

$$\text{and} \quad \frac{dp}{dz} = \frac{dp}{dz}(h, G) \qquad \ldots (2)$$

where L and G are the liquid and gas superficial velocities. Equation (1) implies that the effect of gas flowrate on holdup is taken into account through its effect on pressure gradient. Similarly equation (2) implies that the effect of liquid flowrate on pressure gradient has been taken into account through its effect on holdup.

Two forms for equation (1) have been presented depending on liquid flow pattern. If we assume a model of turbulent liquid flow down a series of short inclined planes, with a fraction of the kinetic energy destroyed at the bottom of each plane as suggested by Buchanan (ref. 3), the following form of equation (1) can readily be derived for counter-current gas-liquid flow:

$$L = \frac{h\ l^{\frac{1}{2}}}{S'} \left[g - \frac{1}{\rho_l} (\frac{dp}{dz}) \right]^{\frac{1}{2}} \qquad \ldots (3)$$

As the pressure gradient is essentially caused by flow through packings, equation (2) was written in the form of the Ergun (ref. 4,5) equation, as follows:

$$\frac{dp}{dz} = \left[\frac{8.5\ \mu_g\ a_v^2\ G}{\rho_g} + \frac{a_v\ G^2}{\rho_g}\left(\frac{\mu_g\ a_v}{G}\right)^{0.1}\right]\frac{1}{(1\text{-}c\text{-}h\text{-}K)^3} \qquad \ldots (4)$$

The term (1-c-h-K) represents the effective voidage in the packed bed. K is a correction factor adjusted to minimise the difference between experimental $(\frac{dp}{dz})$ measurements and $(\frac{dp}{dz})$ calculated by equation (4). The use of K is based on the recognition that some dead space exists in a packed column thus reducing the effective voidage for gas flow. We shall term K the "apparent volume fraction of dead space".

Combination of equations (3) and (4) gives

$$L = \frac{h\ l^{\frac{1}{2}}}{S'}\left\{g - \frac{1}{\rho_l}\left[\frac{8.5\ \mu_g\ a_v^2\ G}{\rho_g} + \frac{a_v\ G^2}{\rho_g}\left(\frac{\mu_g\ a_v}{G}\right)^{0.1}\right]\frac{1}{(1\text{-}c\text{-}h\text{-}K)^3}\right\}^{\frac{1}{2}} \qquad \ldots (5)$$

Equation (5) has been successfully used to predict flooding flowrates by assuming $(\frac{\partial L}{\partial h})_G = 0$ at the onset of flooding (ref. 1) and to predict holdup in cocurrent gas-liquid flow in packed beds (ref. 2). Equation (5) will be used here to show the possibilities of two modes of operation in countercurrent two phase flow below flooding flowrates.

3. TWO MODES OF OPERATION

Figure 1 shows a graphical solution for equation (5) for countercurrent gas-liquid flow in a packed bed. At point B, $(\frac{\partial L}{\partial h})_G = 0$. This corresponds to the flooding point for the gas flowrate of G_1. At this gas flowrate countercurrent flow with liquid rate greater than that at B will be impossible. Below the flooding flowrate however, Figure 1 shows that at a given L and G, two operating points are possible. Point P in Figure (1) corresponds to typical normal operation of a packed column characterized by low liquid holdup (< 0.1) and low pressure gradient. Point Q in Figure 1 corresponds to operation at high liquid holdup and high pressure gradient. Operation at point Q has not been reported previously and we shall define this mode of operation as operation at incipient flooding.

The main reason why the incipient flooding mode of operation has not been reported previously is that such operation is unstable. This can readily be seen by considering local perturbation of liquid holdup. A slight local decrease in holdup at point Q results in an increase in liquid flow (L) away from the point. The increase in drainage at this point results in further drop in holdup (as liquid is arriving at this point at a constant rate). This will continue until the stable operating point P is reached. Similarly it can be shown that the system is also unstable to any small local increase in holdup.

To stabilize operation in the incipient flooding mode, an external control loop has to be introduced. The same control loop we described previously (ref. 6) for stabilizing operation at the flooding point (point B in Figure 1) can be used here. Stable operation is achieved by (i) initiating flooding at the bottom of the column and (ii) allowing flooding to propagate to near the top of the column. The pressure difference across the column is then controlled by either the gas flowrate (Figure 2) or the liquid flowrate (Figure 3) to within a range corresponding to that at the onset of flooding for about 90% to 95% of the entire column. In this way approximately 90% of the column will operate in the incipient flooding mode and the remainder in the normal mode of operation. Initiation of flooding at the bottom of the column can be achieved (ref. 6) by installing a restrictive packing grid support.

4. EXPERIMENTAL WORK

Experiments were carried out in a 10cm diameter 1.53m high laboratory packed column packed with 1.2cm glass Rashig rings. For countercurrent air-water flow, measurements of G, L, h and $\frac{dp}{dz}$ were made both for the normal mode of operation and the incipient flooding mode of operation. The results are summarised in Figure 4 and Table 1. Details of the experimental procedures and mass transfer studies have been reported elsewhere (ref. 7). During operation in the incipient flooding mode fluctuation in pressure differential across the column and liquid flowrate within 10% of the average values have been achieved. The frequency of fluctuations is about 0.05 cycle per second.

The measurements are compared with values calculated from equation (5) for both modes of operation in Table 1 and Figure (4). In the calculation the factor K is taken as 0.25. ε' for the packings were taken as 1.9, as suggested by Buchanan (ref. 3).

It can be seen that the model correctly predicts two possible modes of operation at a given set of gas-liquid flowrates and also predicts correctly the trend of experimental results. Note that the value of K was selected on the basis of minimising the difference between experimental $(\frac{dp}{dz})$ and calculated $(\frac{dp}{dz})$. Using this value of K, liquid holdup is calculated from equation (5) and compared with the measured holdup. Agreement is fair over the whole range of operating conditions. In particular the trend of variation of holdup with gas flowrate is correctly predicted. In the normal operating mode, equation (5) predicts, at a given L, small increase of h with increase of G. In the incipient flooding mode of operation, however, equation (5) predicts a significant *decrease* of h with *increase* in G. (See Figure 4). This can result in a *decrease* in pressure differential across the column with *increase* in gas flowrate when we are operating in the incipient flooding mode at constant L (Table 1).

It should be obvious that the use of a single value for K as the dead space factor is a gross oversimplification. The value of K is expected to be sensitive to gas flowrate. However the reasonable agreement between measured and calculated $(\frac{dp}{dz})$ over the entire range of gas flowrate suggests that the form of equation (4) for correlating $(\frac{dp}{dz})$ is a correct one. For cocurrent flow at very high gas velocity, we have shown (ref. 2) that K = 0 gives reasonable agreement between observed and calculated holdup and pressure drop.

5. DISCUSSION

The most significant outcome of this work is the discovery of a second mode of operation for countercurrent flow in packed columns. One of the main uses of the packed column is for mass transfer between the gas phase and the liquid phase such as in gas absorption, distillation and stripping. By operating a column in the incipient flooding mode instead of the normal mode at the same flowrates, higher mass transfer rates can be achieved at the expense of higher pressure losses. A six-fold increase in the liquid phase mass transfer coefficient has been observed for the absorption of carbon dioxide in water in our laboratory column. We suggest that conversion of an existing column to operate in the incipient flooding mode may provide an inexpensive route for improving separation efficiency.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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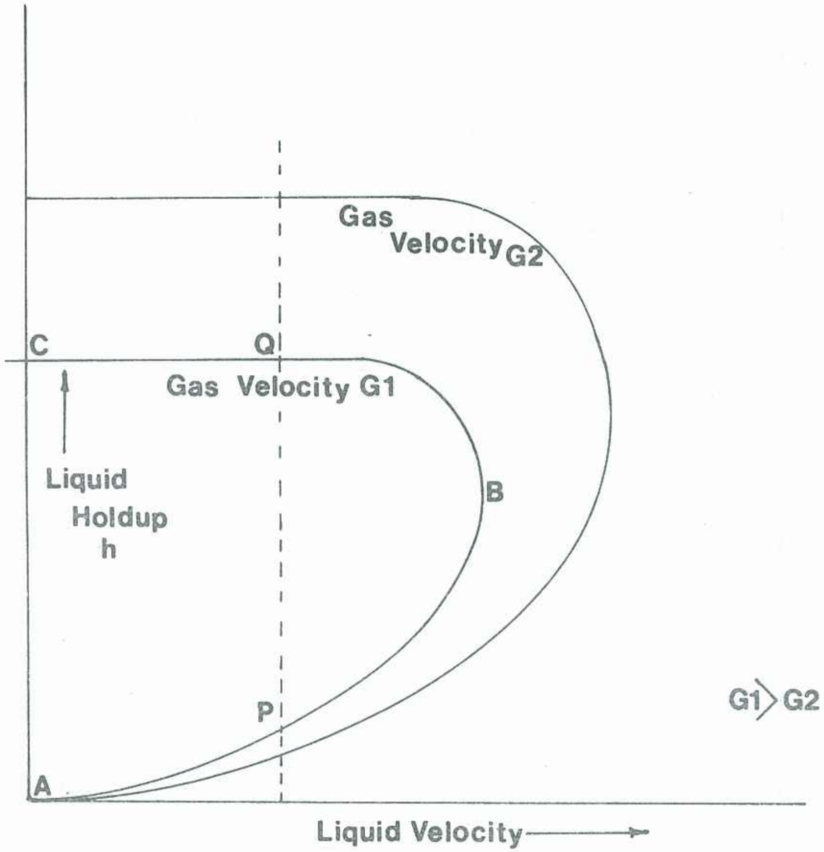
Table 1 Comparison of measured pressure gradient and holdup with calculated values

K = 2.5 S' = 1.9 for calculations

liquid mass velocity - kg m^{-2} hr^{-1}	gas mass velocity - kg m^{-2} hr^{-1}	Operating Mode N-Normal F-Incipient Flooding	$\frac{dp}{dz}$ - N m^{-3}		holdup - h	
			Observed	Calculated	Observed	Calculated
18,000	2,200	N	3,600	4,100	.06	.04
18,000	2,200	F	8,700	9,300	.15	.11
18,000	950	N	740	840	.05	.03
18,000	950	F	9,300	9,600	.25	.21
18,000	700	N	400	500	.05	.03
18,000	700	F	8,800	9,700	.26	.23
36,000	1,100	N	1,500	1,400	.08	.06
36,000	1,100	F	8,100	8,900	.23	.19
36,000	950	N	900	1,100	.07	.06
36,000	950	F	8,700	9,000	.25	.21
36,000	700	N	450	630	.06	.05
36,000	700	F	8,500	9,300	.27	.23
40,500	700	N	580	710	.08	.07
40,500	700	F	8,800	9,100	.27	.23
40,500	300	N	100	190	.07	.06
40,000	300	F	8,600	9,200	.31	.27
51,500	700	N	640	800	.09	.08
51,500	700	F	8,600	8,700	.27	.23
58,900	700	N	950	940	.09	.09
58,900	700	F	5,300	8,500	.32	.22
58,900	300	N	110	250	.08	.09
58,900	300	F	8,500	8,800	.31	.27



Graphical Analysis of Flow in a Packed Column

FIGURE 1

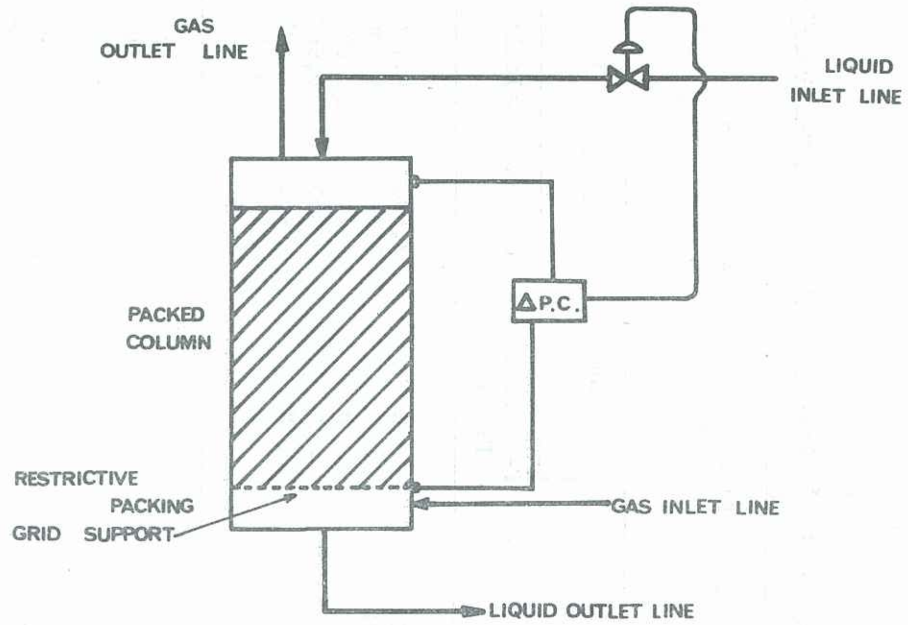


FIGURE 2

OPERATION IN THE INCIPIENT FLOODING MODE BY VARYING LIQUID FLOW

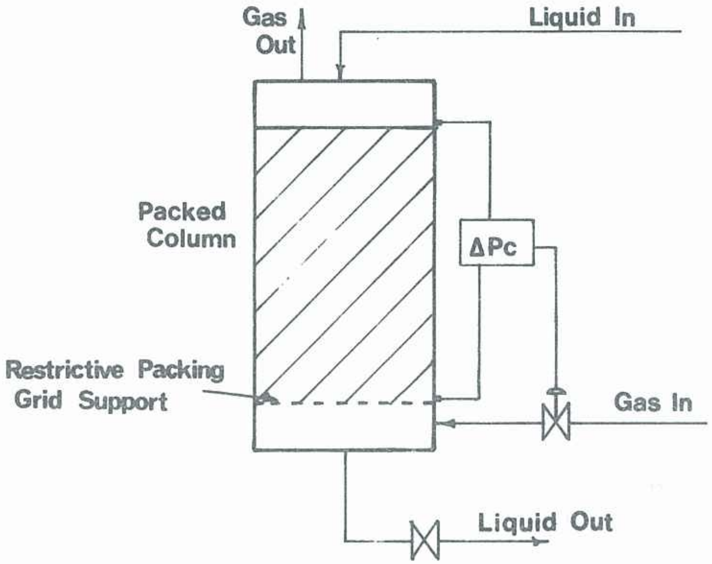


FIGURE 3.
Operation in the Incipient Flooding Mode by Varying GAS Flow.

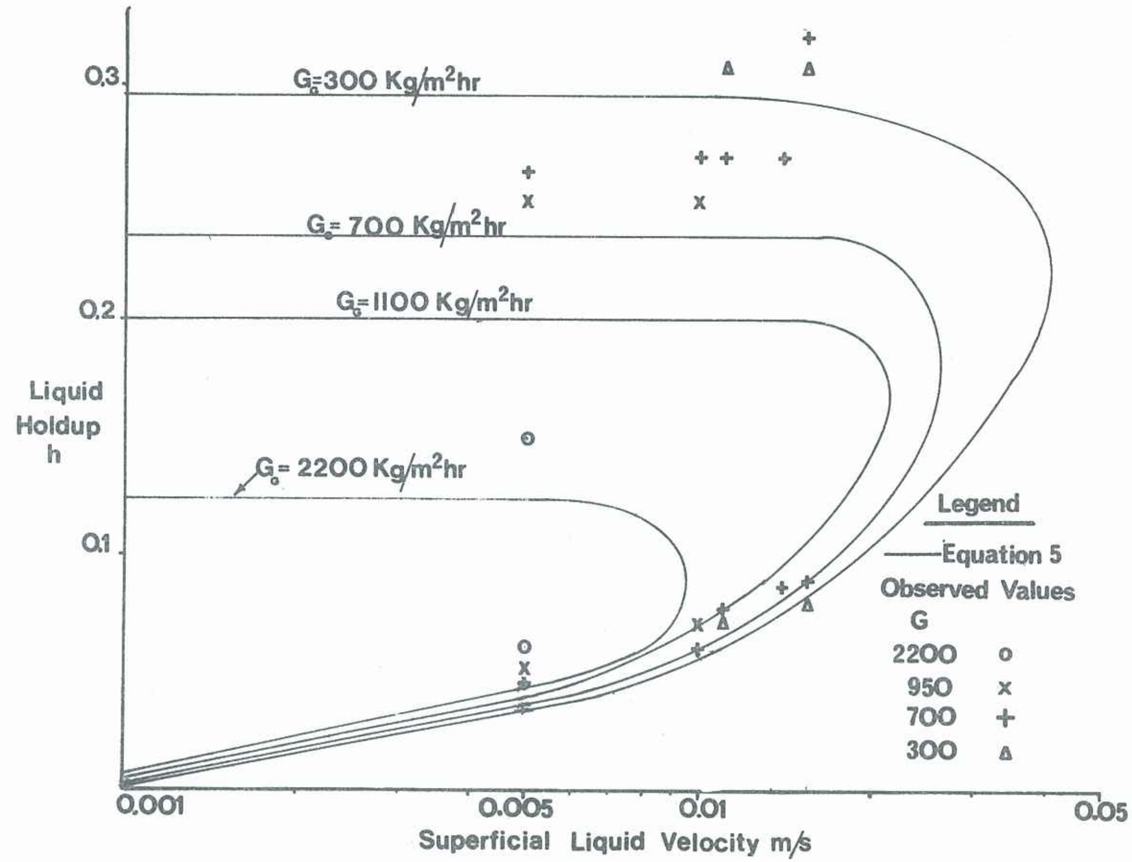


FIGURE 4
Comparision of Measured Holdup and CALCULATED Holdup.