DYNAMIC BEHAVIOUR OF BUBBLED BEDS ON PERFORATED PLATES OF COLUMN REACTORS CHARACTERISTIC PRESSURE FLUCTUATIONS

J. ČERMÁK and F. KAŠTÁNEK

Institute of Chemical Process Fundamentals,
Czechoslovak Academy of Sciences, 165 02 Prague 6 - Suchdol

Received February 25th, 1976

Some aspects of dynamic behaviour are considered of the two-phase system in the bubble-type column reactor. The earlier observed mechanism of single and two-loop circulation is interpreted in relation to characteristic pressure fluctuations as the result of formation of gravitational surface waves. The experiments performed demonstrated the dependence of statistical characteristics of pressure fluctuations on operating parameters.

Recently[1], we have considered the liquid circulation in the bubbled bed in column reactors. On basis of the one and two-loop circulation models in these beds an attempt has been made to model these reactors[2,3]. The recent publication by Kölbel and coworkers[4] has dealt with statistical analysis of porosity fluctuations in this type of reactors. The authors point out to the existence of a steady low-frequency component in the spectrum of these fluctuations and interpret the component in relation to the earlier determined mixing coefficients of the liquid phase. Dynamic studies of the gas–liquid mixture on sieve plates without downcomers[5,6] have demonstrated the random nature of determining structural parameters of the mixture and pointed to the formation of surface gravity waves as the determining factor of the mechanism of flow of both phases through the plate[2,5,6].

THEORETICAL

Let us consider the column reactor with a constant liquid holdup h (usually $h \gg 0{\cdot}1$ m) kept *e.g.* by an external downcomer into which is introduced, through the distributing plate with a very small free plate area, gas at the rate $\bar{G}$ from the chamber below the column. The diameter of the reactor is usually chosen so that the gas velocity in the free area v_G is small and does not exceed 0·3 m. With respect to the small gas momentum for the space below the plate, it can be written

$$\mathrm{d}\tilde{P}_c/\mathrm{d}t = -C(G - \bar{G})\,, \tag{1}$$

where $C = c^2 \varrho_G / V_c$ is the inverse acoustic capacity. For the time averaged values resulting from the momentum balance holds the following relation

$$(\overline{P_c - P_0}) = \varrho_L \bar{h} g + \xi \varrho_G \bar{v}_G^2 / 2 \bar{\varphi}_G^2 . \quad (2)$$

While for the plate without downcomers under conditions usual in the conventional absorption and distillation both terms on the right side are of the comparable magnitude for the bubbled bed, in the column type reactor the second term – in comparison to the first one, – is negligible, so

$$\bar{P}_c \approx \varrho_L \bar{h} g . \quad (3)$$

The two-phase system in the reactor has in the considered range of velocities a very small porosity (Kölbel and coworkers[4] gives in the range of gas velocities $\bar{V}_G = 0-6 \text{ cm s}^{-1}$, $\varepsilon = 0-0{\cdot}20$, or see our recent study[7] *etc.*).

For standing waves in the liquid without internal friction in the vessel of finite depth the following relations between the oscillation frequency ω and wave length λ can be derived by solution of the wave equation for linearized boundary conditions on free surface[8]

$$\omega^2 = (g\, 2\pi/\lambda) \tanh (2\pi h/\lambda) . \quad (4)$$

for $h \gg \lambda$, then

$$\omega^2 = g\, 2\pi/\lambda . \quad (4a)$$

It can be expected that this relation will hold with a fair approximation also in conditions of the considered reactor. The presence of streaming gas and the substitution of the vessel bottom through distributing plate will be reflected in random nature of the whole process.

From two-dimensional wave motion the liquid particles follow approximatelly the paths given by Eqs (in the coordinate system where the plane x, z is situated in the liquid surface):

$$\mathrm{d}x = -\frac{\omega A}{g} \sin \omega t \sinh \frac{2\pi(y + h)}{\lambda} \cos \frac{2\pi x}{\lambda}$$

$$\mathrm{d}y = -\frac{\omega A}{g} \sin \omega t \cosh \frac{2\pi(y + h)}{\lambda} \sin \frac{2\pi x}{\lambda} , \quad (5)$$

thus for the tangents to the paths of particles the relation holds

$$\frac{\mathrm{d}y}{\mathrm{d}x} = -\tanh \frac{2\pi(y + h)}{\lambda} \operatorname{cotg} \frac{2\pi x}{\lambda} . \quad (6)$$

Let us now consider the standing waves in the vessel with circular cross-sectional area with the wave length $\lambda = D$. The liquid then flows according to the Scheme given in Fig. 1. For the state *a*) where the lowest pressure is in the axis of the column the gas flows through the centre of the plate, at the state *b*) at the walls. Alternation of both these states results in entrainment of a certain portion of the gas by liquid which circulates. This state corresponds to the qualitative assumptions of the two-loop circulation[1].

For waving of the wave length $\lambda = 2D$, the liquid flows according to the flow pattern given in Fig. 2. The gas flows through the plate always at one or the other wall and again some of its part can recirculate. This corresponds to the qualitative assumptions on the single-loop circulation[1].

The local fluctuation of the holdup h thus results in pulsation of the gas flow rate through the plate and thus – at the same time – according to Eq. (*1*), in pressure fluctuations in the chamber below the plate. It can be expected, with respect to the above described pattern of waving and the random nature of the process, that these fluctuations will have a stationary ergodic character and their autocorrelation function will be generally of the form

$$R_{PP}(\tau) = \sigma_{PP}^2 \exp(-k\tau) [\cos(2\pi f\tau) + (2\pi f/k) \sin(2\pi f\tau)] \tag{7}$$

with the normal probability distribution of fluctuations P_c.

The autocorrelation function[9] of the gas flow rate fluctuations will be of the form

$$R_{GG}(\tau) = (1/C)^2 [(2\pi f)^2 + k^2] \sigma_{PP}^2 \exp(-k\tau) [\cos(2\pi f\tau) - (2\pi f/k) \sin(2\pi f\tau)] . \tag{8}$$

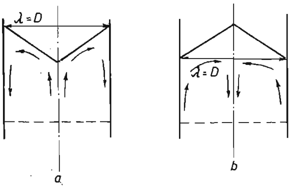

FIG. 1

Liquid Flow in a Vessel with Circular Cross--Sectional Area, $\lambda = D$

a Gas flows through the centre of the plate, *b* gas flows at the walls.

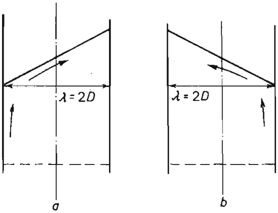

FIG. 2

Liquid Flow in a Vessel with Circular Cross--Sectional Area, $\lambda = 2D$

a, *b* see text.

Standard deviations of fluctuations below the plate and fluctuations in the flow rate are related by the relation

$$\sigma_{GG} = (1/C)\left[(2\pi f)^2 + k^2\right]^{1/2} \sigma_{PP} . \qquad (9)$$

From the known distribution of the amplitude of pressure pulsations below the plate, the distribution of gas flow rates fluctuations can be determined. From these distributions the relative part of the time for which the fluctuations are positive or negative can be also determined. Simultaneously also the relative part of time can be determined for which the gas flows into the reactor through the distributing plate as well as the mean actual flow rate of gas in this interval.

EXPERIMENTAL

The experiments were performed in the column reactor with I.D. 300 mm which was in detail described in the recent publication[1]. The system water–air was used. The distributor was the plate with downcomers with the free plate area 4% and with the hole size 1·6 mm. The level of liquid was maintained by the external siphon seal. The contact of phases was countercurrent. At liquid flow rates 0, 20, 30 l/min in the range of gas flow rates $G = 0-12\ m^3/h$ the pressure fluctuations in the chamber under the distributing plate were measured.

The measurements were performed by use of the inductive transducers of low pressure of the SE Laboratories origin. The tape recorded output signals of approx. 100 s duration were sampled at frequency 30 samples/s and evaluated numerically on ELLIOT 4100 or processed directly on the analogue correlator MUSA. Corresponding characteristic in the amplitude, time and frequency domain were obtained, first of all the standard deviation, the autocorrelation function and spectral densities.

RESULTS

In total 18 experiments were performed. The results obtained are summarized in Table I. These values were obtained as the average of the analog and digital methods of processing the results. The obtained autocorrelation functions were fitted to Eq. (7). The relative deviation of parameter f was for this calculations within the range 0–10% on the average 4·2%. The relative deviation of parameter k from 0–30%, on the average 14·3%. The standard deviation was obtained as the value of autocorrelation function for $\tau = 0$ and was converted to pressure units with the aid of static callibration curve of pressure transducers. The relative deviation of obtained σ_{PP} varied within the range from 0–21%, on the average 13·1%. Results of digital method included also the values of the coefficient of skewness, coefficient of curtosis of the probability distribution as well as of the ratio of mean and standard deviations.

The standard deviations σ_{PP} were transformed according to Eq. (9) to standard deviations of gas flow rates σ_{GG}. The constant equals $C = 5{\cdot}97 \cdot 10^6\ kg\ s^{-2}\ m^{-4}$.

Under the assumption of normal distribution the standardized quantity

$$z = (G - \bar{G})/\sigma_{GG} = \tilde{G}/\sigma_{GG} \quad (10)$$

has the normal distribution N (0; 1).

Then

$$\alpha = \frac{1}{\sqrt{2\pi}} \int_y^\infty \exp\left(-z^2/2\right) dz \; ; \quad y = -\bar{G}/\sigma_{GG} \quad (11)$$

determines the part of time for which the gas flow in the reactor is positive. For the remaining part of time $(1 - \alpha)$ the gas flow is equal to zero or is negative.

The actual mean gas flow rate for the period α is then given by the relation

$$G_{mean} = \bar{G} + \sigma_{GG} z_{mean} \quad (12)$$

TABLE I

Results

L l/min	$\bar{G}$ m^3/h	σ_{PP} Nm^{-2}	$\bar{G}/\sigma_{GG}$	α	$G_{mean}/\bar{G}$	k s^{-1}	f_1 s^{-1}
0	2	35·4	0·085	0·535	5·71	1·56	1·76
	4	46·2	0·116	0·546	4·42	1·86	1·93
	6	53·6	0·149	0·559	3·66	3·14	1·93
	8	71·4	0·167	0·567	3·37	2·02	1·87
	10	80·0	0·166	0·564	3·38	1·87	1·97
	12	90·8	0·166	0·567	3·37	2·24	2·07
20	12	80·5	0·191	0·576	3·06	1·13	2·06
	10	84·4	0·154	0·562	3·57	1·31	2·02
	8	73·6	0·149	0·560	3·65	0·90	1·93
	6	67·7	0·122	0·548	4·27	0·68	1·92
	4	61·7	0·090	0·536	5·43	0·65	1·90
	2	39·9	0·074	0·530	6·37	1·48	1·77
30	2	60·9	0·047	0·519	9·51	0·62	1·85
	4	75·6	0·073	0·529	6·51	0·40	1·93
	6	69·1	0·119	0·548	4·35	0·69	1·93
	8	85·6	0·130	0·552	4·08	1·03	1·91
	10	72·3	0·172	0·568	3·29	1·29	1·96
	12	81·6	0·201	0·580	2·95	1·33	1·94

where

$$z_{mean} = \frac{1}{\sqrt{2\pi}} \exp\left[-(\bar{G}/\sigma_{GG})^2/2\right]. \qquad (13)$$

From values taken from Table I can be seen that the ratio is considerably varying with the flow rates of both phases. It is also obvious that the liquid flow rate has a considerable effect on the standard deviation σ_{PP} at small gas flow rates. As there exists a significant, experimentally found dependence of values σ_{PP} on basic hydrodynamical macro-parameters *e.g.* of the backmixing coefficient it is necessary to stress – unlike to the already published opinions – the effect of liquid flow rate at small gas flow rates.

This is because the use of small gas flow rates in these reactor types is quite frequent (*e.g.* in chlorination). If we *e.g.* analyse the experimentally determined liquid backmixing flow values through perforated plates as published in our recent study[10], (Table I, page 1683) the three-fold increase in the liquid flow rate at gas flow rates corresponding to the linear velocity $\bar{v}_G = 0{\cdot}042$ m/s causes an 1·88-times increase in the backmixing, for the same increase in the liquid flow rate at linear gas velocities $\bar{v}_G = 0{\cdot}008$ m/s the increase in the backmixing is 3·6-times higher. The corresponding relatively highest increase in the standard deviation is exactly in regions of low gas flow rates and it has been determined experimentally that backmixing increases proportionally with the increasing standard deviation of pressure fluctuations.

Qualitatively, it can be said that the standard deviation remains more or less constant from linear gas velocities $v_G \approx 0{\cdot}033$ m/s (in our case this corresponds to standard deviations $\sigma_{PP} \approx 75$ Nm^{-2}), regardless the liquid flow rate, and the effect of the liquid flow rate is already insignificant. The effect of standard deviation on the mean porosity has not been found in our experiments.

From the point of view of our preceding considerations it is possible to expect a significant relation between the diameter of the column and the frequency and amplitude characteristics of pressure pulsations of the bubbled bed. As a formation of circulating loops is affected by the fluctuation characteristics, it is possible to model the effect of the size of bubble-type reactors on this basis with a greater sensitivity. The dynamic modelling aimed at description of the effect of the diameter and the bed height on mass transfer is the primary aim of our future work.

LIST OF SYMBOLS

c	velocity of sound
C	inverse accoustic capacity
D	diameter of column
f	frequency
g	gravitational acceleration

G	gas flow rate
h	holdup (height) liquid
k	parameter of autocorrelation function
Pc	pressure in the distributing chamber
P_0	pressure above the bed
R	autocorrelation function
t	time
v_G	velocity of gas
ε	porosity
ξ	friction factor
λ	wave length
φ_G	relative area for gas flow
ϱ_G	specific mass
$\omega = 2\pi f$	circular frequency
σ^2	variance
τ	time lag
$\sim$	fluctuating component
$-$	mean value

REFERENCES

1. Zahradník J., Kaštánek F., Rylek M.: This Journal *39*, 1403 (1974).
2. Kaštánek F., Rylek M., Nývlt V.: This Journal *39*, 3246 (1974).
3. Kaštánek F.: This Journal, in press.
4. Kölbel H., Beinhauer R., Langemann H.: Chem.-Ing.-Tech. *44*, 697 (1972).
5. Čermák J.: This Journal *38*, 3373 (1973).
6. Shoukry E. I., Čermák J., Kolář V.: Chem. Eng. J. *8*, 27 (1974)
7. Kaštánek F., Nývlt V., Rylek M.: This Journal *39*, 528 (1974).
8. Stokes J. J.: *Water Waves*. Interscience, New York 1957.
9. Ventcel' E. S., Ovcharov L. A.: *Teoriya Veroyatnosti*. Nauka, Moscow 1973.
10. Kaštánek F., Zahradník J., Rylek M.: This Journal *39*, 1672 (1974).

Translated by M. Rylek.