THE GAS CONTENT IN A THREE-PHASE FLUIDIZED BED

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Processes taking place in three-phase systems have been ever more widely introduced in recent years into the chemical industry [1, 2]; in this connection it is of interest to investigate the laws governing the hydrodynamics of a three-phase fluidized bed (gas-liquid-solid particles).

The main body of published work [3-6] is mainly devoted to the study of the partial case of the existence of a three-phase system in which the feed of liquid into the zone of observation is equal to zero, and only the gas is blown through an apparatus, filled with a liquid phase, and containing a solid phase at concentrations not exceeding 40%. The countercurrent motion of a gas and a liquid in columns with a fluidized bed of packing has also been the subject of study [7, 8].

A small number of papers is devoted to the study of the hydrodynamics of a three-phase fluidized bed with the joint passage of the liquid and gas phases through a distributing grid, in an apparatus containing a solid phase [9-11].

There exists an undoubted connection between hydrodynamic conditions and mass transfer in a three-phase fluidized bed; the most important characteristics of the three-phase system are the gas content and the size of the gas bubbles. For example, with the hydrocracking of residual or heavy distillate petroleum feedstock in a three-phase fluidized bed, the number and the size of the bubbles of hydrogen-containing gas characterize, without doubt, the degree of the reserve of hydrogen dissolved in the liquid phase of the reaction mixture, and which is consumed in the reactions taking place in this liquid phase.

The main purpose of the present work is to elucidate the dependence of the gas content, that is, the fraction of the volume of a three-phase bed occupied by bubbles of the gas phase on the reduced gas and liquid velocities, the concentration of the solid phase, and the geometry of the distributing grid. In addition, it was important to establish what factors affect the size of the bubbles of the gas phase, and in what directions.

The investigations were carried out in a transparent reactor model with a diameter of 146 mm and a height of 1270 mm. The upper part of the reactor model ended in a cylinder made of a brass grid, fastened around the periphery of the reactor model. This permitted holding practically constant the dynamic level of the liquid in the apparatus without loss of the solid phase. The size of the grid openings was 300 × 300 microns. A more detailed diagram of the experimental unit is given in [12].

The distributing devices were drilled steel grids with a live cross section of 1.03 and 0.26% of the area of the vessel (55 and 14 openings, respectively, with a diameter of 2 mm). The liquid and gas phases were water and air. The solid phase consisted of three samples of a free-flowing mass, whose properties are given in Tables 1 and 2.

Into the model reactor there was charged a previously fluidized mass of solid particles; then the liquid was fed from under the grid and the bed of solid particles was brought to a determined degree of expansion, after which blowing of the air was started.

The ratio of the water and air rates was so selected that the solid phase was distributed over the whole height of the zone of observation. The quality of the distribution of the solid phase was monitored visually from the presence of solid particles on the surface of the fluidized bed. An increase in the air flow rate above a certain limit with an unchanged water flow rate led to a violent ejection of the suspension, which could not occur in an actual industrial process; therefore, with an increase in the air flow rate, there took place simultaneously a decrease in

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TABLE 1. General Characteristics of Samples of the Solid Phase

Parameters	Glass spheres (sample 1)	Spherical aluminosilicate catalyst (sample 2)	Spherical aluminum-molybdenum-cobalt catalyst (sample 3)
Equivalent diameter, mm	0.730	0.770	0.740
True density, kg/m³.	2700	2220	3470
Poured density, kg/m³	1860	598	688
Apparent density in an air atmosphere, kg/m³ . . .	2700	784	1016
Porosity of particle, vol. %	0.00	64.7	70.0

TABLE 2. Particle-Size Compositions of Samples of Solid Phase

Size of sieve openings	Residue on sieve, mass %		
	sample 1	sample 2	sample 3
1.00.	9.00	8.48	8.88
0.85.	25.44	32.56	33.00
0.63.	32.88	30.40	33.48
0.40.	30.84	26.80	24.08
0.315	1.44	1.68	0.48
0.20.	0.30	0.08	0.08
0.16.	0.10	0.00	0.00

TABLE 3. Values of the Stability Criterion for a Three-Phase Bed

Live cross section of grid, %	Concen. of solid phase, kg/m³	Stability criterion
0,26	965	30,7
1,03	965	30,6
0.26	1247	48,4
1,03	1247	48.3

TABLE 4. Gas Content of a Three-Phase Fluidized Bed

Live cross section of grid, %	Concen. of solid phase γ, kg/m³	Flow rate of gas phase v_g, mm/sec	Gas content ε_3 vol. %	Rate of free emersion v_0, mm/sec
0,26	965	52,9	4,6	280
0,26	1247	40,0	4,4	373
1,03	965	48,9	4,9	362
1,03	1247	38,3	4,3	433

TABLE 5. Values of the Coefficient K and of the Exponents

No. of solid-phase sample	K	m	n	v_g, mm/sec	v_{liq}, mm/sec	γ, kg/m³
1	0.1026	0,780	2.09	40—20	15—90	430—1250
2	0,10[illegible]8	0,630	3,01	20—170	5—30	140—450
3	0,0526	0,670	1,69	20—200	5—40	140—450

the water flow rate. There is observed a clear linear dependence between the gas and liquid rates, bringing about, in each individual case, an optimum degree of completeness of the distribution of the solid phase over the whole volume of the liquid on the grid. This dependence (Fig. 1) is expressed, in the general form, by the equation

$$v_{liq} + av_g = b, \tag{1}$$

where v_{liq} is the flow rate of the liquid, referred to the total area of the cross section of the vessel; v_g is the flow rate of the gas, referred to the total area of the cross section of the vessel; a and b are constants.

In the air-water system, with glass spheres at a concentration of the solid phase of 965 kg/m³, a variation of

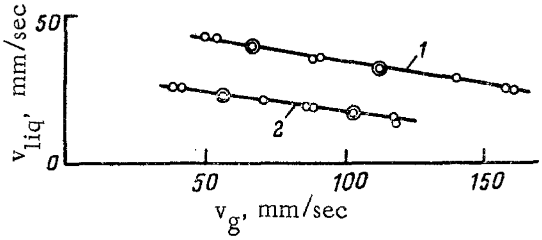

Fig. 1

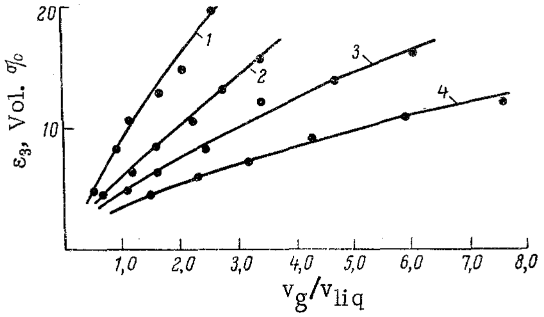

Fig. 2

Fig. 1. Interdependence of the gas and liquid flow rates (solid phase-sample 1, live cross section of the grid – 1.03%): 1) γ = 1246 kg/m³; 2) γ = 965 kg/m³.

Fig. 2. Dependence of the gas content on the concentration of the solid phase for glass spheres. Gas content γ, kg/m³: 1) 429; 2) 682; 3) 965; 4) 1247.

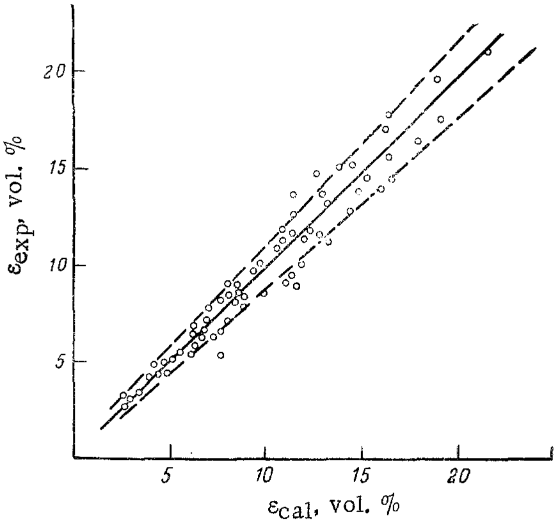

Fig. 3. Comparison of calculated and experimental data on the gas content in the three-phase fluidized bed.

v_{liq} from 25.7 to 15.4 mm/sec leads to an increase in v_g from 40.1 to 116.4 mm/sec; here, a and b remain constant, and Eq. (1) assumes the form

$$x_{liq} + 0{,}129 v_g = 30{,}6$$

The value of b in Eq. (1) can be regarded as a criterion of the stability of a given three-phase fluidized bed (Table 3).

The gas content, that is, the volumetric fraction of gas, suspended in the form of a multitude of bubbles in the liquid, was determined by the method of the simultaneous cutting off of the flows of water and air, with subsequent recording of the height of the quiescent water level.

The value of the gas content was determined using the equations

$$\varepsilon_2 = \frac{v_0 - v_{liq_2}}{v_0},$$
$$\varepsilon_3 = \frac{v_0 - (v_{liq_3} + v_T)}{v_0}, \qquad (2)$$

where ε_2 is the gas content of the two-phase water-air system; ε_3 is the gas content of the three-phase water-air, solid particle system; v_0 is the total volume of the observation zone; v_{liq_2} is the volume of the liquid phase in a two-phase system; v_{liq_3} is the volume of the liquid phase in a three-phase system; v_T is the volume of the solid phase in a three-phase system.

The dependence of the gas content in a three-phase fluidized bed on the live cross section of the distributing grid, with comparable hydrodynamic conditions, is shown in Table 4.

A consideration of Table 4 shows that, with a given concentration of the solid phase, the gas content is almost independent of the live cross section of the distributing grid.

Examination of the experimental data showed that the equation for the gas content, in the most general form, must have the following form:

$$\varepsilon = f(v_g, v_{lig}, \gamma), \qquad (3)$$

where γ is the concentration of the solid phase. Analysis of the curves of Fig. 2, and analysis of the experimental data by the method of least squares permit obtaining the equation for the gas content in the form

$$\varepsilon_3 = K(1 - \gamma_0)^m \left(\frac{v_g}{v_{liq}}\right)^n, \qquad (4)$$

where γ_0 is the volumetric fraction of the solid phase in a three-phase suspension, equal to the ratio of the mass concentration of the solid phase (in kg/m^3) to its apparent density (in kg/m^3).

At $\gamma = 0$ and $\gamma_0 = 0$, ε_3 is then transformed into ε_2 which, with exactly the same pair of values of v_g and v_{liq}, is always greater than ε_3, mainly because the solid phase displaces part of the liquid, while gas bubbles can arise and exist only in the liquid phase.*

The dependence of the coefficient K and of the exponents m and n on the nature of the sample of the solid phase is shown in Table 5.

The empirical Eq. (4), at the given level of the investigations, only within the above interval of velocities and for the given dimensions of the zone of observation, describes the results obtained with an accuracy up to ±10%, which is illustrated by the correlation curve, Fig. 3.

Recording of the duration of the separation of the gas and liquid phases in the experiments on the gas content permitted calculation of the mean rate of the free emersion of the multitude of bubbles forming with the simultaneous feeding of water and air through the grid into the zone of observation. This rate is determined by the equation

$$v_0 = \frac{H'}{\tau_0} \text{ mm/sec}, \tag{5}$$

where H' is the height of the water level in the model, calculated from the grid, after completion of the separation of the gas and liquid phases, mm; τ_0 is the interval of time (in seconds) from the moment of the cutting off of the flows of water and air to the moment of completion of the separation of the gas and liquid phases.

The value of τ_0 is determined with great accuracy, since at the moment when the flows of the phases are cut off, and after the whole emersion time, there is retained a clearly visible flat lower boundary of the multitude of bubbles.

Summaries of the study of the rate v_0 of free emersion are shown in Table 4.

Examination of the experimental data shows that:

1) The velocity v_0 increases, with an increase in the concentration of the solid phase in the model up to the moment when the flows are cut off;

2) The velocity v_0 increases with an increase in the live cross section of the grid, with openings of the same diameter.

The reason for the increase in the rate v_0 in the given stage of the investigation must be explained by an increase in the diameter of the bubbles, assuming that they retain a spherical form. It follows from this that collision between the bubbles and the suspended solid particles leads to an increase in the size of these bubbles. Further, once the rate of free emersion of the bubbles can be regarded as a certain criterion of the degree of dispersion of the gas phase and, as has been noted above, the gas content ε_3 is almost independent of the live cross section of the grid, then, the smaller the value of v_0, the smaller the volume of each bubble and the greater their number and, consequently, the greater the total mass-transfer surface between the gas and liquid phases of the reaction mixture.

The increase in the mass-transfer surface with a decrease in the live cross section of the grid, and the consequent increase in the rate of feeding of the liquid phase by the gaseous reagent consumed in an industrial process, have been confirmed by experiments under the operating conditions in a pilot plant for the hydrocracking of a heavy petroleum feedstock, where a decrease in the live cross section of the distributing grid brought about a substantial increase in the hydrogenation effect [13].

CONCLUSIONS

1. The interrelationship between the working rates of the gas and liquid phases in a three-phase fluidized bed has a linear character.

2. The gas content of a three-phase bed, determined by Eq. (4), depends on the nature and the concentration of the solid phase and on the ratio of the flowing phases, but does not depend on the live cross section of the distributing grid.

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* The rigorous connection between v_g and v_{liq} is determined by Eq. (1).

3. The contact surface between the gas and liquid phases (the mass-transfer surface) decreases with an increase in the concentration of the solid phase, and increases with a decrease of the live cross section of the distributing grid.

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