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SCIENTIFIC PAPER

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MASS TRANSFER IN A MULTIPHASE VIBRATION COLUMN.
II – INTERFACIAL AREA

The results of the analysis of the mass transfer characteristics of a reciprocating plate column (RPC) of the Karr type (2.54 and 9.2 cm internal diameter) in the cases a of two–phase (gas–liquid) and three–phase system (gas–liquid–solid) are presented. The specific gas–liquid interfacial area (a) was determined at different operating conditions by applying the chemical method of sodium sulfite oxidation.

The obtained results showed that the specific interfacial area depended on the vibration intensity, the superficial gas velocity and physical characteristics of the liquid phase, as well as on the solid content in the RPC in the case of the three–phase system. An empirical correlation was derived indicating that the specific interfacial area did not depend on the column diameter and that it might be applied for two– and three–phase systems in a RPC.

$a = 18883\ (P_{av})^{0.31} u_g^{0.97}$

The interfacial gas–liquid area is one of the most important mass–transfer characteristics of multiphase column contactors. It directly influences the mass transfer between the gas and liquid phase, and mostly depends on the hydrodynamic conditions in the column and, of course, on the physical characteristics of the liquid phase. The interfacial area in a multiphase (gas–liquid or gas–liquid–solid) reciprocating plate column (RPC) depends on the operating conditions (vibration intensity, i.e. on the power consumption for mixing and on the superficial gas and/or liquid velocity), column geometry (diameter, number of perforated plates situated on the axial rod, and free cross section area of the plate) and on the physical characteristics of the liquid phase (presence of different compounds: electrolytes or non–electrolytes).

INFLUENCE OF THE OPERATING PARAMETERS

The interfacial area increases by increasing the vibration intensity (defined as the product of the amplitude and vibration frequency, Af) and the superficial gas velocity [1–5]. The influence of the vibration intensity on the interfacial area strongly depends on the regime of the gas–liquid dispersion in the column [4]. By increasing the vibration intensity in the regime of low vibration intensity, although the gas hold–up slightly decreases, the interfacial area increases which is caused by a decrease of the bubble diameters [3], or remains constant as a consequence of the same and opposite changes of the two quantities which directly influence the interfacial area: gas hold–up (increases) and bubble diameter (decreases) [4–6]. The interfacial area is not changed by the vibration intensity if Af < 2 cm/s [5], and for greater values of the vibration intensity both values (gas hold–up and bubble diameter) positively act increasing the interfacial area.

The influence of the superficial gas velocity on the interfacial area is very important especially in the case of low vibration intensities. For a low value of the superficial gas velocity, an increase of the gas–liquid dispersion in the RPC by the motion of perforated plates in the column intensifies the breaking of the bubbles and causes an increase of the interfacial area [7]. At a higher superficial gas velocity, when a greater part of the RPC is filled by the gas phase (large value of gas hold–up), the bubble size increases and they start to be densely packed in the column, favoring their coalescence [6]. Although the bubble size increases, the specific interfacial area might be increased as an effect of the larger gas hold–up in the column [2–5].

There is no agreement in the literature about the influence of liquid superficial velocity, primarily as a result of the different applied operating conditions for interfacial area determination. So, one group of researchers reported that the influence of the liquid superficial velocity might be neglected [4], presumably as a consequence of the slight influence on the bubble size and on the gas hold–up. According to others, the interfacial area increases with increase of the superficial liquid velocity as a result of bubble size decrease [1, 2, 5].

The flow arrangement of the gas and liquid phase contact in a RPC influences the interfacial area. It was determined that larger values of the interfacial area could be obtained by co–current flow of the phases compared to counter–current flow due to the larger value of the gas hold–up [3].

Influence of the liquid physical characteristics

There are only few data concerning the dependence of the interfacial area on the liquid physical characteristics. Only some positive influence of the electrolytes present in water and larger values of the interfacial area than in pure water have been reported in

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the literature. The diminishment of bubble size in the presence of such compounds is the main reason for this effect [8, 9]. Namely, the electrolytes hindered coalescence of the bubbles by the electrostatic potential on the gas–liquid interface causing smaller bubble size compared to the sizes in pure water. On the other hand, on the basis of the fairly similar values of the interfacial area determined by applying the chemical and photographic method it was indirectly concluded that the characteristics of the liquid phase do not affect bubble coalescence or the interfacial area in a RPC to a larger extent [4]. That was explained as a result of the same effect of the electrolyte present in water. Namely it hindered bubble coalescence, but on the other hand, the influence of vibration created a fine gas–liquid dispersion by diminishing the bubble size during their flow through the holes of the perforated plates.

Influence of column geometry

Increase of the column diameter and free cross section of the plate decreases the gas hold–up and interfacial area in a RPC, although only a minor decrease of the bubble size was detected if the hole diameter of the plate was increased, and only a minor increase of the bubble size by increasing the free area of the plate [3].

Influence of the solid phase present in a column

This phenomenon was investigated only in one paper. By adding Rashig rings in the column in every space between two plates (2.5 % vol.), an increase of 30% of the interfacial area was reported [3].

Correlation for interfacial area calculation

It was found that some critical value of the vibration intensity exists determining different types of the correlation equation, i.e. the relation between the interfacial area and vibration intensity and the superficial gas velocity. Namely, the critical vibration intensity, which corresponds to some value of the critical power consumption, depends on the superficial gas velocity [6], while the critical power consumption depends not only on the critical value of the superficial gas velocity but also on the critical gas hold–up [4]. So, for vibration intensities lower than the critical one, the specific interfacial area only depends on the superficial gas velocity and there is only a minor influence of vibration [4–6]. The behavior of a RPC in such a case is very similar to a bubble column, because the gas hold–up and interfacial area do not depend on the vibration intensity [4]. Both the aeration (i.e. the superficial gas velocity) and power consumption (i.e. vibration intensity) significantly influence the status of the gas–liquid dispersion if the vibration intensity is greater than the critical one. It might be explained by the influence of aeration and vibration on bubble breaking and coalescence, which is the main factor influencing the bubble size and interfacial area.

Correlations from the literature, useful for calculating the interfacial area in a RPC, are given in Table 1. These empirical correlations include the most important parameters influencing and determining the value of the interfacial area.

Comparison of different reactor types

At the same specific power used for mixing and for the same superficial gas velocity, the determined

Table 1. Correlation for determining the gas–liquid interfacial area

Liquid flow	D_c cm	n_p	h cm	d_o mm		A cm	Methods	Correlation	Reference
Charge	2,54	65 33	25–5.0	8 7	0.51 0.41	2.35	Chemical and physical (photography)	For $P_g^* > P_{g,cr}^*$: $a = 1783\ (P_g^*)^{0.3}\ u_g^{0.6}$ For $P_g^* < P_{g,cr}^*$: $a = 1583\ u_g^{0.6}$	[10] [4]
↑↑	5.08	84	2.54	15	0.53	0–1.88	Photography	$a = 0.333\ (Af)^{0.593}\ u_g^{0.912}\ u_l^{0.133}$	[5]
↑↑	9.3	10	5.6	3–65	0.09–0.306	–	Chemical	For $Af \geq 5$ cm/s: $a = 0.284\ (Af)^{0.8}\ u_g^{0.5}\ u_l^{0.35}\ d_o^{-0.1}\ \varepsilon^{-0.3}$	[3]
↑↓								For $Af < 5$ cm/s: $a = 0.63\ (Af)^{0.2}\ u_g^{0.76}\ u_l^{0.3}\ d_o^{-0.2}\ \varepsilon^{-0.1}$	
↑↓	10	–	10–30	1.6	0.23 0.38^a	0.16–0.32	Measurement of transferred light	For $u_g < 0.1$ m/s: $a = \frac{425\ u_g^{0.5}\ (1+8.15\ u_l)\ [1+5.5(Af-Af_{cr})^{0.43}]}{h^{0.14}}$ For $u_g \geq 0.1$ m/s: $a = \frac{24.5\ (1+2.31\ u_l)\ [1+5.5(Af-Af_{cr})^{0.43}]}{h^{0.38}}$ For $u_g \geq 0.1$ m/s: $a = \frac{24.5\ (1+2.31\ u_l)\ [1+5.5(Af-Af_{cr})^{0.43}]}{h^{0.38}}$	Š2]

interfacial area in a gas–liquid RPC is several times greater than those reported in a stirred tank reactor and other columns such as: a bubble column, a packed bed column and a column with plates [1, 2, 5, 8]. This is the result of the higher gas hold–up and smaller bubble size obtained in a RPC. The differences between the determined interfacial areas was reported for different types of RPC. At the same superficial gas velocity a larger interfacial area was determined in the Prochazka type RPC (column with segmented plates) [1,2], compared to the Karr type RPC characterized by perforated plates with a fairly large free area of one plate [5]. A greater rate of local energy dissipation and concentrated scatter of the mechanical energy in the vicinity of the segmented cross section of the plate was used to explain the phenomena observed in the Prochazka type RPC.

In the present paper the interfacial area was analyzed at different operating conditions in a Karr type RPC of 2.54 and 9.2 cm diameter. The main goals of the investigation were to determine the influences of mixing (vibration), aeration and the presence of solid phase in the column on the interfacial area. Also, the evaluation of a useful correlation was targeted as the final goal of such investigations also taking into account column geometry (diameter) and system type (two– or three–phase). The derived correlation could be used for comparing the mass transfer characteristics of a RPC and other types of gas–liquid reactors at the same operating conditions.

EXPERIMENTAL PART

A chemical method (sodium sulfite oxidation) was used for interfacial area experimental determination in an experimental unit and under working conditions described in detail in the first part of the paper dealing with the mass transfer characteristics of a RPC [9]. The same experimental procedure was applied as those in the case of volumetric mass transfer coefficient determination [Part I; 9]. Only an other type of catalyst ($CoSO_4$; concentration 10^{-3} kmol/m^3) was used. The specific interfacial area was calculated on the basis of the experimentally determined rate of oxygen consumption [10]:

$$a = \frac{(r_{O_2})_{max}}{M^{0.5} \cdot (c^*_{O_2})^{1.5}} \qquad (1)$$

Oxygen solubility ($c^*_{O_2} = 1.67 \cdot 10^{-4}$ kmol/m^3) at the different conditions applied in this investigation was calculated for the aqueous solution of sodium sulfite (conc. 0.8 kmol/m^3), and the value of the parameter $M = (1.5\, k_2\, D_{O_2})^{1/2}$ was experimentally determined (0.095 m$^{2.5}$/ /(kmol$^{0.5}$s)) [9].

The specific interfacial area was analyzed on the basis of gas–liquid photography made at one moment and calculated the Sauter bubble size and the experimentally determined gas hold–up:

$$a = \frac{6\varepsilon_g}{d_{3,2}} \qquad (2)$$

The gas hold–up was determined, after stopping all the flows (gas and liquid) and mixing in a column, by measuring the liquid volume remaining in the column. It represented the ratio of the gas volume and the volume of the gas–liquid dispersion.

RESULTS AND DISCUSSION

Figure 1 presents the interfacial area dependency of the vibration intensity in the case of the two–phase and three–phase operation modes of a RPC. For

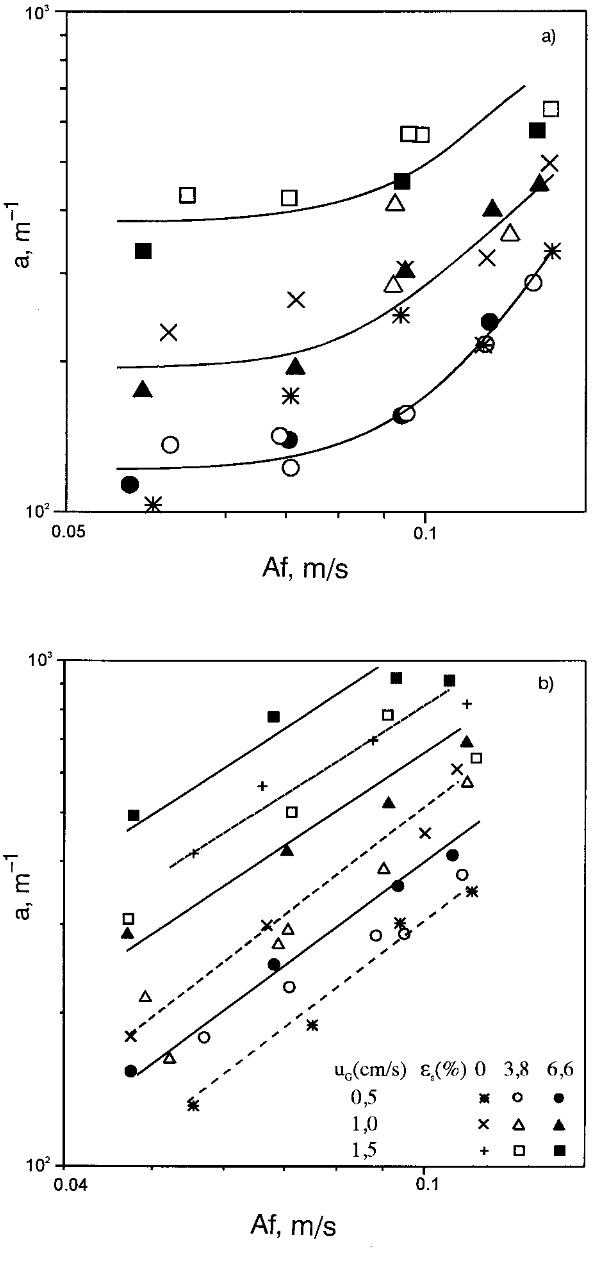

Figure 1. Dependency of the specific interfacial area and vibration intensity: a) D_C = 2.54 cm (system gas–liquid; [4]) and b) D_C = 9.2 cm

comparison, the results of some previous investigations performed in a column of 2.54 cm diameter (only a two–phase system) are shown with the present one in Figure 1a [4]. A negligible influence of the vibration was determined at lower vibration intensities in the smaller diameter RPC (Figure 1b). Such an effect was not observed in the larger diameter column, mainly caused by the higher energy dissipation in a column with a larger diameter at the same vibration intensity. An increase of the interfacial area was detected at a higher vibration intensity in both columns (2.54 and 9.2 cm diameter), as a consequence of reducing the bubble size and increasing gas hold–up in a column. Although an increase of the superficial gas–velocity increases the average bubble diameter in the column, it also increases the gas hold–up in the column thus also leading to an increase of the interfacial area [3–5].

The presence of solid phase in a column of 2.54 cm diameter did not influence the interfacial area, although in such a geometry a larger power consumption for mixing the gas–liquid dispersion (compared to the case of two–phase flow at the same operating parameters) is used. However, in a column with 9.2 cm diameter, the interfacial area increases by increasing the solid phase and also, it is higher compared to a two–phase column of larger diameter operated at other conditions the same.

Table 2. Influence of the liquid characteristics on the interfacial area (ug = 0.5 cm/s)

Liquid	a*, m^{-1}		
	D_C = 2.54 cm		D_C = 9.2 cm
	f = 2.2 Hz	f = 3 Hz	f = 2.3 Hz
Water	103	170	60
n–butanol solution (0.5 %)	172	462	119
Sodium sulphite (0.8 mol/dm^3)	182	378	87
Glycerin (64%)	105	178	66

*Determined by the photographic method

The results of the interfacial area determined by applying the photographic method are present in Table 2 (for different gas–liquid dispersions at the same vibration intensity and aeration). The obtained data indicated that practically the same values of the interfacial area are found in the case of viscous solution (glycerin) and water. It can be explained by the counter effect of the gas hold–up and the bubble size in water and glycerin solution. Namely, a higher value of both parameters exists in water and, a smaller one in a glycerin solution. Moreover, the inhibiting effect of bubble coalescence in the case of a n–butanol solution and aqueous solution of sodium sulfite, as well as a larger gas hold–up, cause an increase of the interfacial area in the RPC compared to the system with pure water.

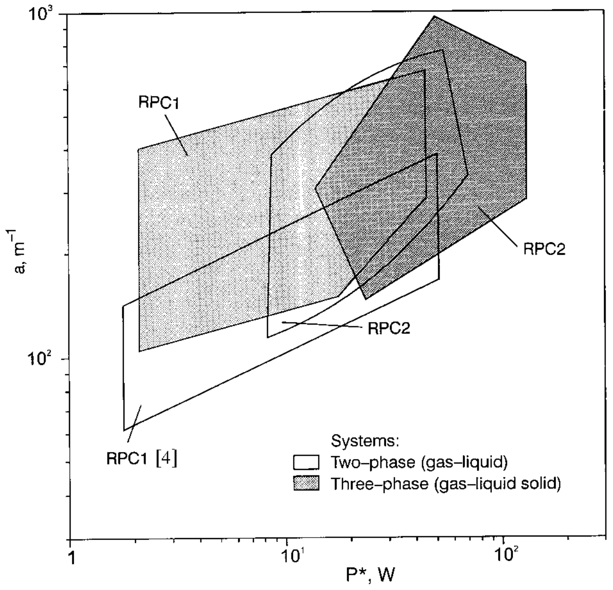

Figure 2. Comparison of the specific interfacial area in a RPC of different geometry: D_C = 2.54 cm (RPC1) i D_C = 9.2 cm (RPC2)

Comparison of the interfacial area in a RPC with different column diameter and some other gas–liquid bioreactors is given in Figures 2 and 3. Generally, a larger interfacial area in a column of larger diameter could be established in three–phase and two–phase systems (Figure 2) as a result of the higher power consumption in a column with a larger diameter used for the gas–liquid dispersion mixing at other operating conditions the same (aeration and vibration intensity). A higher interfacial area could be obtained in a two–phase RPC than in some other column types: e.g. comparison was made at the same aeration intensity used in a

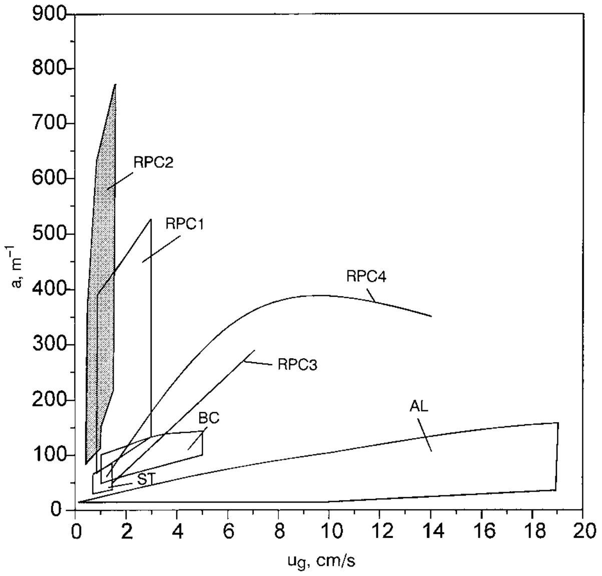

Figure 3. Comparison of the specific interfacial area in different types of gas–liquid reactors: RPC1 – D_C = 2.54 cm [6] ; RPC2 – D_C = 9.2 cm [this paper] ; RPC3 – D_C = 9.3 cm [5] ; RPC4 – D_C = 5.08 cm [2] ; BC – [11] ; AL (external loop) [12] ; ST – [13]

Table 3. Empirical correlation for determining the gas–liquid interfacial area in different systems

Dc (cm)	System	s (%)	Correlation	r^2	Relative deviation (%)
2.54	Three–phase	3.8 6.6 3.8 and 6.6	$a = 104546(P_{av})^{0.39}u_g^{1.31}$ $a = 29733(P_{av})^{0.45}u_g^{1.081}$ $a = 28029(P_{av})^{0.24}u_g^{1.031}$	0.98 0.97 0.81	± 6.3 ± 7.8 ± 18.2
9.2	Two–phase	0	$a = 17070(P_{av})^{0.49}u_g^{1.0}$	0.97	± 8.2
	Three–phase	3.8 6.6	$a = 5893(P_{av})^{0.49}u_g^{0.84}$ $a = 43800(P_{av})^{0.48}u_g^{1.23}$	0.93 0.94	± 9.3 ± 11.2
	Two– and Three–phase	0–6.6	$a = 14800(P_{av})^{0.49}u_g^{1.01}$	0.84	± 17.7

bubble column and air–lift reactor (with external or internal circulation of the liquid phase) or in the case of a gas–liquid stirred tank reactor. The vibration mixing of the gas–liquid dispersion in a RPC causes such an effect (Figure 3).

The empirical correlations linking the interfacial area and the average power consumption and superficial gas velocity are given in Table 3. Because the higher exponent of the dependency of the interfacial are on the superficial gas velocity than the corresponding exponent of dependency on power consumption, one may conclude that the effect of aeration on interfacial area is more important than the effect of mechanical mixing. The values of both exponents in these correlations (for two–phase gas–liquid and three–phase gas–liquid–solid) in the case of a column with different diameters are very close. So, as in the case of the correlation of the volumetric mass transfer coefficient [9], in this situation, the interfacial area is correlated to the values of the average power consumption and to the superficial gas velocity, independently of column size (diameter), on the solid phase content in the column (two– or three–phase system). Finally, this approach gives the following correlation:

$$a = 18883\,(P_{av})^{0.31}\,u_g^{0.97} \qquad (3)$$

An agreement between the calculated and experimentally determined values of interfacial area is fairly good (± 17.7 %; 59 data), as may be seen in Figure 4.

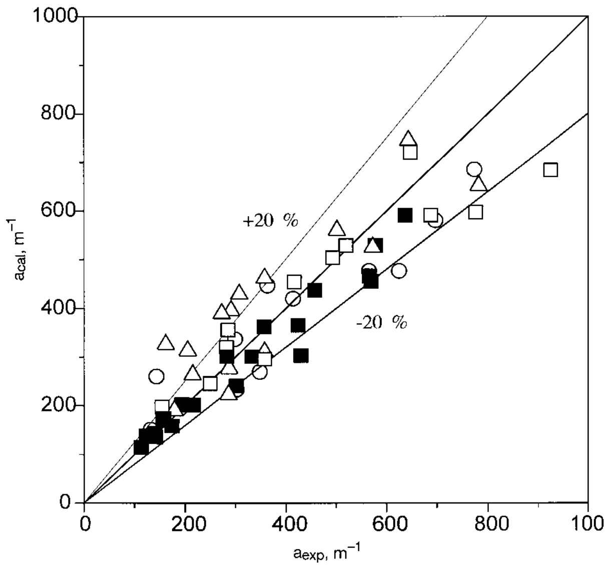

Figure 4. Comparison of the calculated and experimentally determined interfacial areas (Dc, cm: 2.54 – black symbols; 9.2 – open symbols; %: 0 – circle; 3.8 – triangle; 6.6 – square)

CONCLUSION

The interfacial area depends on the vibration intensity, the superficial gas velocity, and solid phase content in the RPC and the liquid characteristics. An increasing the superficial gas velocity could be obtained by increasing of the vibration intensity and the superficial gas velocity. Increasing the solid phase content in the RPC causes an increase of the interfacial area, but only in the case of the larger column diameter (9.2 cm). However, such an effect was not observed in the RPC of 2.54 cm diameter. The specific interfacial area in a three–phase RPC is larger than in the case of a two–phase RPC and, generally, it increases with column diameter. Finally, the results of the investigation performed in this paper indicate that a larger interfacial area could be obtained in a RPC compared to some other column types (bubble column, air–lift reactor with external or internal loop; stirred tank reactor) at the same superficial gas velocity, because additional breaking of the bubbles is caused by the vibrating motion of the perforated plates in the column. The derived empirical correlation for the interfacial area calculation indicates a larger influence of aeration than of mechanical mixing, according to the values of the exponents in an equation which combines the effect of the power consumption (mechanical mixing) and superficial gas velocity (aeration).

SYMBOL USED

a	– specific interfacial area, m^2/m^3
A	– amplitude of vibration, m
A_c	– cross section area (column), m^2

A_f – vibration intensity, m/s
c_l* – equilibrium concentration in solution, mol/dm$_3$
d_o – hole diameter, m
$d_{3,2}$ – Sauter average bubble diameter, m
D_c – column diameter, m
f – frequency, Hz
h – distance between two plates, m
n_p – number of plates
P_{sr} – average power consumption, W
P^* – total power consumption, W
r^2 – correlation coefficient
r_{O2} – mass transfer rate of oxygen, mol/m^{3}s
u_g – superficial gas velocity, m/s
u_l – superficial liquid velocity, m/s
u_s – motion rate of vibration set with perforated plates, m/s

GREEK LETTERS

D – diffusion coefficient
ε – free cross section of the plate
ε_g – gas hold–up
ε_s – solid content in the column

INDEX

cr – critical value
g – gas
l – liquid
max – maximal value
av – average value

ABRREVIATIONS

BC – bubble column
AL – air lift reactor
RPC – reciprocating plate column
ST – stirred tank reactor

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IZVOD

PRENOS MASE U VIŠEFAZNOM REAKTORU SA VIBRACIONOM MEŠALICOM II. SPECIFIČNA MEĐUFAZNA POVRŠINA

(Naučni rad)

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Drugi deo analize maseno–prenosnih karakteristika kolone sa vibracionom mešalicom (KVM) daje rezultate o međufaznoj površini gas–tečnost koja se može postići u kolonama različite geometrije (prečnika) i pri korišćenju različitih tečnosti. U prvom radu ispitivan je zapreminski koeficijent prenosa mase sa strane tečnosti, k_la (Hem. ind., 55(2001)345–349). Eksperimentalna ispitivanja su izvedena u KVM tipa Karr u slučaju dvofaznog (gas–tečnost) i trofaznog (gas–tečnost–čvrsta faza) sistema, korišćenjem hemijske i fotografske (fizičke) metode.

Utvrđeno je da specifična međufazna površina zavisi od intenziteta vibracije, protoka gasa, osobina tečnosti i udela čvrste faze u koloni. Izvedena je empirijska korelacija, primenljiva nezavisno od prečnika kolone i vrste sistema:

$$a = 18883\,(P_{av})^{0.31} u_g^{0.97}$$

Ključne reči: Kolona sa vibracionom mešalicom • Međufazna površina • Dvofazni sistem • Trofazni sistem •
Key words: Reciprocating plate colum • Interfacial area • Two–phase system • Three–phase system •