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ANALYSIS OF LIQUID FLOW IN A KARR RECIPROCATING PLATE COLUMN

Mathematical modeling of the liquid flow in a gas–liquid and gas–liquid–solid Karr reciprocating plate column (RPC) of different column geometry (diameter and height, number of vibrating plates) is presented. The experimental investigations were based on tracer flow analysis (stimulus–response technique). The experimentally determined density of the residence time distribution function (C–function) was used for detecting the parameters of different mathematical models. Three models, very often used in the literature, were adopted for such an analysis: the axial dispersion model (ADM), a model based on the existence of N–perfectly mixed compartments (N–PMC) and a model of N–perfectly mixed compartments (sections) with a back flow between each section (N α –PMC).

A flow of fluids (gas, liquid or solid or multiphase flow) throughout some unit (reactor, distillation column, absorber, heat exchangers etc) is always different to a smaller or larger extent from two idealized situations: ideal plug flow, i.e. flow without mixing as one limit and completely or perfectly mixed flow as the other limit. In some cases deviation from these two idealised flow models can be very large causing channeling, flow recirculation inside a unit or the creation of so-called dead zones. In real reactor the fluid(s) never completely flow ideally (with or without mixing) and in some cases deviation from ideality may be considerable. The effects of non-ideal flow influence unit efficiency and their scale-up [1,2].

In some cases it is only necessary to know the residence time distribution function (F, or C function) which can be determined by using specific tracers and the corresponding method of stimulus and response. This method is based on producing some disturbances of the tracer concentration at the inlet of the unit and determining its concentration at its outlet. Usually these techniques are based on the usage of different analytical methods for the determination of tracer concentration (pH-analysis, spectrophotometry, conductometry)[2]. In this paper the liquid flow was analysed in a RPC followed by the cocurrent flow of gas phase (air) with and without the presence of a solid phase (polypropylene spheres, < 10 vol%) in a column.

The vibration column has been used successfully in processes of liquid–liquid extraction (Van Dijk, 1935) and for many subsequent years it was used for such purposes [3]. This type of unit has been known to have good characteristics regarding non-ideality of liquid flow. Namely, flow of the liquid phases (organic and aqueous in the case of extraction) is followed by the

vibration of a set with a large number of perforated plates mounted on a rod which is driven axially by reciprocating motion. Karr (1959) patented a specific type of such a column, the same construction as used in this work, with perforated plates of larger free area (< 60%)[4]. Such perforated plates are called Karr type plates, so this column is very often determined in the literature as a Karr reciprocating plate column (KRPC). Today there are KRPC in industrial application with a diameter of 1.7m [5]. Our research work in the past was oriented to the analysis of this type of RPC as a bioreactor for different applications in the case of two or three phases present in the column (D. Skala, 1980; V. Veljković, 1985, I. Banković-Ilić, 1993;1999) [6–9]. Taking into account the specific tasks of the investigations presented in this paper, of most interest are those works and papers dealing with the analysis of liquid flow in a RPC and the determination of adequate models for presenting liquid flow and the real state inside a column [6,10,11].

AXIAL MIXING IN A RPC

The published results in the literature in the case of single (liquid), two-phase (gas–liquid) and three-phase (gas–liquid–solid) flow in RPC indicate the advantages of this type of column compared to some other ones (bubble column, fixed bed, sieve tray column). Namely, low power consumption for mixing of the column content in the case of RPC increases gas hold-up, decreases the diameter of the bubbles and, consequently, increases the gas–liquid interfacial area and mass transfer rate of the gas reactant (e.g. oxygen) into the liquid phase. This is very important when RPC are used for biochemical and aerobic processes. Such processes are usually followed by counter current contact of the gas and liquid phase, so the efficiency of RPC is larger if the flow of both phases (gas and liquid) is closer to ideal plug flow. Namely, the large effect of backmixing of the liquid phase will cause decreases of the favorable mass transfer rate caused by vibration of

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the perforated plates. The main task of the present study was determining the axial dispersion of the liquid phase and its dependences on various operating conditions (gas and liquid flow rates, intensity of vibration – i.e. amplitude and frequency of vibration, solid phase content inside a column).

Some results recently published in the literature have shown that axial mixing in a RPC (single phase flow) could be correlated by a linear function of the intensity of vibration ($l=A \cdot f = 2-5 \text{ cm/s}$) [12]:

$$D_L/A \cdot f = 0.6 \text{ cm} \quad (1)$$

A similar correlation was obtained in the case of liquid flow throughout pulsation [13].

In the case of two phase flow in a RPC there is a larger extent of axial mixing caused by gas bubbles and liquid circulation and turbulency between two adjacent plates. However, compared to axial mixing in a bubble column, one can conclude that the most important conditions which influence axial mixing are: column diameter, superficial gas velocity, gas hold-up, liquid viscosity. On the basis of the Kolmogoroff theory of isotropic turbulencies the following correlation was established which related the axial dispersion coefficient and working parameters which have the most important influence [14]:

$$D_L = 1.4 D_c^{1.4} \cdot U_G^{0.33} \quad (2)$$

THEORETICAL PART

In this paper three models were used for determination of the liquid flow in a KRPC: ADM, N-PMC and $N\alpha$ -PMC. In the case of the compartment model (PMC) with a backmixing effect (α), the α -parameter was calculated on the assumption that a determined number of compartments exists which is equal to $(n-1)$ perforated plates mounted on the central rod.

ADM and N-PMC

Determination of the parameters of both models (D_L and N) was based on the application of the experimentally determined C function and in the case of ADM applied closed-closed boundary conditions for a column [1,2]. Parameters were determined by calculating j – non-central

$$\mu'_j = \int_0^{\infty} t^j E_t dt \quad (j=0,1,2,\dots) \quad (3)$$

and k – central moments of the C function

$$\mu_k = \int_0^{\infty} (t - \mu'_1)^k E_t dt \quad (k=1,2,3,\dots) \quad (4)$$

or by applying the corresponding Laplace transformation of the C-function [2, 15].

MODEL OF N PERFECTLY MIXED COMPARTMENTS AND BACKMIXING BETWEEN EACH COMPARTMENT ($N\alpha$ -PMC)

The model is represented by N -compartments with complete mixing of equal volumes (Figure 1) and with backmixing between each compartment. The volume of one compartment is V/N and volume of all compartments (the column) is V . The liquid flow through the RPC is v , so the residence or nominal time of the liquid in a RPC is $t = V/v$, and in one compartment $t_0 = t/N$. This is not an average residence time in one compartment, because the flow rates of the liquid phase in each compartment are much larger and depend on the backmixing [$v(1 + 2\alpha)$].

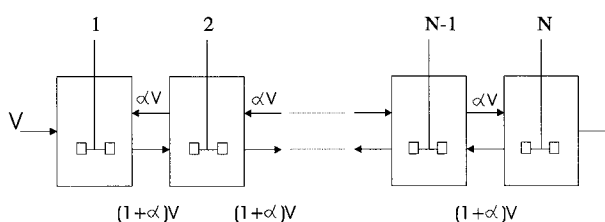


Figure 1. Model with N -stages and back flow between them

Determination of the model parameters (N , α and t_0) was based on solving a set of differential equations of the mass balance for tracer inserted in such a system as a Dirac impulse function [2].

PARAMETER IDENTIFICATION – Moments method [2]

The first non-central moment ($j=1$) of the C function determines the average residence time in a column with a volume V , while the second central-moment ($k=2$) determines the distribution of the residence time of the tracer from the average residence time ($\mu_2 = \sigma_t^2$). These moments were used for the determination parameters of the ADM, N-PMC and $N\alpha$ -PMC models.

In the case of ADM and N-PMC, a small deviation of plug flow (large value of Pecckle-number), both central and non-central moments determine the coefficient of axial dispersion or N -number of compartments:

$$\mu'_1 / t = 1 \text{ and } \sigma_0^2 = \frac{\sigma_t^2}{t^2} = \frac{2D_L}{u \cdot L} = \frac{1}{N} \quad (5)$$

and in the case of $N\alpha$ -PMC the average residence time

$$\mu'_1 = \bar{t} = N / v = N \cdot V_i / v \quad (6)$$

and α and N :

$$\sigma_0^2 = \sigma_t^2 / (\mu'_1)^2 = (1 + 2\alpha) / N \quad (7)$$

In this study N was fixed in advance as the number of physically existing compartments, i.e., $(n-1)$ plates on

the rod, so eq. (7) was only used for the calculation of the backmixing coefficient between the compartments.

So if the length of the column is expressed as the length of one compartment (d) multiplied by the number of compartments ($n-1$ plates): $L = N \cdot d$, where d – is one compartment in which there exists perfect mixing, the following relation between the parameters of ADM and $N\alpha$ -PMC exists:

$$Pe' = \frac{u \cdot L}{D_L} = \frac{2}{(1 + 2\alpha)} \quad (8)$$

EXPERIMENTAL PART

Experimental set-up

The schematic presentation of the experimental setup, consisting of a 2.54 and 9.2 cm i.d. RPC and auxiliary equipment, is shown in Figure 2. Other dimensions of the RPCs are given in Table 1.

The experiments were performed with tap water and the gas phase (air) flowing countercurrently. In the case of a three-phase system, the polypropylene spheres (mean diameter, 8.4 mm; density, 930 kg/m³)

Table 1. Geometry of the RPCs and operating conditions

	RPC1 (A)	RPC2 (B)
Column diameter, cm	2.54	9.2
Column length, cm	200	105
Dispersion height, cm	183.6	85.6
Diameter of nozzle, cm	0.385	0.3 (two nozzles)
Diameter of rod, cm	0.32	0.6
Length of tie-rod, cm	12.4	12.4
Number of plates	65	15
Spacing between plates, cm	2.54	5.0
Plate thickness, cm	0.1	0.15
Plate holes (internar/external), cm	0.8/0.6	0.8/0.8
Fraction free area, %	51	45.4
Material:		
Column	Glas	Plexyglass
Rod	Stainless steel	Stainless steel
Plates	Stainless steel	Aluminium
Spacers	Teflon	Teflon
Amplitude of reciprocation, cm	2.35	
Frequency of reciprocation, s ⁻¹	2 to 6	
Superficial gas velocity, cm/s	0 – 1.9	

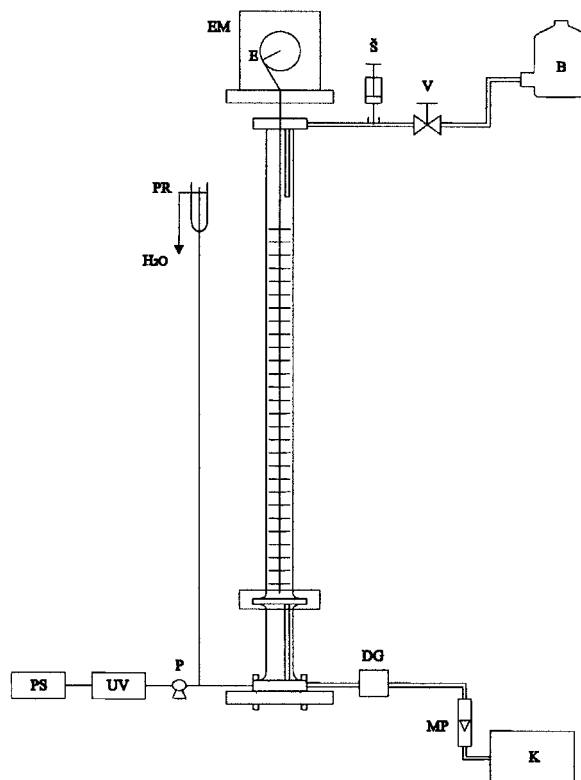


Figure 2. Scheme of the experimental set-up. EM–electromotor; B–vessel; PR–liquid outlet; V–valve; S–syringe; PS–recorder; UV–detector; P=pump; DG– gas distributor; K–compressor; E–ex-center.

were used as the solid phase. The content of solid phase was varied from 0 to 8.3 % by volume. Air of ambient temperature was fed at the column base through a nozzle. The gas flow rate was measured by a rotameter. The static pressure of the gas near the rotameter was measured by a manometer. The superficial gas velocity was less than 2 cm/s.

Stimulus–response technique (S–R)

Liquid flow in a column was analysed by the S–R technique using an aqueous solution of sorbic acid as the tracer. Defined amount of sorbic acid solution was inserted at the inlet of the column by a syringe for a less than 0.5 s. The tracer concentration was measured at the outlet of the RPC using a UV detector. Detailed description of the applied S–R techniques is given in a recently published paper [16]. Figure 3 represents the concentration of sorbic acid versus time at the outlet of the column.

RESULTS AND DISCUSSION

This response curve is typical for the case of short (Figure 3a) or long (Figure 3b) residence time of the liquid phase in a column. The initial concentration of sorbic acid was calculated on the basis of the volume of the column.

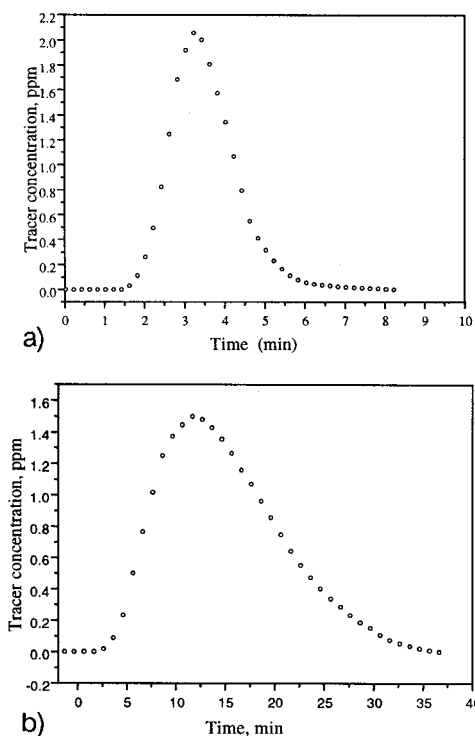


Figure 3. Concentration of tracer at the outlet from the RPC versus time for the case of: a) very rapid, and b) very slow tracer rinsing [16]

DEPENDENCE OF MODEL PARAMETERS (D_L , α , N_{exp}) ON MIXING INTENSITY

Column A (2.54 cm i.d.)

The dependences of the axial dispersion coefficient, (D_L in ADM), the number of compartments with complete mixing (N_{exp} in N -PMC) and the coefficient of backmixing (α in $N\alpha$ -PMC) on the vibration intensity (gas-liquid system) are presented in detail for a RPC of 2.54 cm i.d. (gas-liquid system) in recently published paper [16]. It was shown that the minimal value of axial dispersion exists for a vibration intensity between 3 and 4 cm/s. Axial dispersion in the case of the smaller column diameter is not greater than 10 cm^2/s , and this minimal value is between 3 and 5 cm^2/s depending on the gas superficial velocity.

Similar conclusions were derived in the case of the $N\alpha$ -PMC model, or N -PMC model, where minimal backmixing coefficient (α) or maximal N_{exp} – number of compartments with ideal mixing exist for vibration intensities between 3 and 4 cm/s. Increase of the vibration intensity above this value causes an increase of the backmixing coefficient or a decrease of N_{exp} ; such an influence is more expressed at higher gas superficial velocity.

Column B (9.2 cm i.d.)

Gas-liquid system

In a column of larger diameter there is a more expressed influence of the vibration intensity on liquid flow through the RPC. Namely, the smallest axial dispersion,

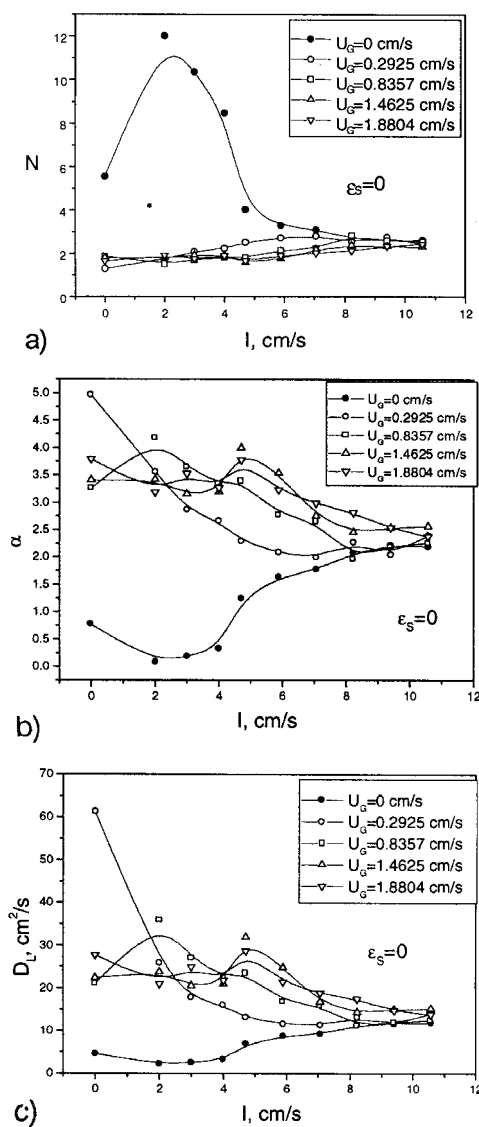


Figure 4. Determination of model parameters in a two-phase RPC (i.d. 2.54 cm): a- N -PMC; b- $N\alpha$ -PMC; c-ADM

or backmixing coefficient was determined for single phase flow (only water), while with introducing gas as the second phase causes an increase non-ideality of the liquid flow; expressed with parameters of three models used in this study that means a higher value of the axial dispersion and backmixing coefficient (ADM and $N\alpha$ -PMC) or a smaller value of N (N -PMC). However, increase of the vibration intensity (< 11 cm/s) decreases flow non-ideality i.e. decreases of D_L and α , and increases N . Obviously in a shorter RPC and with a larger diameter there is considerable deviation from ideal plug flow; D_L is in the range of 15-60 cm^2/s , and α between 2 and 5, while N has a value not larger than 3. Determined dispersion coefficient is in concordance with some recently published data [17]. Knowing that this column has 15 compartments that means that each stage, i.e. distance between two adjacent plates has only 20% efficiency in performing ideal mixing.

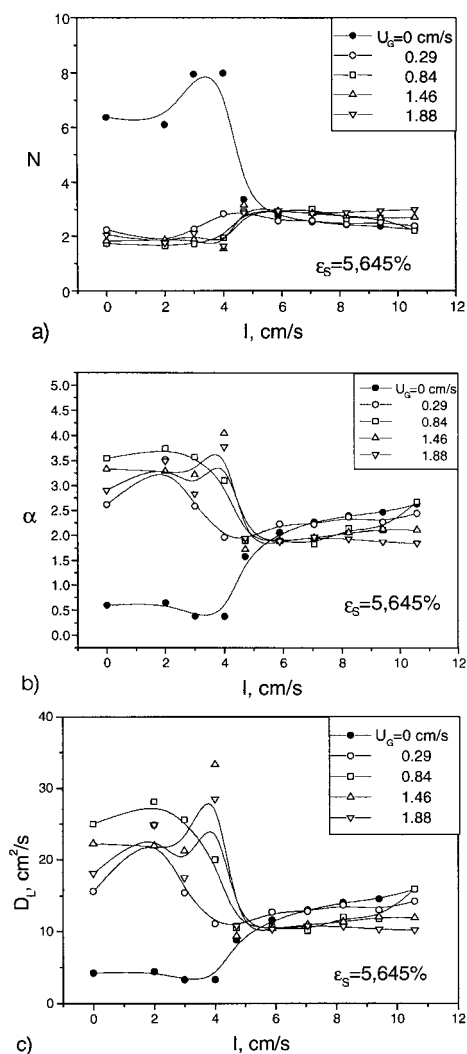


Figure 5. Determination of the model parameters in a three-phase RPC (i.d. 9.2 cm): a-*N*-PMC; b-*N α* -PMC; c-ADM

Liquid-solid and gas-liquid-solid system

The influence of the solid phase on axial mixing is shown in Figure 6 for various superficial gas velocity ($u_G = 0-1.9$ cm/s) and mixing intensity. ($l = 0-10.6$ cm/s). As expected, there is a significant increase of axial mixing for a liquid-solid system ($u_G = 0$ cm/s) and a vibration intensity greater than 4 cm/s. In this case, axial dispersion is almost constant (about 3-5 cm²/s) for $l < 4$ cm/s and for different contents of polypropylene spheres in a RPC (< 10 vol%); it is almost three times higher (15-20 cm²/s) by increasing the vibration intensity to 10 cm/s and the content of the solid phase (to 10 vol%).

Much higher axial dispersion was determined after introducing the gas phase in a RPC (case of a three phase system), but it decreases with increase of the vibration intensity and solid content in a RPC. The non-ideality of liquid flow is more expressed in the case of lower solid content (<3-4 vol%) and for all investigated vibration intensities. In this region, increase of the superficial gas velocity also causes, not significantly, an increase of axial mixing. However, for a large content of

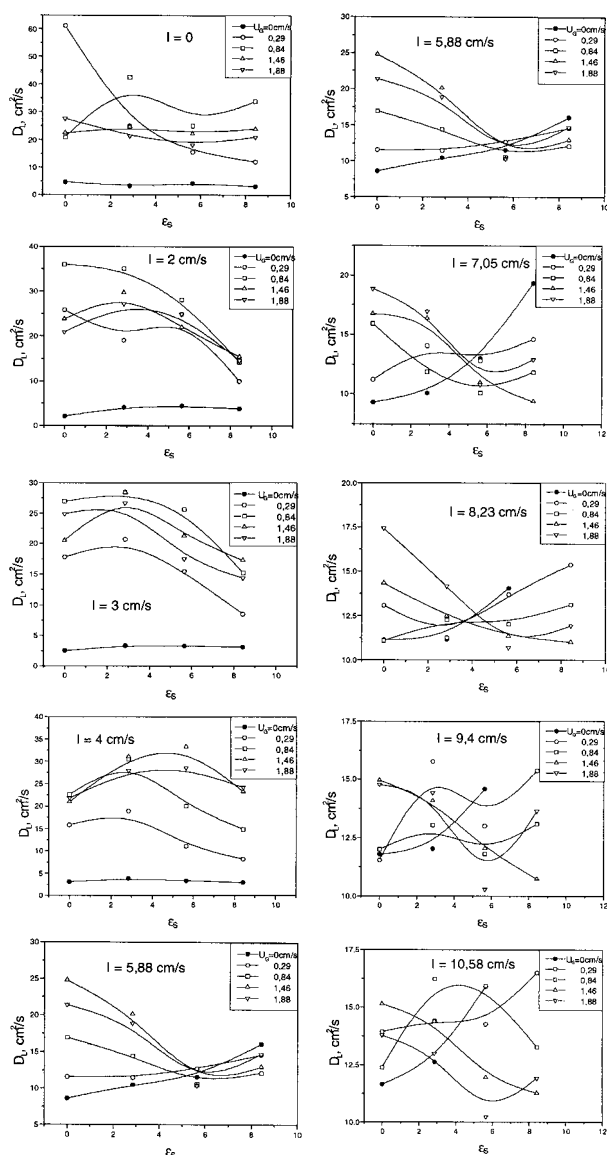


Figure 6. Axial dispersion coefficient in a three-phase RPC (i.d. 9.2 cm)

the solid phase in a RPC and a vibration intensity greater than 4.5 cm/s, axial dispersion is smaller for a three-phase (gas-liquid-solid) than for a two-phase (liquid-solid) system. This "critical" content of solid phase in a RPC where such an "inverse" effect of axial dispersion was observed, is smaller and smaller depending on the vibration intensity. For example, smaller axial dispersion was observed in the case of a three phase system and $l = 4.7$ cm/s compared to two phase system (liquid-solid) only for the highest content of polypropylene spheres in a RPC (<7-8 vol%); this critical content decreases to 6, 4-5 and finally to 3 vol% by increasing the vibration intensity from 5 to 10.6 cm/s. That means that a combination of a large gas flow rate and its unfavorable effect on axial mixing, well known in the case of a bubble column, could be suppressed by the vibration intensity of perforated plates and by the presence of a small amount of solid phase in a RPC.

CONCLUSION

The results of this study indicate that axial dispersion is much higher in the case of a RPC of larger diameter. The correlation proposed by other authors for predicting the influence of bubble column diameter on axial dispersion could be also used for predicting such an effect in a RPC.

It was shown that in the case of a gas-liquid RPC some minimal value of axial dispersion exists at the vibration intensity of 3–4 cm/s. A small presence of solid particles (polypropylene spheres) increases non-ideality of the liquid flow and it can be reduced by increased vibration intensity. Moreover, at higher contents of PP spheres in a gas-liquid-solid RPC and at high vibration intensity, non-ideality of the liquid flow becomes identical or even less expressed than those determined in a liquid-solid RPC.

List of used symbols

V	– volume of column, cm^3
V_k	– volume of cascade, cm^3
t	– time, min
\bar{t}	– average residence time, min
v	– liquid flow rate, cm^3/min
θ	– reduced time, dimensionless
D_L	– axial dispersion coefficient, cm^2/s
L	– length of the column, cm
U	– superficial velocity, cm/s
N	– number of section with perfect mixing
α	– backmixing coefficient
σ^2	– dispersion of reduced residence time
E_t	– external age distribution function, s^{-1}
F_t	– residence time distribution function

μ_k	– k -th non central moment of C function
μ_1	– first central moment

Index

exp	– experimentally determined
G	– gas
L	– liquid

REFERENCES

- [1] O. Levenspiel, "Chemical Reaction Engineering", 2nd ed., J. Wiley, N. York, 1974.
- [2] D. Skala, J. Mičić, Hem. ind. (Belgrade), **36** (1982) No 1–5, 28; 75; 105; 136; 163.
- [3] W. J. Van Dijk, U.S. Patent 2.011.186 (1935)
- [4] A.E. Karr, AIChE. J., **5** (1959) 446.
- [5] M.H.I. Baird, N.V. Rama Rao, Can. J. Chem. Eng. **76** (1998) 370.
- [6] D. Skala, Ph D., University of Belgrade, 1980.
- [7] V. Veljković, Ph D., University of Belgrade, 1985.
- [8] I. Banković-Ilić, M.S. Thesis, Faculty of Technology and Metallurgy, University of Belgrade, 1993.
- [9] I. Banković-Ilić, Ph D., University of Niš, 1999.
- [10] G.V. Stevens, M.H.I. Baird, Chem. Eng. Sci., **45** (1990) 457.
- [11] D. Skala, S. Zubović, J. Mičić, Bull. Soc. Chim. Belgrade, **46** (1981) 513.
- [12] M.M. Hafez, M.H.I. Baird, I. Nirdosh, Can. J. Chem. Eng., **57** (1979) 150.
- [13] M.H.I. Baird, Can. J. Chem. Eng., **52** (1974) 750.
- [14] M.H.I. Baird, R.G. Rice, Chem. Eng. J., **9** (1975) 171.
- [15] P. V. Danckwerts, Chem. Eng. Sci. **2** (1953) 1.
- [16] Lj. Nikolić, N. Djoković, V. Veljković, D. Skala, Hem. ind., **53** (1999) 300.
- [17] O. Louines, J. Thibault, Can. J. Chem. Eng., **74** (1996) 187.

IZVOD

ANALIZA STRUJANJA FLUIDA U KAROVOJ KOLONI

(Naučni rad)

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Strujanje tečne faze u trofaznoj (gas-tečnost-čvrsto) koloni sa vibracionom mešalicom tipa Karr ispitivano je primenom tehnike pobude i odziva. Analiziran je uticaj različitog prečnika i visine kolone i broja perforiranih pločica na vibracionoj mešalici. Eksperimentalno određena funkcija gustine raspodele vremena zadržavanja (C-kriva) je upotrebljena za određivanje parametara usvojenog matematičkog modela kojim može da se opiše strujanje tečne faze u koloni. Pri tome su analizirana tri modela, često korišćena u literaturi u cilju opisivanja strujanja fluida: model klipnog toka tečne faze uz postojanje aksijalnog mešanja (ADM), model od N-sekcija sa potpunim (idealnim) mešanjem (N-PMC), i model od N-sekcija sa potpunim (idealnim) mešanjem gde postoji i povratni tok između svake sekcije (Na-PMC). Analiziran je uticaj radnih uslova: prividna brzina gasa, intenzitet vibracije seta sa perforiranim pločicama u koloni (prečnika 2,54 i 9,2 cm) na promenu vrednosti parametara izabranih modela. Pokazano je da je manje izražena aksijalna disperzija tečne faze, pri manjim intenzitetima vibracije, ukoliko je u koloni prisutna i čvrsta faza (kuglice od polipropilena, 5-6 vol% smeštene u prostoru između dve susedne perforirane pločice). Opšti zaključak je da je u koloni izraženo neidealno strujanje, posebno kod kolone većeg prečnika.

Key words: Reciprocating plate column • Karr column • Residence time distribution • Models • Axial dispersion •

Ključne reči: Vibraciona kolona • Karova kolona • Raspodela vremena zadržavanja • Modeli strujanja fluida • Aksijalno mešanje •

