

## BACK-MIXING IN FULL-SCALE ARD AND RDC EXTRACTORS

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The longitudinal mixing is a phenomenon, which affects deeply the overall efficiency of mechanically agitated extraction columns. For the purposes of designing the full-scale equipment a reliable description of this quantity is urgently needed and namely its dependence on column diameter and on the arrangement of the internal parts. This paper represents an attempt at theoretical solution of this problem.

In the past 15 years wide interest has been devoted to the phenomenon of longitudinal mixing; the prevailing number of papers, however, deals with mathematical models of flow in column apparatuses and only minority of them with the values of coefficients of those models. From this minority only a small number treats the measurements performed on plant scale and the method of study is in most cases purely empirical. Because of this fact the few papers containing data about longitudinal mixing in rotating disc extractors (RDC) are of a very high value; this concerns especially the papers of Stemerding<sup>1</sup>, Strand<sup>2</sup> and Miyauchi<sup>3</sup> even if the presented relationships are inconsistent concerning the influence of geometry. Only Miyauchi's paper<sup>3</sup> presents an attempt at general theory; for final correlation, however, a semiempirical equation has been used. Data concerning the longitudinal mixing in full scale ARD extractors have not been published yet.

Owing to the fact that back-mixing is one of the decisive factors for the efficiency and full-scale suitability of the extractors, it is desirable to know not only the values measured on models, but also the dependence of the longitudinal mixing coefficients on the extractors' size and on their internal arrangement.

Beside of this the endeavour of this publication is to give a more general solution which could be applied for other types of agitated column extractors.

## THEORETICAL

The physical model, depicted in Fig. 1, of the back-mixing in continuous phase of an agitated column extractor assumes: a) ideal mixing in every compartment, delimited with some flat stator plates and caused by an arbitrary mixer, the power consumption of which is known and may be described as

$$N_p = P/n^3 D^5 \varrho_c. \quad (1)$$

b) The compartments are interconnected by arbitrary openings in the stator plates, the relative free area of which is  $\varepsilon$ . For the liquid mixture inside this area applies the

theory of Kolmogoroff local isotropic turbulence. *c*) It is possible to define some distance  $l$ , greater than the plate thickness, roughly corresponding to the distance between main radial flows in both neighbouring compartments and influenced to some extent by design and manufacturing perfection of the extractor. For the inter-compartment mixing the velocity difference over this distance,  $u_1$ , is responsible. The back-flow  $U_z$  is proportional to  $u_1$ .

Mathematical description of the above mentioned model is based on Kolmogoroff's theory of turbulence, according to which the velocity difference over the distance  $l$  equals

$$u_1 = k_2(\varepsilon_0 l)^{1/3}, \quad (2)$$

where  $\varepsilon_0$  is energy dissipation in unit mass

$$\varepsilon_0 = \frac{4P}{\pi h_m D_c^2 \varrho_c}. \quad (3)$$

For the back-flow  $U_z$  we may write

$$U_z = k_1 \varepsilon u_1. \quad (4)$$

The value  $U_z$  corresponds to the transfer of all the dispersion; the back-flow of continuous phase only corresponds to

$$U_{z_c} = U_z(1 - X), \quad (5)$$

where  $X$  is the hold-up of dispersed phase. Because of the low value of hold-up ( $X \ll 1$ ) an approximation may be used

$$U_{z_c} \approx U_z. \quad (6)$$

Miyauchi<sup>4</sup> has shown that for the number of agitated compartments greater than 10 the back-flow and the diffusional models are equivalent, if the relationship

$$\xi_i/U_i h_m = 0.5 + U_{z_i}/U_i; \quad i = c, d \quad (7)$$

for the respective coefficients is fulfilled. Combining Eqs (1)–(4) and (6) the final relation is obtained

$$U_{z_c} \approx U_z = k_3 l^{1/3} N_p^{1/3} n D / \kappa, \quad (8)$$

$$\kappa = \frac{h_m^{1/3}}{\varepsilon} \left( \frac{D_c}{D} \right)^{2/3}.$$

The physical picture in an ARD extractor is similar, as may be shown by comparing the Fig. 1. and Fig. 2. The difference between both extractors is in  $\varepsilon_0$  value in the neighbourhood of the opening in the stator plates. The value for ARD is expected to be lower because the opening is divided from the agitated part of the compartment by the vertical baffle.

No agreement has been achieved till now between theory and measurements for the dispersed phase back-mixing by means of the diffusion or the back-flow model only. The paper by Rod and Míšek<sup>5</sup> illustrated the influence of droplet velocity distribution and coalescence rate on the residence time distribution of the dispersed phase. The net back-mixing effect according to this paper is usually small, compared to the other ones. A simplified treatment of the back-mixing is therefore considered to be adequate.

Assuming that all the droplets are fully entrained by the dispersion a relation (7) for the longitudinal diffusivity of the dispersed phase applies, where

$$U_{zd} = XU_z. \quad (9)$$

Because the  $X$  values are usually comparatively small and the  $U_d$  values are of the same order as  $U_c$ , the diffusivity approximates the value for a series of ideal mixers.

$$\frac{\xi_d}{U_d h_m} \approx 0.5. \quad (10)$$

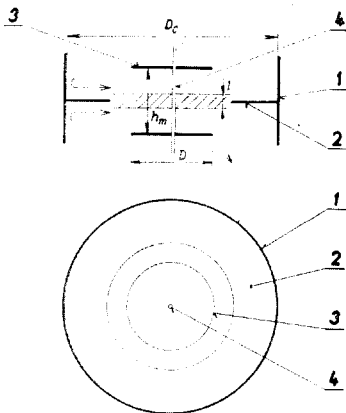


FIG. 1

Schematic Drawing of the RDC Extractor

1 Column, 2 stator plate, 3 rotating disc,  
4 shaft.

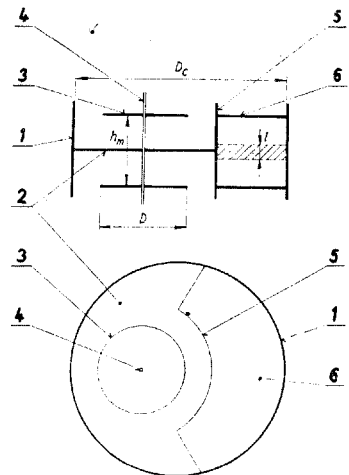
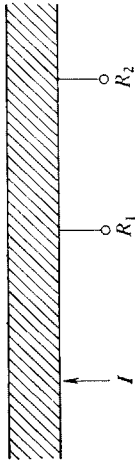
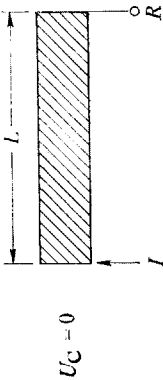


FIG. 2

Schematic Drawing of the ARD Extractor

1 Column, 2 stator plate, 3 rotating disc,  
4 shaft, 5 vertical wall, 6 horizontal baffle.

TABLE I  
Sources of Experimental Data

Author	Column type and diameter	Injection mode	Experimental scheme	Model description
Stemering and coworkers <sup>1</sup>	RDC; 64, 300, 640, 2 180 mm	$\delta$ (except of $D_c = 64$ mm) radioactive tracer	one phase flow active part	Van der Laan <sup>6</sup>
Míšek <sup>7-11</sup>	ARD, RDC; 50, 200, 1 000, 1 500, 2 000 mm	any; methylene blue, radioactive tracer		Double-infinite equipment, Bischoff <sup>12</sup> ; $\frac{t_2 - \bar{t}_1}{\bar{t}_0} = \bar{T} = 1$ ; $\frac{2}{Pe} = \frac{\sigma^2(t)_2 - \sigma^2(t)_1}{(t_2 - t_1)^2}$
Martínková and coworkers <sup>13</sup>	ARD, ARD/LS; 2 800, 4 000 mm	$\delta$ , calcium nitrate tracer	one phase study; active column part only:	stationary liquid, Pebalk and Pekovich <sup>15</sup> $\xi_c = 0.14 \frac{L^2}{\tau_{50\%}}$ ; $\frac{\xi_c}{h_m} = k_4 n D$
Rozkoš and coworkers <sup>14</sup>				

## EXPERIMENTAL

This part introduces experimental results of our own and of other authors, which were thoroughly described elsewhere, and which refer to the full-scale RDC and ARD extractors. All these results were obtained by means of the tracer injection method, with measuring the concentration response. The influence of the rate of mixing for the individual studied apparatuses was expressed by the dependence of the type

$$U_{zc} = k_4 n D. \quad (11)$$

As a result therefore the compensated value of the  $k_4$  constant can be considered, a representative of the whole set of measurements obtained from one equipment.

The individual sets of data were obtained in the following way (see Table I).

The respective results are given in summary in the Table II. Fig. 3 demonstrates the conformity of the measured values of  $k_4$  constants with the theory for both types of the studied equipment. The data support the meaning that the value  $k_3 l^{1/3} N_p^{1/3}$  may be considered constant for RDC and ARD extractors respectively. The agreement of the measurements with the theory is very satisfactory.

Also the agreement of the experimental data obtained from one single equipment, with the Eq. (11) can be considered as a very satisfactory. This can be shown on an example of ARD column of 2800 mm in diam. (Fig. 4), confronting the calculated longitudinal diffusivity by means of the average  $k_3 l^{1/3} N_p^{1/3}$  value (solid line) with the individual measurements (blank circles).

On the example of the large-scale extractor ARD/LS of 4000 mm in diam., equipped with 3 mixing systems, a case was verified, where the power input in the column was realized using several discs of smaller size. The comparison of the results and prediction

TABLE II  
Data Summary

Author	Column		$\alpha$ , cm <sup>1/3</sup>	$k_3 l^{1/3} N_p^{1/3}$ , cm <sup>1/3</sup>
	type	diameter, mm		
Marek <sup>7</sup>	ARD	200	10.88	$3.04 \cdot 10^{-2}$
Rozkoš <sup>8</sup>	ARD	1 500	19.75	$2.96 \cdot 10^{-2}$
Martínková <sup>13</sup>	ARD	2 800	19.05	$2.88 \cdot 10^{-2}$
Míšek, Rod <sup>9</sup>	RDC	50	3.18	$4.45 \cdot 10^{-2}$
Rozkoš, Míšek <sup>10</sup>	RDC	1 000	9.25	$3.98 \cdot 10^{-2}$
Rozkoš, Míšek <sup>11</sup>	RDC	2 000	6.52	$3.92 \cdot 10^{-2}$
Stemerding <sup>1</sup>	RDC	300	6.00	$3.54 \cdot 10^{-2}$
Stemerding <sup>1</sup>	RDC	640	8.69	$4.57 \cdot 10^{-2}$
Stemerding <sup>1</sup>	RDC	2 180	9.8	$5.88 \cdot 10^{-2}$

is shown in Fig. 5. The results proved the real dependence of longitudinal mixing on the power input in unit mass whereas its dependence on the RPM is only indirect.

FIG. 3  
Experimental Results  
1 RDC, 2 ARD.

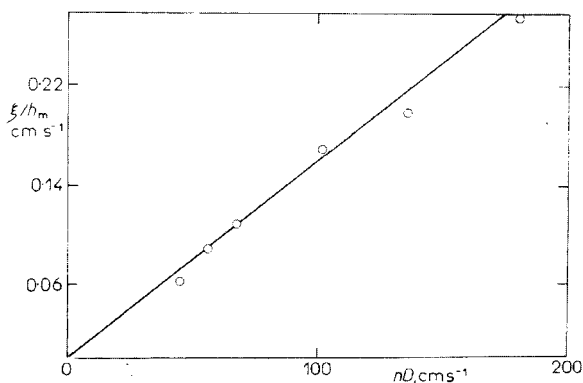
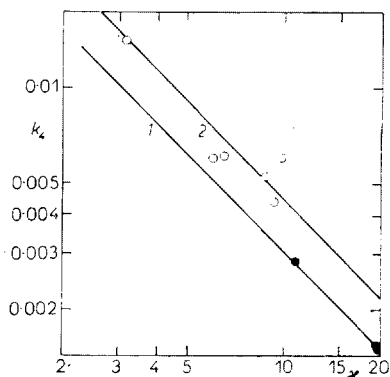


FIG. 4  
The Influence of Rotor Speed on Axial Diffusivity  
ARD extractor, diam. 2800 mm.

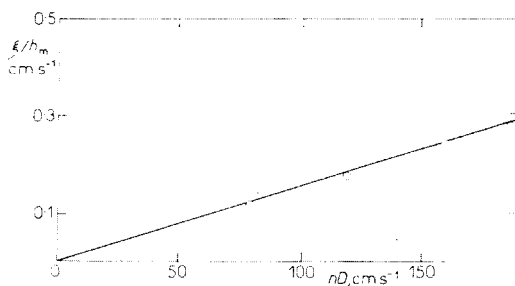


FIG. 5  
Measured (blank circles) and Calculated (full line) Diffusivities in the ARD/LS Extractor with  
3 Rotating Systems and Column Diameter 4000 mm

## DISCUSSION

The usefulness of the suggested theory of the longitudinal mixing in the agitated extractors of two different types has been proved within the wide range of variables, especially column diameters. The lower limit for the validity of linear dependence found by Stemerding<sup>1</sup> for the mixing intensity, is evidently dependent on the measuring method used. This limit does not occur when measuring with stationary continuous phase, which gives evidence of the fact that the phenomenon involved is connected with phase flow and not with the mixing itself.

The suggested theory presumes the independence of the longitudinal mixing on physical properties of the system and therefore these properties were not included in the experimental program. The full justification of this procedure presents the work of Kagan and coworkers<sup>16</sup>.

The experimental program also does not prove the conclusions of the theoretical part, valid for the dispersed phase. A partial confirmation is quoted in the referred publication<sup>5</sup>, further evidence will be possible after refining the accessible measuring methods or after finding new ones, able to distinguish better the influences of longitudinal and forward mixing.

Single-phase studies of the longitudinal mixing with stationary phase yield very accurate results. The reason is that influence of the longitudinal mixing itself is studied here, without mutilating it by other processes. This is, however, not the case with the momentum method, where it is necessary to reckon with strong decreasing accuracy of the determination with introducing further possible sources of residence time distribution. This refers to flow fluctuations, actions of the second, dispersed phase and its hold-up, respectively of all control actions in full-scale columns.

This work does not cover problems of longitudinal mixing, caused by entrainment of the continuous phase in the wakes of individual droplets of the dispersed phase. However, evidence of such an influence exists, especially in the range of higher hold-ups and in columns with modified transfer openings (Ingham<sup>17</sup>).

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## LIST OF SYMBOLS

$D$	diameter of the mixer (cm)
$D_c$	column diameter (cm)
$h_m$	compartment height (cm)
$I$	injection point
$k$	constant
$l$	length (cm)
$n$	rotations per second ( $s^{-1}$ )
$N_p$	power number

$P$	power input ( $\text{g cm}^2 \text{s}^{-3}$ )
$R$	response point
$t$	residence time (s)
$t_0$	residence time, calculated from the phase velocity (s)
$u_1$	velocity difference over the distance 1 ( $\text{cm s}^{-1}$ )
$U$	superficial velocity ( $\text{cm s}^{-1}$ )
$U_Z$	back-flow superficial velocity ( $\text{cm s}^{-1}$ )
$X$	hold-up
$\xi$	longitudinal diffusivity ( $\text{cm}^2 \text{s}^{-1}$ )
$\varkappa$	as defined by the Eq. (8) ( $\text{cm}^{1/3}$ )
$\rho$	density ( $\text{g cm}^3$ )
$\varepsilon$	relative free area of the stator opening
$\varepsilon_0$	power input per unit mass ( $\text{cm}^2 \text{s}^{-3}$ )
$\tau_{50\%}$	response time, at which 50% of the maximum concentration is achieved (s)

## Indices

c	continuous phase
d	dispersed phase

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