HUNGARIAN JOURNAL
OF INDUSTRIAL CHEMISTRY
VESZPRÉM
Vol. 30. pp. 137 - 142 (2002)

STUDY ON THE TURBULENCE IN PULSED STAGEWISE EXTRACTION COLUMNS: TURBULENT MACROSCALE

G. ANGELOV and C. GOURDON[1]

(Institute of Chemical Engineering, Bulgarian Academy of Sciences, Acad. Bonchev St., Bl. 103, 1113 Sofia, BULGARIA
[1]Ecole Nationale Supérieure d'Ingénieurs en Arts Chimiques et Technologiques, Toulouse, FRANCE)

Received: February 06, 2002

The authors studied a particular turbulent parameter – turbulent macroscale, which characterizes the size of large energy containing eddies, and it is one of the basic parameters with essential role in the concept of turbulent motion. Pulsed turbulent liquid flow in stagewise column type apparatuses with internals of disks and rings is considered. The distribution of turbulent macroscale L over the stage is determined as depending on stage geometry and Re number. Insignificant changes of L are registered in the course of pulsation cycle. Similarly, the dynamic flow parameters, expressed by the value of Re number, pulse amplitude and frequency, demonstrate slight and not pronounced influence on the size of turbulent macroscale. Most important effect on L has the stage geometry with pronounced influence of interplate distance and lesser dependence on plate free area. It was found that the zones of large L-values correspond to zones of intensive drop breakage, located experimentally.
A correlation is proposed for determination of the mean value of turbulent macroscale as a function of stage geometry parameters. Comparison with other correlations is made along with discussion on their advantages and inconveniences.

Keywords: plate extraction columns, flow hydrodynamics, pulsed flow, turbulent macroscale

Introduction

As known from practical experience, the turbulence increases the efficiency of transfer processes. Many chemical apparatuses operate under turbulent flow regimes, although in most cases they are empirically tuned. Studies on turbulent flows are helpful for understanding and quantification of the influence of turbulence on process intensification. This paper focuses on a particular turbulent parameter – turbulent macroscale. It characterizes the size of energy containing eddies and is one of the basic parameters with essential role in the concept of turbulent motion. As far as the energy containing eddies produce larger interphase contact surface by dispersing greater drops to smaller droplets, it is worthy to study them through the behavior of their characteristic parameter.

Turbulence model

The expression for turbulent macroscale is derived applying dimensional analysis with assumption that the amount of dissipated turbulent energy is determined by the energy containing large-scale motion at high Re numbers [1,2]

$$L = C_L \frac{k^{3/2}}{\varepsilon} \tag{1}$$

where L is turbulent macroscale characterizing the size of the large energy containing eddies, k is the kinetic energy of turbulent motion per unit mass, ε is the dissipation rate of kinetic energy, C_L is an empirical constant of order of unity [1].

Regarding *Eq.(1)*, larger L-value means higher kinetic energy with respect to its dissipation rate. Consequently, larger turbulent macroscale means larger level of non-dissipated energy that can provoke drop breakage, respectively, increase of the interphase surface. Thus, the zones of higher values of L should be expected to be places of drop breakage and interface surface production.

It is seen from *Eq.(1)* that L depends on the ratio of two other terms – kinetic energy and its dissipation rate (k and ε). Their distribution over the flow field can be derived from their transport equations, included in the standard k – ε model of turbulence [2].

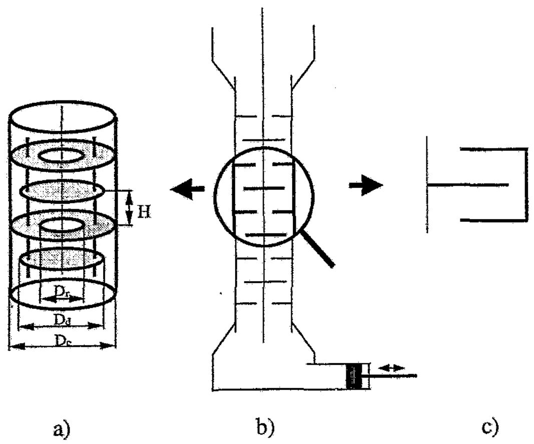

Fig.1 Apparatus scheme: a) internals axonometry; b) general column scheme; c) limits of simulation domain

$$\frac{\partial k}{\partial t}+U_i\frac{\partial k}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\nu+\frac{\nu_t}{C_k}\right)\frac{\partial k}{\partial x_i}\right]+\nu_t\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}-\varepsilon \quad (2)$$

$$\frac{\partial \varepsilon}{\partial t}+U_i\frac{\partial \varepsilon}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\nu+\frac{\nu_t}{C_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+\frac{\varepsilon}{k}C_{\varepsilon 1}\left[\nu_t\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}\right]-C_{\varepsilon 2}\varepsilon \quad (3)$$

where U_i is the mean velocity vector, ν - kinematic viscosity, ν_t - turbulent viscosity, x - space coordinate, C_μ, C_k, C_ε, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$ are constants of the model taking standard values, recommended in the relevant literature [3].

In previous papers [4,5] we have reported in details the full set of model equations for the considered case along with the method of resolution and boundary conditions for the particular apparatus geometry described below. So, adapted k – ε model equations are resolved in order to determine the distribution of L.

Apparatus description

The turbulent macroscale L is studied in case of stagewise pulsed columns (*Fig.1*) with internals of discs and rings (called also discs and doughnuts column [6]). This apparatus design has shown great performance in various solvent extraction applications [7-10] and is produced in large scale for industrial applications [11].

Immobile discs and rings are alternately placed at equal distance in cylindrical column body forming a series of identical stages. The turbulence is enhanced by a piston like mechanical device inducing oscillati ıg motion to the fluids.

As should be expected, the geometrical periodicity creates flow periodicity along the column. Previous experimental hydrodynamic studies have shown that in reality the flow picture is repeatedly reproduced on the adjacent stages, and flow symmetry with respect to column axis exists [12]. So, a typical flow pattern is observed in the vertical cross-section of a stage limited by the axis, column wall, and two rings (*Fig.1c*).

The stage geometry is defined by two dimensionless parameters:

– the ratio of interplate distance H and column diameter D_c bounds the stage height to column size

$$h = H/D_c \quad (4)$$

– the ratio of plate cross-section open to flow S_p and column cross section S_c defines the plate free area e

$$e = S_p / S_c = D_r^2 / D_c^2 = (D_c^2 - D_d^2) / D_c^2 \quad (5)$$

The free area of both plate configurations – disc and ring, is taken equal as practiced in the real DRC design.

Results and Discussion

The results for turbulent macroscale L are obtained by simulation of incompressible Newtonian liquid flowing in a typical stage at various flow regimes and variable stage geometry. Their effect on turbulent macroscale L is registered and discussed below.

Evolution of Turbulent Macroscale during a Pulsation Cycle

The pulsation created by a piston device corresponds to periodic sinusoidal pulsation described by the expression

$$U(t) = \pi A_p f \cos(2\pi f t) \quad (6)$$

where U(t) is the superficial velocity of pulsed flow at the instant t, A_p is pulsation amplitude, f = 1/T is pulsation frequency, T is the period of pulsation.

The results show that turbulent macroscale L is slightly changed during the pulse period T. For example, the maximal values of L at two moments of the pulsation corresponding to rather different instant flow velocities (t/T = 0 - maximal velocity and t/T = 0,2 – flow velocity approaches zero) are changed from $3{,}8.10^{-2}$ m to $4{,}1.10^{-2}$ m. It can be concluded that the value of the turbulent macroscale L does not depend significantly on the instant flow velocity during the pulsation cycle.

Influence of Flow Regime

The above result implies that the flow regime in the apparatus should not affect pronouncedly the turbulent macroscale. This suggestion is verified below.

The mean flow regime is defined by Re number

$$Re = \frac{U_m D_c}{\nu} \quad (7)$$

where U_m is the mean superficial flow velocity; ν is kinematic viscosity.

Integrating *Eq.(7)* over a period of pulsation, the mean flow velocity is obtained

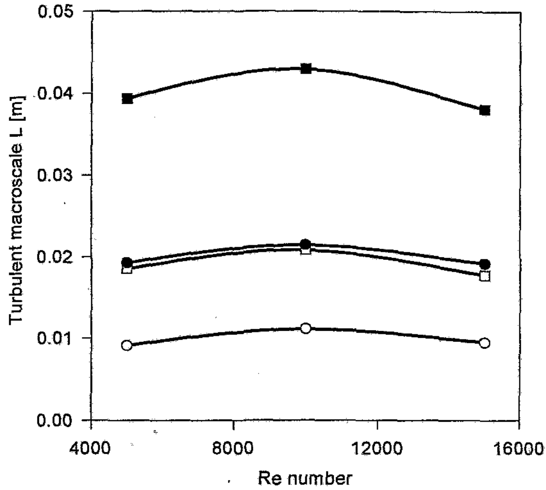

Fig.2 Influence of Re number on turbulent macroscale L: ■ L_{max} (h=0,155; F=0,43); □ L_m (h=0,155, F=0,43); ● L_{max} (h=0,086; F=0,23); ○ L_m (h=0,086; F=0,23)

$$U_m = 2\ A_p f \quad (8)$$

and *Eq.(7)* becomes

$$Re = \frac{2A_p f D_c}{\nu} \quad (9)$$

In this study, Re number of a water flow has been varied from 5 000 to 15 000. It corresponds to pulse regimes with different intensity of the turbulence - from unstable transition regimes at lower Re to established turbulent regimes at higher Re values [13].

Fig.2 represents maximal (L_{max}) and mean (L_m) values of turbulent macroscale on the stage as depending on Re number. The results illustrate two extreme stage configurations – smaller interplate distance with small plate free area and larger interplate distance with large plate free area. It is seen that in all cases the flow regime has slight and not pronounced influence on the size of turbulent macroscale. Similar weak influence was observed by Aoun et al. [6] that have reported a correlation for L with small power terms for the quantities A_p and f.

On the contrary, the curves on *Fig.2* indicate qualitatively for stronger influence of the stage geometry on both mean and maximal L-values.

Influence of Stage Geometry

The range of variation of geometry parameters in this study is

- Plate free area e = 0,2 – 0,5
- Interplate distance to column diameter ratio h = 0,08 – 0,4

The above values have been selected by practical considerations [14]. For example, a direct vertical flow through the column will reduce apparatus efficiency due to axial mixing phenomena. To avoid it, the disc diameter D_r should not be smaller than ring aperture D_r. The above requirement limits the possible upper value of e to 0,5, at which $D_r = D_d$.

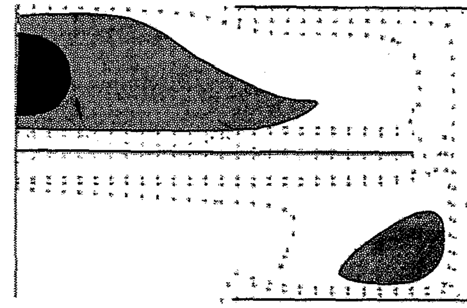

Fig.3a Size and distribution of turbulent macroscale L on stages at same interplate distance and different plate free area e:

e = 0,23; $L_{max} = 3,8.10^{-2}$ m; ▒ $2,5.10^{-2} < L < 3,5.10^{-2}$ m; ■ $3,5.10^{-2} < L < 3,8.10^{-2}$ m

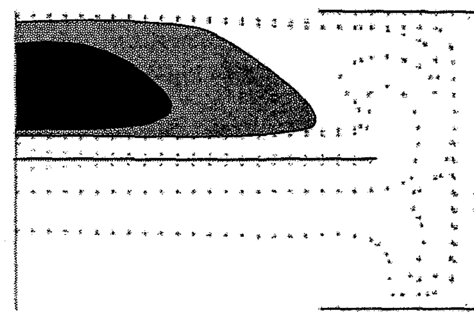

Fig.3b Size and distribution of turbulent macroscale L on stages at same interplate distance and different plate free area e:

e = 0,43; $L_{max} = 4,1.10^{-2}$ m; ▒ $2,5.10^{-2} < L < 3,5.10^{-2}$ m; ■ $3,5.10^{-2} < L < 4,1.10^{-2}$ m

Influence of Plate Free Area

The distribution of L on the stage is shown for a lower and a higher value of the free area at fixed interplate distance h (*Fig.3*). It is seen that in case of small free area, the zones of high L-values are smaller in volume and are found in both parts of the stage over and under the disk. In case of large free area, the zones of high L-values become larger. However, the zone under the disk has disappeared. The maximal values of L in these two cases are rather similar, i.e. there are no significant changes in the turbulent macroscale due to plate free area, only the volume and location of the zones are affected.

Influence of Interplate Distance

Fig.4 illustrates the case of different interplate distance h at fixed plate free area. It is seen that the interplate distance affects strongly the volume and the maximal values of the turbulent macroscale. When doubling the interplate distance, L increase significantly, the maximal

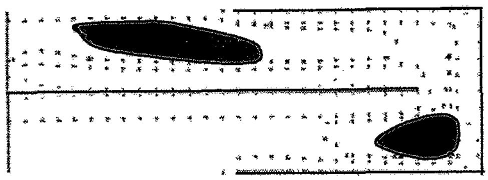

Fig.4a Size and distribution of turbulent macroscale L on stages at same plate free area and different interplate distance h: $h = 0{,}086$; $L_{max} = 1{,}9.10^{-2}$ m; ▇ $1{,}5.10^{-2} < L < 1{,}9.10^{-2}$ m

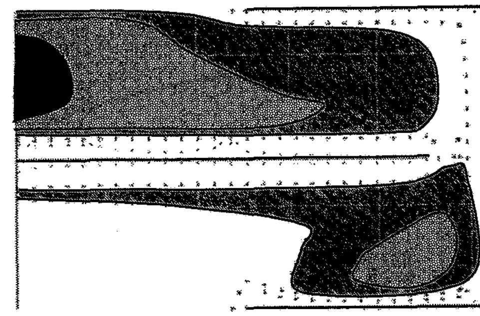

Fig.4b Size and distribution of turbulent macroscale L on stages at same plate free area and different interplate distance h: $h = 0{,}155$; $L_{max} = 3{,}8.10^{-2}$ m; ▇ $1{,}5.10^{-2} < L < 2{,}5.10^{-2}$ m; ▇ $2{,}5.10^{-2} < L < 3{,}5.10^{-2}$ m; ▇ $3{,}5.10^{-2} < L < 3{,}8.10^{-2}$ m

L-value is increased as much as twice, and the zones of high L-values become much larger in volume. The conclusion is that the interplate distance is the most important parameter controlling the size of turbulent macroscale.

The results of *Figs. 3* and *4* refer to ascending (down to up) flow. The picture for the descending phase of the pulsation is symmetrical with respect to disk – the marked zones take mirror positions on the other side of the disk. In all cases, larger values of turbulent macroscale are located in the median zones between the disk and respective ring.

The experimental observations [15] in a column of same geometry have shown that namely these median zones in the stage are places of intensive drop breakage. This fairly good correspondence of modeling and experience attributes more reliability to the simulation results obtained here.

Correlation Development

Summarizing the influence of geometry and dynamic parameters, the following general tendencies have been put in evidence:

- The dynamic parameters A_p and f (Re) have negligible influence on L;
- The turbulent macroscale rises when increasing the interplate distance or/and plate free area;
- The influence of interplate distance on L is stronger than that of plate free area.

Additional considerations are taken into account in the development of corresponding correlation:

- When plate free area e approaches 1 – case of hollow column, no matter the value of h, L should tend to a value L_0 corresponding to hollow column;
- The interplate distance parameter $h = H/D_c$ should control L when $h \le 1$, i.e. until the interplate distance is smaller than the column diameter. At interplate distance larger than column diameter, the latter becomes the limiting geometry dimension and the influence of h should diminish.

An expression translating these tendencies has been developed

$$\frac{D_c}{L_m} = \frac{D_c}{L_0} + \left(\frac{1}{h}\right)^{\alpha}\left(\frac{1}{e} - 1\right)^{\beta} \qquad (10)$$

The unknown empirical terms have been identified by a procedure based on Gauss-Newton algorithm, using the mean space and time values (L_m) of computed discrete values of turbulent macroscale at various geometry parameters:

$D_c/L_0 = 22{,}38$; $\alpha = 1{,}49$; $\beta = 0{,}48$

Comparison with Existing Correlations

For a hollow column, Brodkey [16] has proposed the expression (subscript o designates the terms in a hollow column)

$$\varepsilon_0 = \frac{8{,}8}{D_c} k_0^{3/2} \qquad (11)$$

From *Eqs.(1)* and *(11)* it is derived

$$L_0 \approx \frac{k_0^{3/2}}{\varepsilon_0} = \frac{D_c}{8{,}8}$$

$$L_0 \approx 0{,}1 D_c \qquad (12)$$

This result shows also, that the turbulent macroscale in a hollow column depends only on column diameter and is independent on flow regime (Re).

Our correlation (10) can provide the value of L in a hollow column. In this limit case, the free area e becomes equal to 1 and *Eq.(10)* is reduced to

$$D_c/L_m = D_c/L_0 = 22{,}38$$

from where

$$L_0 = 0{,}045\, D_c \qquad (13)$$

The results (12) and (13) are of the same order. Their similarity could be considered as relatively good, accounting that the empirical coefficient C_L in (1) has been taken approximately equal to 1.

More fine coincidence is found applying another approach. The friction velocity in the wall zone U_f is bound to the kinetic energy and its dissipation rate by the equations [1,2]

$$k = U_f^2 / C_\mu^{1/2} \qquad (14)$$

$$\varepsilon = U_f^3/C_k L \quad (15)$$

From (14) and (15) it is obtained

$$\varepsilon = \frac{C_\mu^{\ 3/4}}{C_k L} k^{3/2} \quad (16)$$

In the above relation C_k = 0,41 is von Karman constant [2], C_μ = 0,09 is standard constant of k-ε turbulence model [3].

Applying *Eq.(16)* for hollow column with use of our result for L_0 (13), it follows

$$\varepsilon_0 = \frac{8{,}9}{D_c} k_0^{\ 3/2} \quad (17)$$

Comparing *Eq.(17)* to the relation of Brodkey (11), encouraging similarity is seen.

Aoun et al. [6] have proposed the correlation

$$\frac{L_m}{D_c} = ah^b e^c \left(\frac{A_p}{D_c}\right)^d \left(\frac{fD_c^{\ 2}}{\nu}\right)^g \quad (18)$$

with the following values of the empirical coefficients:

$a = 8{,}4.10^{-2}$; $b = 0{,}27$; $c = 0{,}31$; $d = -0{,}05$; $g = -0{,}05$

The above values show relatively weak dependence of L_m on the pulsation parameters A_p and f. This is close to our observations that allowed us to develop a simpler correlation excluding the participation of dynamic terms.

Regarding the free area term e in (18), its influence is even more important than that of interplate distance. In our opinion, the main parameter defining the space where the vortices can develop and extend to the available geometry limits, is the interplate distance and not the plate free area. For this reason, it seems more logical to expect stronger influence of the interplate distance as we have registered, studying the stage distribution of L. This dependence is clearly reflected by the correlation (10).

Unfortunately, correlation (18) cannot be unconditionally applied for parameter values outside the particular studied range, which is approximately the same as our parameter range. For example, the increase of h will produce unlimited rise of L_m. It is known, however, that the size of eddies is limited by the column diameter when interplate distance is too large.

In the considered case of hollow column, the influence of dynamic parameters still remains, which is in conflict with relation (11) and its result (12). Nevertheless, if assume for hollow column case h=1 and e=1, *Eq.(18)* produces for L_0 values around $0{,}04D_c$, which is close to our result (13). In case of various stage geometry parameters, correlations (10) and (18) give rather similar results although their different structure.

Conclusions

The turbulent macroscale L of a pulsed liquid flow in stagewise column apparatuses with internals of discs and rings was studied by use of k-ε model of turbulence. The local distribution of L on the stage is thoroughly studied as a function of flow regime and stage geometry parameters. Small variation of L during the pulsation cycle is registered, i.e. the size of large eddies does not depend on the instant superficial flow velocity changes during the pulsation. Similarly, low dependence of L on Re number, pulse amplitude and frequency is observed. Strong influence of the geometry parameters on L was found, not too pronounced for the plate free area, but rather significant as regarding the interplate distance. The zones of high values of turbulent macroscale are located. They correspond in position to the zones where intensive break-down of drops has been experimentally observed. This fact attributes reliability to the results obtained. A correlation for determination of mean value of turbulent macroscale is proposed that reflects adequately the influence of main process parameters.

Acknowledgements

The study is carried out with partial financial support from CNRS - France and Bulgarian Academy of Sciences.

SYMBOLS

A_p pulsation amplitude, m
C_μ, C_k, C_ε, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$ standard constants of k – ε turbulence model, -
C_k von Karman constant, -
D_c column diameter, m
D_d disc diameter, m
D_r ring diameter, m
e plate free area, -
ε dissipation rate of turbulent kinetic energy, m^2s^{-3}
f pulsation frequency, s^{-1}
H interplate distance, m
h ratio of interplate distance and column diameter, -
k turbulent kinetic energy, m^2s^{-2}
L turbulent macroscale, m
L_m mean value of turbulent macroscale, m
L_{max} maximal value of turbulent macroscale, m
L_0 turbulent macroscale for hollow column, m
ν kinematic viscosity, m^2s^{-1}
ν_t turbulent viscosity, m^2s^{-1}
Re Reynolds number, -
S_p plate cross-section open to flow, m^2
S_c column cross section, m^2
t time, s
T period of pulsation, s
U_f friction velocity, ms^{-1}
U_i mean velocity vector, ms^{-1}
U_m mean superficial flow velocity, ms^{-1}
U(t) flow superficial velocity at the moment t, ms^{-1}
x space coordinate, m

REFERENCES

1. RODI W.: Introduction to modeling of turbulence, Von Karman Institute, Karlsruhe, 1985
2. SCHIESTEL R.: Modélisation et simulation des écoulements turbulents, Hermes, 1993
3. LAUNDER B. E. and SPALDING D. B.: Comp. Meth. in Appl. Mech. Eng., *1974*, 3, 269-289
4. ANGELOV G. and GOURDON C.: Hung. J. Ind. Chem., *1997*, 25, 223-228
5. ANGELOV G. and GOURDON C.: Hung. J. Ind. Chem., *1999*, 27, 281-286
6. AOUN NABLI M. S., GUIRAUD P. and GOURDON C.: Trans. IChemE, *1998*, 76, 951-960
7. MILOT J. F., DUHAMET J., GOURDON C. and CASAMATTA G.: Chem. Eng. Sci., *1990*, 45, 111-116
8. HAUNOLD C.: Extraction of pyrethrines – modeling and development of a continuous process, Ph.D. Thesis, INP-Toulouse, 1991
9. HANSSENS A.: Scale-up in diameter of pulse columns, Summer School on Liquid Extraction, Toulouse, 1991
10. NGAMPRASERTSITH S.: Solvent extraction of vegetable materials in a discs and rings column, Ph.D. Thesis, INP-Toulouse, 1993
11. BATEMAN: Pulsed Columns – making solvent extraction work better, www.bateman.co.za presented at technical exhibition, Int. Solvent Extraction Conf., Barcelona, 1999
12. ANGELOV G., JOURNE E., LINE A. and GOURDON C., Chem. Eng. J., *1990*, 45, 87-97
13. OH W. Z.: Hydrodynamics of a pulsed column with discs and rings – study of velocity field Ph.D. Thesis, INP-Toulouse, 1984
14. ANGELOV G., GOURDON C. and LINE A.: Chem. Eng. J., *1998*, 71, 1-9
15. LAULAN A.: Hydrodynamics and drop breakage in a pulsed column with disks and rings, Ph.D. Thesis, INP-Toulouse, 1980
16. BRODKEY R.: Turbulence in mixing operations, Academic press Inc., 1975