PROCESS CHARACTERISTICS OF SCREW IMPELLERS WITH A DRAUGHT TUBE FOR NEWTONIAN LIQUIDS. TIME OF HOMOGENIZATION

Pavel SEICHTER

Research Institute of Chemical Equipment, 638 00 Brno

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A conductivity method has been used to assess the homogenation efficiency of screw impellers with draught tubes. The value of the criterion of homochronousness, *i.e.* the dimensionless time of homogenization, in the creeping flow regime of Newtonian liquids is dependent on the geometrical simplexes of the mixing system. In particular, on the ratio of diameters of the vessel and the impeller and on the ratio of the screw lead to the impeller diameter. Expression have been proposed to calculate the mixing times. Efficiency has been examined of individual configurations of screw impellers. The lowest energy requirements for homogenization have been found for the system with the ratio $D/d = 2$.

By homogenization of highly viscous liquids it is understood equalization of the concentration or temperature gradients within the mixed batch. The mechanism of blending one viscous liquid with another one by effectively working impellers is a combined action of the recirculatory flow and the shearing strain on individual elements of the batch. Screw impellers with a draught tube exhibit relatively high pumping capacities[1] and their use for homogenation of highly viscous liquids is therefore justified[2-6].

As the scale of homogenization abilities of a rotating impellers one usually takes the homogenization time τ_H. This characteristic, however, depends not only on the physical and geometrical characteristics of the system, including the frequency of revolution of the impeller, but also significantly on a number of other factors. Of these one can name, for instance: the used experimental method and the degree of homogeneity[3,4], the number and location of probe[7,8]; the amount of component added[6]; rheological properties of mixed liquid[2,6]. A more detail analysis of experimental methods to determine the homogenization time has been published elsewhere[4,9].

The time of homogenization, expecially in case of mixing highly viscous liquids, may be taken as a process characteristic only from the qualitative stand point. Keeping constant all above factors affecting the overall course and the time of homogenization, the results of such homogenization runs can be utilized for comparison of the efficiency of the arrangement of the given mixing system.

Theoretical solution of the transient change of concentration in an arbitrary point of the mixed batch (after adding a well-defined amount of another substance) could be determined only with the knowledge of the flow pattern of the highly viscous liquid. For this purpose one can utilize the equation[10]

$$\frac{\partial c}{\partial t} + \mathbf{v}\,\nabla c = D_{\mathrm{m}}\,\nabla^2 c \tag{1}$$

together with the equation of continuity.

To solve this equation one would have to know, appart from the velocity field in the batch, also the appropriate initial and boundary conditions. Introducing characteristic quantities of the mixed system: n, d, Eq. (*1*) can be rendered dimensionless. The dimensionless quantities

$$\mathbf{v}^* = \mathbf{v}/nd\,, \quad \nabla^* = \mathrm{d}\nabla\,, \quad \nabla^{*2} = \mathrm{d}^2\nabla^2\,, \quad t^* = nt\,, \quad c^* = \frac{c_{\mathrm{k}} - c}{c_{\mathrm{k}} - c_0}\,. \qquad (2a)-(2e)$$

Eq. (*1*) takes the following dimensionless form

$$\frac{\partial c^*}{\partial t^*} + \mathbf{v}^*\,\nabla^* c^* = \left(\frac{D_{\mathrm{m}}}{nd^2}\right)\nabla^{*2} x^*\,. \tag{3}$$

In view of the fact that the transport of mass by molecular diffusion ($\sim D_{\mathrm{m}}$) is negligible with the convective transport due to mixing of highly viscous liquids, the right hand side of Eq. (*3*) may be neglected. This assumption, moreover, corresponds to the experimental techniques of determination of the homogeneity of mixtures. The effect of molecular diffusion may show practically on the micromixing scale while the size of the probes enables determination of the homogeneity on the macro--scale.

Then we may write

$$\frac{\partial c^*}{\partial t^*} = -\mathbf{v}^*\,\nabla^* c^*\,. \tag{4}$$

In a mixing equipment with a screw impeller and a draught tube under the creeping flow regime we have not that $\mathbf{v} = f(\mathrm{Re})$. The field of velocities in this case depends on the geometrical configuration of the system. For a given degree of inhomogeneity we have

$$c^* = \text{const.} \tag{5}$$

and for the conditions considered we shall have that

$$t^* = t^* \quad \text{(system geometry)}\,. \tag{6}$$

On designating the time, t, neccessary to reach a predetermined degree of homogeneity, c^*, ($e.g.$. $c^* = 0{\cdot}05$) in a given position, as τ_H, *i.e.*the time of homogenation, we shall have for geometrically similar systems that

$$\text{Ho} = \text{const.} \tag{7}$$

Ho is the so-called criterion of homochronousness

$$\text{Ho} = n\tau_H\,. \tag{8}$$

The results of measurement with screw impellers equipped with a draught tube[2-6] entirely confirmed the conclusions of the inspection analysis of Eq. (*1*). The measured value of the criterion Ho though differed due to, on the one hand, different geometrical arrangement, and on the other hand, due to the various experimental techniques employed.

EXPERIMENTAL

The course of the homogenization process in the mixing vessel was detected by a conductivity probe in the mixed batch. The probe consisted of a pair of circular electrodes (the radius of the electrodes was 1·2 cm) 0·8 cm apart. The principle of the function and electric wiring have been described in detail elsewhere[11]. The arrangement of the mixing system is apparent from Fig. 1.

The probe was submerged into the batch mostly into the space between the wall of the vessel and the draught tube. The dimensions of the used screw impellers and their designation are identical with the data published in our previous paper[12]. Also the mixing vessels were the same. As mixed batches we used Newtonian solutions of the starch syrup in water.

The measurements were carried out in such a way that 1—3 cm^3 of concentrated NaCl solution were injected by a syringe into the mixing batch. The point of injection was in all cases the entrance into the screw impeller, see Fig. 1. This moment was at the same time recorded by a short tick of the pen of the recorder. The amplified and rectified signal of the probe, corresponding to the change of conductivity, was registered on an in parallel connected coordinate recorder BAK 4T.

The method of evaluation and determination of the times of mixing is apparent from Fig. 2. In the course of equalization of NaCl concentrations at the point of location of the probe we determined: t_A — the dead time, $t_{0.2}$ — the time of homogenization for $c^* = 0{\cdot}20$; $t_{0.1}$ — the time of homogenization for $c^* = 0{\cdot}10$; $t_{0.05} - \tau_H$ — the time of homogenization for $c^* = 0{\cdot}05$, taken to be the time of thorough homogenization.

Each experiment was repeated 5 times under identical conditions and the resulting homogenation times were take as arithmetic averages from repeated experiments.

RESULTS

A significant factor affecting both the course of equalization of concentration and the time of homogenization turned out to be the position of the probe in the bath. Fig. 3 evidences this finding by five different curves obtained under otherwise the same conditions of mixing. Individual curves differ by the dead time (t_A), the number

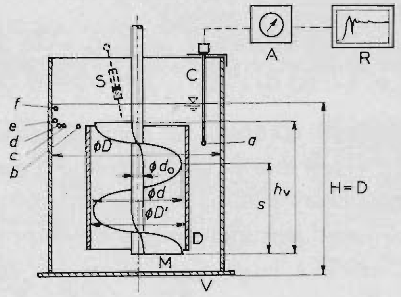

FIG. 1

Scheme of experimental set-up to measure the homogenation effects of impellers. M Screw impeller; D draught tube; V mixing vessel; C conductivity probe; S syringe; A conductometer; R recorder; *a, b, c, d,* e, *f* positions of probe within the mixed batch

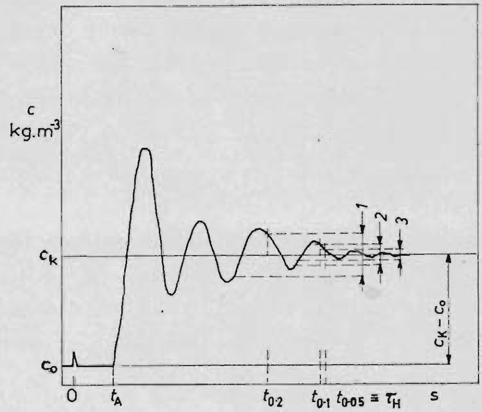

FIG. 2

Method of evaluation of the mixing times from the record of concentration equalization in a given position in the batch *1* $2|C_k - C_0|$ 0·2, *2* $2|C_k - C_0|$ 0·1, *3* $2|C_k - C_0|$ 0·05

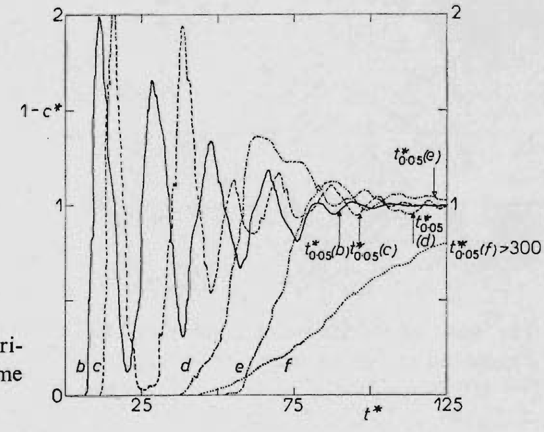

FIG. 3

Course of the homogenation process in various positions within the mixed batch (same caption as in Fig. 1) of the peaks on the record (corresponding to the recirculation of the batch) and the overall time of homogenization (τ_H). Location of the probe in the "corner" ((*f*)) signalizes that virtually no circulation exists in this region and that apparently molecular diffusion significantly affects the course of homogenization. In addition, the overall time of homogenization here ((*f*)) is substantially longer than anywhere else in the batch.

The prolonged time of homogenization in the mixed batch is affected primarily by the dead period, t_A (Fig. 3). The influence of probe location on the evaluated time of homogenization was therefore eliminated by substracting the time t_A from the time of homogenation τ_H. The time ($\tau_H - t_A$) apparently corresponds to the measurements of homogeneity of the batch somewhere within the screw impeller (near the point of injection).

Individual records of the course of homogenization were processed to give mean values of the four defined times: t_A; $t_{0.2}$; $t_{0.1}$ and τ_H. Thus we could evaluate for all arrangements of the mixing system the dimensionless times of homogenization t_A^*; $t_{0.2}^*$, $t_{0.1}^*$ and Ho, defined in Eq. (*2d*) and (*8*). Fig. 4 and 5 plot the found dimensionless mixing times for two geometrical arrangements studied as functions of the Reynolds criterion, Re. It is seen that the dead times at constant position of the probe display the minimum variance of all examined times. A large variance, on the con-

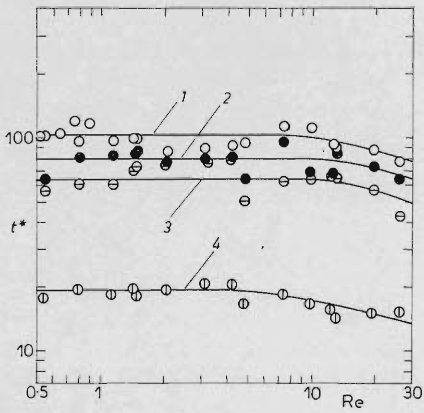

FIG. 4

The effect of the Reynolds number on the dimensionless mixing time, screw impeller No 2*D*: $D/d = 2{\cdot}30$ $s/d = 0{\cdot}75$. *1* $t_{0.05}^*$ (○); *2* $t_{0.1}^*$ (●); *3* $t_{0.2}^*$ (⊖); *4* t_A^* (⦶)

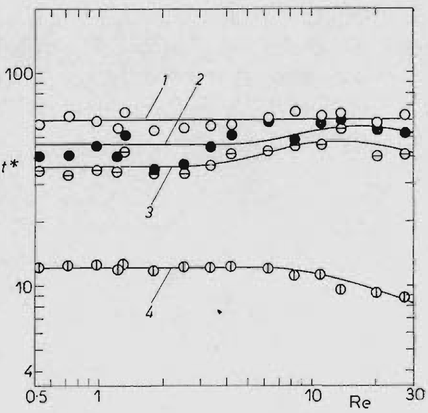

FIG. 5

The effect of the Reynolds number on the dimensionless mixing time; screw impeller No 2F: $D/d = 2{\cdot}30$ $s/d = 1{\cdot}50$. *1* $t_{0.05}^*$ (○); *2* $t_{0.1}^*$ (●); *3* $t_{0.2}^*$ (⊖); *4* t_A^* (⦶)

trary, carry the times $t_{0.1}$ and $t_{0.2}$. Similar results were obtained for all geometrical configurations.

The effect of the Reynolds number, Re, on the magnitude of the criterion of homochronousness can be seen in Figs 6 and 7. In Fig. 6 the parameter is the simplex of geometrical similarity s/d, keeping D/d constant. Clearly, the times of homogenization markedly grow with decreasing lead of the screw.

The variable parameter in Fig. 7 is the simplex of the relative size of the impeller D/d, keeping s/d constant. Decreasing size of the impeller (increasing D/d ratio) brings about a significant increase of the time of homogenization.

From the two diagrams (Fig. 6 and 7) it may be concluded that in spite of the greater scatter of experimental data, the values of Ho in the creeping flow regime ($Re < 20$) do not depend on Re. This is fully in accord with the theoretical assumptions and results of other authors[2–6].

Since for both sets of data (Figs 6 and 7) we did not use the same location of the probe in the mixed batch, the effect of the geometrical simplexes D/d and s/d on the dimensionless time of mixing or homogenization was sought in the form of the following correlation

$$t^* - t_A^* = k_2 \left(\frac{D}{d}\right)^{a_2} \left(\frac{s}{d}\right)^{b_2} \left(\frac{d_0}{d}\right)^{c_2} . \qquad (9)$$

From our experimental measurements it follows that for a given level of significance 0·05, all regression coefficients for the degree of homogeneity $c^* = 0{\cdot}2$ and $0{\cdot}1$ are statistically significant. For $c^* = 0{\cdot}05$ the value of the coefficient c_2 is statistically insignificant. In the investigated region the changes of the simplex $d_0/d \in \langle 0{\cdot}17; 0{\cdot}37 \rangle$, the homogenation time τ_H is independent of the diameter of the screw core, d_0.

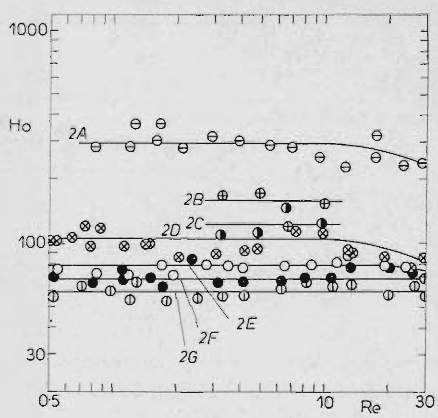

FIG. 6

Ho = f(Re) dependence for screw impellers with draught tube and $D/d = 2{\cdot}30$; the effect of the simplex s/d. 2A $s/d = 0{\cdot}33$ (⊖); 2B $s/d = 0{\cdot}46$ (⊕); 2C $s/d = 0{\cdot}60$ (◑); 2D $s/d = 0{\cdot}75$ (⊗); 2E $s/d = 1{\cdot}00$ (○); 2F $s/d = 1{\cdot}33$ (●); 2G $s/d = 1{\cdot}50$ (⦶)

The resulting expression for the calculation of the criterion of homochronousness in the creeping flow for the screw impellers with the draught tube then takes the form

$$\mathrm{Ho}' = 11{\cdot}23\left(\frac{D}{d}\right)^{2.27}\left(\frac{s}{d}\right)^{-0.98}, \tag{10}$$

where

$$\mathrm{Ho}' = \mathrm{Ho} - nt_\mathrm{A}\,. \tag{11}$$

The magnitude of the dead time, t_A, depends on position of the probe in the mixed batch (for regions within the channel of the screw $t_\mathrm{A} \to 0$). The regions of validity of Eq. (*10*) are following: Re < 20, $1{\cdot}59 \leqq D/d \leqq 3{\cdot}37$, $0{\cdot}33 \leqq s/d \leqq 1{\cdot}50$, $0{\cdot}17 \leqq d_0/d \leqq 0{\cdot}37$, $1{\cdot}37 \leqq h_\mathrm{v}/d \leqq 1{\cdot}50$, at constant value of the geometrical similarity: $H/D = 1{\cdot}0$, $D'/d = 1{\cdot}1$, $h_\mathrm{D}/D' = 1{\cdot}15$
$H_2/d = 0{\cdot}5(D/d - 1{\cdot}5)$, *i.e.* half-way to the level of the mixed batch.

Mean values of $\overline{\mathrm{Ho}}$, $\overline{nt_\mathrm{A}}$ and $\overline{\mathrm{Ho}'}$, for the creeping flow region are given in Table I and compared with the calculated values of the criterion of homochronousness from Eq. (*10*). The agreement of the values from the last two columns of that table is satisfactory (excepting the arrangements with $D/d = 1{\cdot}59$), which is in accord with the results of the regression analysis.

The found values of Ho enable the dimensionless power requirements of homogenization[3,5] to be computed.

$$E_\mathrm{H}^* \equiv \frac{P\tau_\mathrm{H}^2}{\mu D^3} = \mathrm{Po}\ \mathrm{Re}\ \mathrm{Ho}^2\left(\frac{d}{D}\right)^3 \tag{12}$$

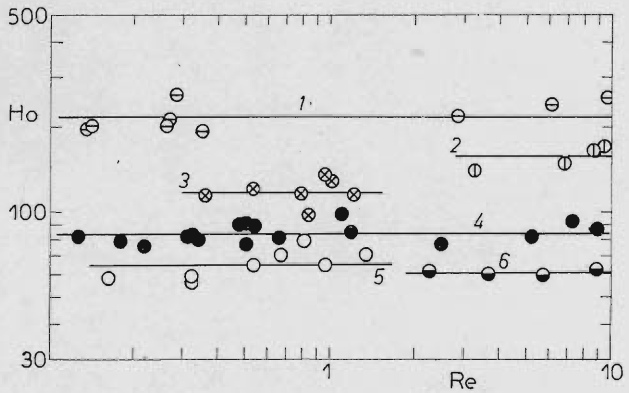

FIG. 7

Ho = f(Re) dependence for screw impellers with a draught tube and $s/d \approx 1{\cdot}0$; the effect of the simplex D/d. *1* $D/d = 3{\cdot}19$ (⊖); *2* $D/d = 2{\cdot}74$ (⦶); *3* $D/d = 2{\cdot}69$ (⊗); *4* $D/d = 2{\cdot}13$ (●); *5* $D/d = 1{\cdot}59$ (○); *6* $D/d = 2{\cdot}00$ (◒)

Values of E_H^* in the creeping flow region depend on the geometrical configuration of the mixed system and are plotted in Fig. 8.

The least energy consumption $(\sim E_H^*)$ for homogenization display thus screw impellers with a high lead of the employed screw. For the simplex D/d there is an optimum in the neighbourhood of $D/d = 2$ (Fig. 8).

DISCUSSION

The results of experimental measurements have shown that for mixing of highly viscous liquids the times of homogenization measured in various points of the batch may be widely different. This is due to the fact that the velocities of the flow within the batch are small and, moreover, a distinct velocity profile exists there[1].

Also the mechanism of mixing in different positions within the mixed batch is different. Equalization of concentration in those locations where the controlling mechanism is molecular diffusion proceeds very slowly. The course of homogenization in the substantial part of the mixed batch, where the controlling mechanisms of mixing are shearing stresses and convective flows, remains then free of the diffusion.

The scatter of the evaluated homogenization times, which was higher especially for greater degrees of inhomogeneity, may then be explained by random distribution of the added solution of NaCl with respect to the radial and angular coordinate and at the beginning of the experiment in particular.

The magnitude of the measured values of Ho in the creeping flow regime for screw impellers with a draught tube was compared with the data of other authors (Table II). The data in this table show, that in spite of the difference in the experimental techniques employed[2,3] the agreement of results is very good.

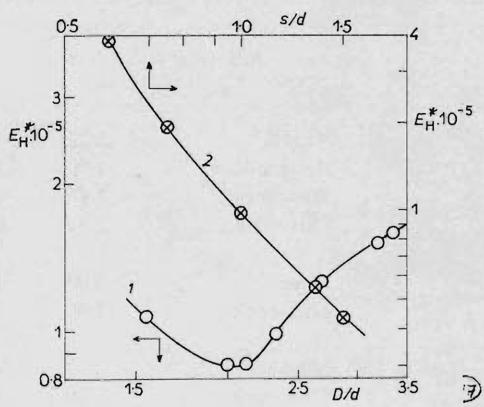

FIG. 8

Energy criterion E_H^* as a function of the geometrical similarity simplexes of the screw impeller in the creeping flow region. *1* $E_H^* = f(F/d)$ (○); 2 $E_H^* = f(s/d)$ (⊗)

TABLE I

Values of the criterion of homochronousness in the creeping flow region (Re < 20)

Impeller	D/d	s/d	$\overline{\mathrm{Ho}}$	$\overline{n t_A}$	$\overline{\mathrm{Ho}'}$	Ho′ Eq. (*10*)
1	3·37	1·00	203·3	31·5	171·8	177·1
2A	2·30	0·33	295·6	70·0	225·6	220·8
2B	2·30	0·46	153·3	26·2	127·1	159·6
2C	2·30	0·60	123·3	16·0	107·3	123·0
2D	2·30	0·75	100·6	17·2	83·4	98·8
2E	2·30	1·00	78·0	13·8	64·2	74·6
2E	3·14	1·00	241·0	40·1	200·9	150·8
2E	3·19	1·00	205·0	35·7	169·3	156·3
2F	2·30	1·33	70·5	12·2	58·3	56·3
2G	2·30	1·50	59·7	11·4	48·3	50·1
3	2·00	1·00	66·7	7·7	59·0	54·2
3	2·69	1·00	118·3	21·8	96·5	106·1
3	2·73	1·00	159·1	36·5	122·6	109·8
4	1·59	0·93	66·4	8·1	58·3	37·8
4	2·13	0·93	80·1	9·8	70·3	67·2
4	2·16	0·93	84·8	10·3	74·5	69·2
4	2·20	0·93	83·2	9·6	73·6	72·2
5	1·98	1·00	61·2	12·7	48·5	52·9

TABLE II

A comparison of Ho for screw impellers with results of other authors

Ref.	D/d	s/d	h_v/d	D/d	Ho
Nagata[2]	2·22	0·67	2·00	1·11	102
Hoogendoorn[3]	2·50	1·15	2·50	1·15	140
This work	2·30	0·60	1·50	1·10	123
This work	2·30	0·75	1·50	1·10	101
Rieger[13,14]	2·00	1·00	1·50	1·10	68
This work	2·00	1·00	1·50	1·10	67
Novák[4]	2·92	1·00	1·50	1·10	190
This work	3·19	1·00	1·50	1·10	205

The influences of the geometrical simplexes of the screw impeller, D/d and s/d, on the value Ho′ in this work can be compared with the results of Novák[4], where

$$\text{Ho} \sim \left(\frac{D}{d}\right)^{2.0}$$

for $s/d = 1$ (the other geometrical parameters were identical).

The magnitudes of the exponents over the simplex D/d thus agree well. The effect of s/d on the time of homogenization was not found in the literature. It may be concluded though that the extended times of homogenation for lower screw leads are in full agreement with the results of measurement of pumping capacity of screw impellers[1].

Analogous agreement with the measurement of the pumping capacity of screw impellers[1] has been achieved also in case of the power requirements for homogenization and circulation following from the criterion E_H^* are very similar to the conclusions arrived at in the previous part[1]. The results of this work, from the standpoint of the effect of the D/d ratio on the efficiency of mixing agree also very well with the results of Novák[4,5].

Based on the results of this work and its preceeding parts[1,12] one can recommend for the homogenization mixing of highly viscous Newtonian liquid as the optimum size of the screw impeller the ratio $D/d = 2$. Use of high lead screws is impeded by the difficulties of their manufacture and the maximum value of s/d for the plant-scale screw is $s/d = 1$. The influence of other geometrical parameters of the mixing system is probably not so important. These findings though cannot be probably generalized to non-Newtonian liquids, for the conditions of the flow may in this case markedly differ.

LIST OF SYMBOLS

a_2, b_2, c_2	exponents in Eq. (*9*)
c	concentration (*o*-initial, *k*-final)
D	inner vessel diameter
D'	inner diameter of draught tube
D_m	molecular diffusivity
d	impeller diameter
d_0	screw core diameter
H	clear liquid height
H_2	height of impeller above bottom
h_D	height of draught tube
h_v	height of screw impeller
k_2	constant in Eq. (*9*)
n	frequency of revolution of impeller
s	screw lead

t	time, time of mixing (t_A — dead time, see Fig. 2)
v	velocity of the flow
μ	dynamic viscosity
ϱ	density
τ_H	time of homogenization (for $c^* = 0{\cdot}05$)
E_H^*	energy criterion, Eq. (*12*)
Ho	criterion of homochronousness
Ho′	corrected value of Ho, Eq. (*11*)
$Po = P\varrho^{-1}n^{-3}d^{-5}$	power input criterion
$Re = nd^2\varrho\mu^{-1}$	Reynolds criterion
*	dimensionless value
—	mean value

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