STUDY OF SPATIAL DISTRIBUTION OF KINETIC ENERGY OF TURBULENCE IN A CYLINDRICAL SYSTEM WITH TURBINE IMPELLERS AND RADIAL BAFFLES*

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The paper deals with the description and results of experimental investigation of spatial distribution of kinetic energy of turbulence in a cylindrical system with one or two standard turbine impellers on the same shaft and with radial baffles at the vessel wall. The time-averaged specific kinetic energy of turbulence of agitated liquid is measured with a stirring-intensity-meter (SIM) consisting of mechanical-piezoelectric sensor and an auxiliary electronic device for processing the scanned fluctuation signal (the SIM calibration was carried out by means of a laser-doppler anemometer). The measurements were performed in a model vessel of diameter $D = 350$ mm, in the range of values of Reynolds number for mixing $Re_M \in \langle 1{\cdot}2 \,.\, 10^3, 1{\cdot}06 \,.\, 10^5 \rangle$ and relative size of impeller and vessel $d/D = 0{\cdot}286$ in the single-phase and two-phase system (air was blown into the system through a sparger ring under the lower impeller). It follows from the measured and processed results that the spatial distribution of mean specific kinetic energy of turbulence in systems with turbine impellers is considerably influenced by the amount of blown air: the mean specific kinetic energy of turbulence decreases with growing volumetric flow rate of air in the stream streaking from blades of rotating impeller, and, in the region outside this stream, it significantly increases.

Kinetic energy of turbulence is a quantity which influences in a significant way the rate of mass, heat and momentum transfer in equipment of chemical and food industry when flowing liquids and dispersed systems with prevailing liquid phase. Study of this quantity therefore contributes to the knowledge of mechanism of the transfer phenomena in turbulent flows and can be further applied to the design and intensification of chemical-engineering and bioengineering processes. The published works on kinetic energy of turbulence in agitating with the standard[1]

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(Rushton) types of turbine impellers can be divided into the following two main groups:

1) The experimental investigations of this quantity which were carried out by means of the photographic method of traces along with the pressure sensors[2-5], by heated sensor of thermoanemometer (CTA)[6-8] or by the laser-doppler anemometer (LDA)[9-12]. All those measurements were carried out in single-phase systems with radial baffles at the wall of cylindrical vessel in the region of Reynolds number $Re_M > 1{\cdot}0 \,.\, 10^4$. In the two-phase liquid–gas system, the experiments with hot film element of thermoanemometer were carried out by Lu and Ju[13].

2) Theoretical (and as a rule simultaneously also experimental) determination of this quantity was carried out on the basis of a so-called model of specific kinetic energy of turbulence – volumetric rate of dissipation of mechanical energy developed by Launder and Spalding[14]. By using the numerical solution of the set of Reynolds equations of flow expressed in terms of the above-mentioned hydrodynamic quantities, the spatial distribution of specific energy of turbulence in the investigated agitated system was obtained, the results of experimental investigation being used partly as the boundary conditions of solution, partly for the verification of results of calculation models[15-21].

It follows from the results of the works cited that the distribution of specific kinetic energy of turbulence in cylindrical systems with standard turbine impellers and radial baffles at walls is inhomogeneous, and the maximum values are reached in the region of stream streaking from the blades of rotating impeller. The knowledge of this distribution contributes then to the finding of the spatial distribution of volumetric rate of dissipation of mechanical energy in the system, i.e., the quantity which characterizes the rate of mass and heat transfer in the bulk phase of agitated homogeous and heterogeneous charge[22,23].

THEORETICAL

Let us consider the time-averaged (mean) specific kinetic energy of liquid flow containing N phases:

$$\bar{e} = \tfrac{1}{2} \sum_{i=1}^{N} \overline{\varphi_i \varrho_i \mathbf{w}_i^2}\,, \tag{1}$$

where φ_i and ϱ_i are the volume fraction and density of *i*-th phase, respectively. For the turbulent quasistationary flow we consider the validity of the following relations

$$\mathbf{w}_i = \overline{\mathbf{w}}_i + \mathbf{w}_i'\,, \tag{2a}$$

$$\varphi_i = \bar{\varphi}_i + \varphi_i'\,, \tag{2b}$$

$$\varrho_i \approx \bar{\varrho}_i\,. \tag{2c}$$

Then, on the assumption that the fluctuation of concentrations (φ_i') and velocities (w_i') are completely correlatable, the mean specific kinetic energy of turbulence $\bar{e}'$ in the considered N-phase flow can be expressed by the relation

$$\bar{e}' = \tfrac{1}{2}\sum_{i=1}^{N} \varrho_i(\overline{\bar{\varphi}_i + \varphi_i'})\,\mathbf{w}_i'^2\,. \tag{3}$$

In case of a single-phase system ($\varphi_l = 1$), Eq. (3) can be expressed in the form

$$\bar{e}' = \tfrac{1}{2}\varrho_l\overline{\mathbf{w}_l'^2} \tag{4}$$

and for a two-phse system liquid (subscript l)–gas (subscript g) we have

$$\bar{e}' = \tfrac{1}{2}[\varrho_g(\overline{\bar{\varphi}_g + \varphi_g'})\,\overline{\mathbf{w}_g'^2} + \varrho_l(\overline{\bar{\varphi}_l + \varphi_l'})\,\overline{\mathbf{w}_l'^2}]\,. \tag{5}$$

The validity of the following simplifications is considered as well:

$$\overline{\varphi_g'} = \overline{\varphi_l'} \approx 0\,, \quad [\text{quasistationary flow}]\,, \tag{6a}$$

$$\varrho_l/\varrho_g \approx 10^3\,, \tag{6b}$$

$$\overline{\varphi}_g \leqq 0{\cdot}1\,. \tag{6c}$$

Then it is possible to neglect the first term on the right-hand side of Eq. (5) with respect to the magnitude of the second term on the same side of Eq. (5), and with regard to the validity of relation (6a) as well, it is possible to express Eq. (5) in the simplified form

$$\bar{e}' = \tfrac{1}{2}\varrho_l\overline{\varphi}_l\overline{\mathbf{w}_l'^2}\,. \tag{7}$$

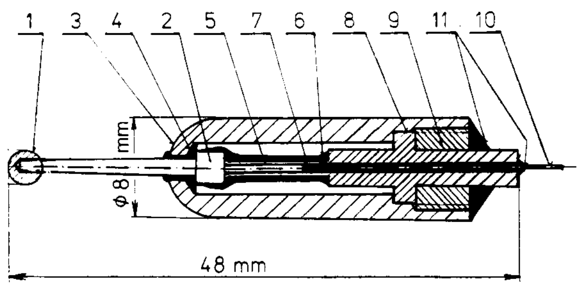

FIG. 1

Sketch of mechanical-piezoelectric sensor: 1 sphere, 2 needle, 3 tube, 4 silicon rubber seal, 5 piezoelement, 6 silicon rubber jacket for piezoelement protection, 7 glue for electrical contact, 8 holder, 9 screw, 10 wire, 11 epoxy glue

The stirring-intensity-meter (SIM)[24] consists of a mechanical-piezoelectric sensor (see Fig. 1) and of an auxiliary electronic device for processing the charge signal sensed from piezocrystal into which a small beam of spherical element is fixed on which acts force of flowing liquid. The charge signal of the sensor is converted to the voltage signal and further adapted to the form of time-averaged value of fluctuation component of the quantity measured (the mean value of the sensed signal $\bar{u}_{SIM}$ is simultaneously electronically filtered off):

$$\bar{e}'_{SIM} \approx \frac{1}{T}\int_0^T |u'_{SIM}|(t)\,dt\,. \tag{8}$$

The scanned mean value $\bar{e}'_{SIM}$ is directly proportional to the quantity $\bar{e}'$:

$$\bar{e}' = k\bar{e}'_{SIM}\,, \tag{9}$$

assuming that the coefficient of proportionality k in Eq. (*9*) depends neither on the direction of flow around the spherical element (sensor) of SIM, nor on the value of turbulence intensity in the place of its position. Its value can be determined on the one hand from the knowledge of constant drag coefficient in turbulent flow around the spherical element itself with medium[25] in which it is placed, on the other hand from the knowledge of parameters of adjusting the elements of electronic circuits when processing the signal measured. The actual value for the developed equipment and sensor itself is therefore necessary to be determined by calibrating by another independent and absolute method of determining the mean specific kinetic energy of turbulence.

EXPERIMENTAL

The experiments were carried out in a model system (for its sketch, dimensions and media used see Fig. 2) with two standard (Rushton) turbine impellers on the same shaft. As the independent variables were chosen: frequency of revolutions of impellers n, kinematic viscosity of agitated charge η_l/ϱ_l, flow rate of air blown into the charge $\dot{V}_g$ and the position of the SIM sensor for measuring the mean specific kinetic energy of turbulence (coordinates r and z). The accuracy of adjusting all the independent variables was approximately one order higher than the accuracy of determination of the dependent variable — the mean specific kinetic energy of turbulence.

Quantity e'_{SIM} (see Eqs (*8*) and (*9*)) was measured[26] with the mechanical-piezoelectric sensor (see Fig. 1). The piezoelectric crystal situated in the sensor body was accoustically isolated from the noises which may enter into the body from the surroundings and was also grounded through the steel beam of the spherical element (∅ 4·5 mm). A commutator inserted into the device made it possible to connect several sensors to the evaluating electronic block. The value of the integration time of measured signal, T (see Eq. (*8*)) was found to be $T = 120$ s for the conditions in this work. The own frequency of the mechanical-pizoelectric sensor used amounted to 360 Hz. Then it is possible to consider the found values of $\bar{e}'_{SIM}$ and/or $\bar{e}'$ quasistationary.

The size of parameter k in Eq. (9) was found by comparing the values of quantity $\bar{e}'_{SIM}$ and the values of quantity $\bar{e}'$ determined in terms of Eq. (4) (ref.[26]). The mean value of square of fluctuation local velocity $\overline{\mathbf{w}_1'^2}$ was calculated from its components:

$$\overline{\mathbf{w}_1'^2} = \overline{w_{1,ax}'^2} + \overline{w_{1,rad}'^2} + \overline{w_{1,tg}'^2} \tag{10}$$

measured by the laser-doppler anemometer (LDA) with backscatter mode[26]. A constant value of parameter k – independent either of the direction of flow around the spherical element of probe (see Fig. 1) or of the level of local value of mean specific kinetic energy of turbulence $\bar{e}'$ – followed for the developed equipment (SIM) from the comparison of quantities $\bar{e}'$ and $\bar{e}'_{SIM}$ in 200 positions of the model agitated system with inclined blade impeller and radial baffles at the vessel wall. The above-mentioned effects caused that the magnitude of constant k found in this way varied within the limits $\pm 20\%$ about its mean value (arithmetic mean) calculated from all 200 measured values.

In Fig. 3 we plotted the dependences of dimensionless mean specific kinetic energy of turbulence

$$E = \bar{e}'/[\varrho_1(\pi d n)^2] \tag{11}$$

and the dimensionless radial coordinate $2r/d$ in the stream streaking from blades of rotating turbine impeller so as they follows partly from the literature sources, partly from the measurement by the SIM method in the system mentioned. It is evident from the figure that the data from the literature obtained by the LDA or CTA methods agree with the data measured by the SIM method and corrected by means of parameter k following from the calibration of the probe used as described above. With respect to the fact that the value of parameter k in Eq. (9) was found to be identical when comparing the results of direct methods (LDA and CTA) and the SIM method in two quite independent systems, it is possible to consider its found value with

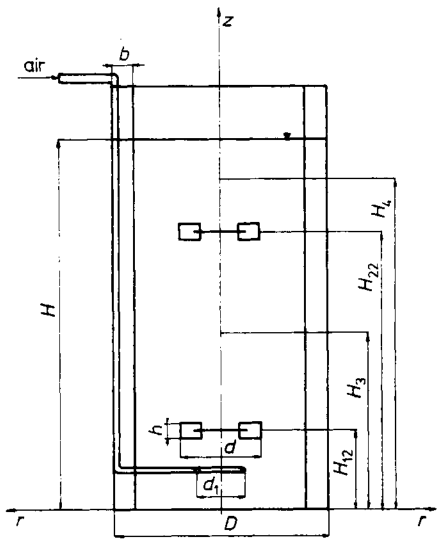

FIG. 2

The agitated system with two standard turbine impellers on the same shaft; $D = 350$ mm, $d = 100$ mm, $d_1 = 66$ mm, $b = 0{\cdot}1D$, 4 radial baffles, $H = 500$ mm, $H_{12} = 90$ mm, $H_{22} = 287$ mm, $H_3 = 187$ mm, $H_4 = 412$ mm, $h = 20$ mm, charge: *a* water ($\varrho_1 \approx 1\,000$ kg m^{-3}, $\eta_1 = 1$ mPa s), *b* aqueous glycerol solution ($\varrho_1 \approx 1\,150$ kg m^{-3}, $\eta_1 = 32$ mPa s), blown-in gas: air at 20°C the above-mentioned accuracy of its determination to be proved. Results of all the SIM measurements were corrected by this value in further calculations.

RESULTS AND DISCUSSION

The examples of results of performed experiments are illustrated in Figs 4 – 10 for the investigated model system with two standard turbine impellers (see Fig. 2). The radial profiles of quantity E (see Eq. (*11*)) at different values of dimensionless Reynolds number Re_M and flow-rate number Kp_g of gas:

$$Re_M = nd^2 \varrho_l / \eta_l \,, \qquad (12a)$$

$$Kp_g = \dot{V}_g / nd^3 \,, \qquad (12b)$$

are plotted here for the investigated radial rays (levels of axial coordinate $z = H_{12}$, H_{22}, H_3, and H_4). For the given radial courses of quantity E, such axial coordinates were chosen that the characteristic courses of function $E = f(2r/d)$ should be indicated. The choice of dimensionless quantity E (see Eq. (*11*)) follows from the fact that the velocity field in the agitated geometrically similar systems can be scaled up by the peripheral velocity of impeller blade tips, πdn (refs[2,5,10,12,16]), and therefore the identical profiles of the corresponding hydrodynamic quantities normalized by the corresponding power of the quantity mentioned mutually coincide in one curve for different frequencies of impeller revolution or even the system size. These facts are illustrated by profiles $E = f(2r/d)$ in Fig. 3 and, after all, in Fig. 4, too, which otherwise strengthens the adequacy of ideas of interpretation of the measured quantity – mean specific kinetic energy of turbulence.

The form of dependence of dimensionless mean specific kinetic energy of turbulence E on dimensionless radial coordinate $2r/d$ in cross sections H_{22} and H_{12} (streams of single or two-phase liquid–gas mixture leaving the blades of the upper or lower turbine impeller) corresponds to the measured, e.g. refs[5,11,12], or calculated, e.g. refs[19,20], radial profiles of quantity E (see Fig. 4); as far as the value of $Re_M > 1{\cdot}0 \,.\, 10^4$, the effect of Reynolds number does not manifests itself in the turbulent regime of flow of agitated charge. However, the effect of volumetric flow rate of blown air $\dot{V}_g$ manifests itself significantly. It is characterized by the value of flow rate number of gas Kp_g: With increasing quantity Kp_g decreases quantity E for the given value of coordinate $2r/d$. Radial profiles $E = f(2r/d)$ were correlated in heights (stream jets) H_{22} and H_{12} by the relation

$$E = C/R \,, \quad [H_{i2} = \text{const.}, Re_M \approx \text{const.}] \,, \qquad (13)$$

the power dependence being considered for parameter C in the form

$$C = C_0 + AKp_g^a \,, \quad [H_{i2} = \text{const.}] \,. \qquad (14)$$

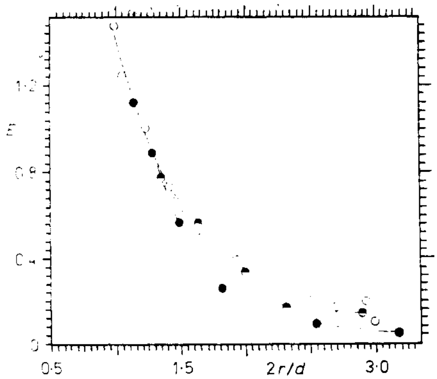

FIG. 3

The dependence of dimensionless mean specific kinetic energy of turbulence E on dimensionless radial coordinate $2r/d$; $z = H_{12}$, $d/D \in \langle 1/4, 1/3 \rangle$, standard (Rushton) turbine impeller, $H_2/D \in \langle 1/3, 1/2 \rangle$, $H/D = 1$, 4 radial baffles, $b/D = 0{\cdot}1$, $Re_M > < 1{\cdot}0 \cdot 10^4$, ○ ref.[11], ◒ ref.[6], ● this measurement in terms of SIM

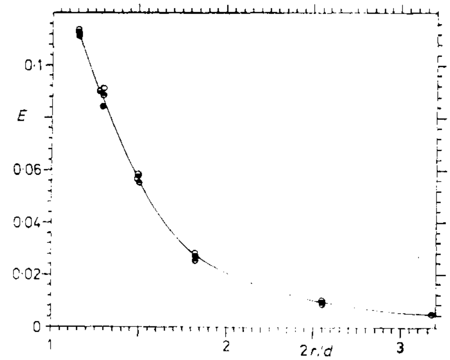

FIG. 4

The dependence of dimensionless mean specific kinetic energy of turbulence E on dimensionless radial coordinate $2r/d$; measured in terms of SIM, charge: water, $z = H_{22}$, $Kp_g = 0$; ○ $Re_M = 3{\cdot}33 \cdot 10^4$, ◒ $Re_M = 5{\cdot}33 \cdot 10^4$, ◓ $Re_M = 8{\cdot}0 \cdot 10^4$, ● $Re_M = 10{\cdot}63 \cdot 10^4$

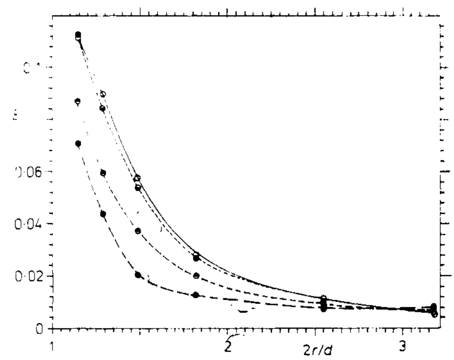

FIG. 5

The dependence of dimensionless mean specific kinetic energy of tubulence E on dimensionless radial coordinate $2r/d$; measured in terms of SIM, $z = H_{22}$, charge: water, $Re_M = 5{\cdot}33 \cdot 10^4$; ○ $Kp_g = 0$, ◒ $Kp_g = 0{\cdot}013$, ◓ $Kp_g = 0{\cdot}031$, ● $Kp_g = 0{\cdot}094$

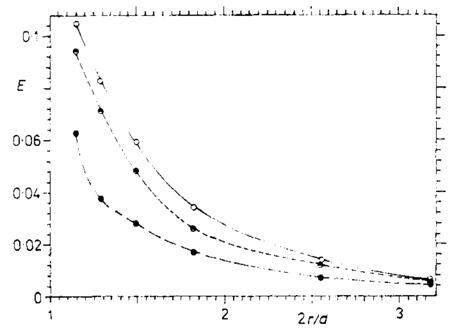

FIG. 6

The dependence of dimensionless mean specific kinetic energy of turbulence E on dimensionless radial coordinate $2r/d$; measured in terms of SIM, $z = H_{12}$, charge: water, $Re_M = 8{\cdot}0 \cdot 10^4$; ○ $Kp_g = 0$, ◓ $Kp_g = 0{\cdot}021$, ● $Kp_g = 0{\cdot}063$

Radial coordinate R in Eq. (*13*) was considered in the form

$$R = (2r/d) - 1 . \qquad (15)$$

The results of statistic treatment[27] of measured dependences $E = f(R)$ always for two ranges of values Re_M are given in Table I. Those cases were excluded from the

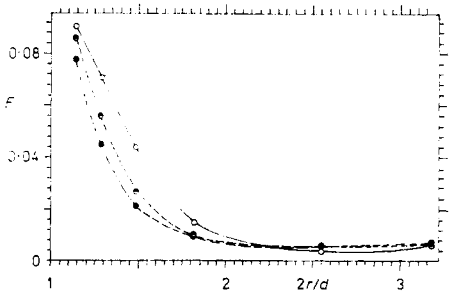

FIG. 7

The dependence of dimensionless mean specific kinetic energy of turbulence E on dimensionless radial coordinate $2r/d$; measured in terms of SIM, $z = H_{22}$, charge: aqueous glycerol solution, $Re_M = 3{\cdot}89 \, . \, 10^3$; ○ $Kp_g = 0$, ◓ $Kp_g = 0{\cdot}015$, ● $Kp_g = 0{\cdot}046$

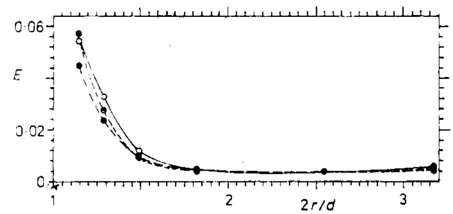

FIG. 8

The dependence of dimensionless mean specific kinetic energy of turbulence E on dimensionless radial coordinate $2r/d$; measured in terms of SIM, $z = H_{12}$, charge: aqueous glycerol solution, $Re_M = 3{\cdot}89 \, . \, 10^3$; ○ $Kp_g = 0$, ◓ $Kp_g = 0{\cdot}015$, ● $Kp_g = 0{\cdot}046$

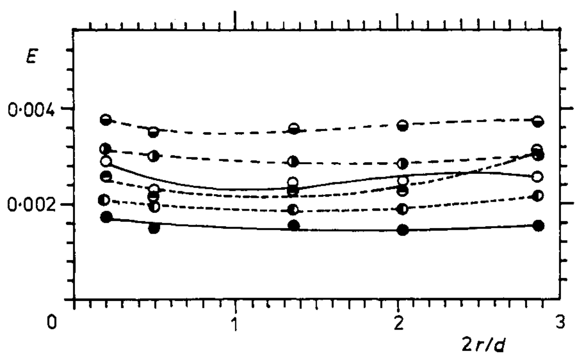

FIG. 9

The dependence of dimensionless mean specific kinetic energy of turbulence E on dimensionless radial coordinate $2r/d$; measured in terms of SIM, $z = H_4$, charge: water or aqueous glycerol solution; $Re_M = 8{\cdot}0 \, . \, 10^4$: ○ $Kp_g = 0$, ◓ $Kp_g = 0{\cdot}021$, ◒ $Kp_g = 0{\cdot}063$; $Re_M = 2{\cdot}88 \, . \, 10^3$: ● $Kp_g = 0$, ◐ $Kp_g = 0{\cdot}021$, ◑ $Kp_g = 0{\cdot}C63$

treated sets when the upper or lower impeller was flooded[28] by the blown-in gas, i.e., the cases $Kp_g = 0{\cdot}15$ for H_{12} and H_{22}. Further, the values of quantity E for coordinate $2r/d > 3{\cdot}0$ were not included into the calculation of parameter C in Eq. (*13*), for here the effect of wall on the properties of investigated stream has manifested itself[5,10].

It follows from the measured results that the effect of both considered criteria Re_M and Kp_g on the course of dependence $E = f(2r/d)$ and/or $E = f(R)$ is significant. The effect of Reynolds number (the ratio of inertial and viscous forces) manifests

TABLE I

Parameters of power dependence $C = C_0 - AKp_g^a$

Range of Kp_g	Range of $Re_M \cdot 10^{-3}$	A	a	C_0	R
		$z = H_{22}$			
0·0062–0·15	33·3 – 106·3	0·033	0·71	0·0191	0·992
0·015 – 0·15	1·20 – 3·89	0·048	0·74	0·0161	0·986
		$z = H_{12}$			
0·015–0·15	33·3 – 106·3	0·088	0·78	0·0126	0·915
0·015–0·15	1·20 – 3·89	0·056	0·55	0·0082	0·936

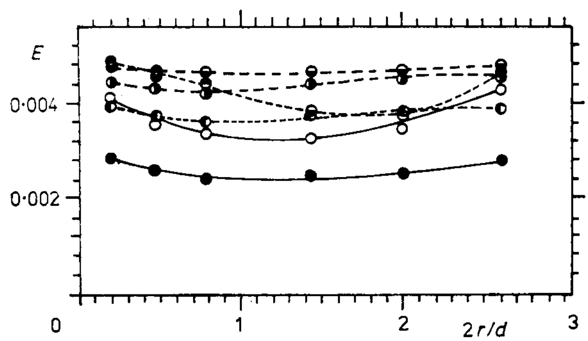

FIG. 10

The dependence of dimensionless mean specific kinetic energy of turbulence E on dimensionless radial coordinate $2r/d$; measured in terms of SIM, $z = H_3$, charge: water or aqueous glycerol solution; $Re_M = 8{\cdot}0 \cdot 10^4$: ○ $Kp_g = 0$, ◓ $Kp_g = 0{\cdot}021$, ◒ $Kp_g = 0{\cdot}063$; $Re_M = 2{\cdot}88 \cdot 10^3$: ● $Kp_g = 0$, ◐ $Kp_g = 0{\cdot}021$, ◑ $Kp_g = 0{\cdot}063$

itself significantly with increasing kinematic viscosity of charge, η_l/ϱ_l: The values of specific kinetic energy of turbulence decrease as much as decreases the total level of turbulence intensity with downward tendency of values of quantity Re_M below ten thousand[29]. Likewise the effect of quantity Kp_g manifests itself negative: The presence of gas in stream jet decreases the kinetic energy of turbulence in the investigated flow for it considerably changes the conditions in the source of this flow – region of rotating turbine impeller[13]. With this the mean value of local hold-up (volume fraction of gas) $\bar{\varphi}_g$ in this region does not reach on the average more than 10 vol. % (refs[13,30]) so that the decrease of quantity $\bar{e}'$ (or E) in this region is given above all by the decrease in values of quantity $\overline{w_1'^2}$ (see Eq. (7)); volume fraction of liquid $\bar{\varphi}_l$ in this flow therefore does not decreases below the value of $\bar{\varphi}_l \approx 0.9$.

The effect of volumetric flow rate of gas $\dot{V}_g$ on the magnitude of quantity E in the measured radial profiles between impellers (height H_3) and above the upper impeller (height H_4) is favourable. With increasing quantity Kp_g increases also quantity E since the present bubbles of gas increase the turbulence intensity in the given region (quantity $\overline{w_1'^2}$), the local value of gas hold-up (quantity $\bar{\varphi}_g$) reaching only units of percent[30]. The effect of kinematic viscosity of charge, η_l/ϱ_l on the mutual position of radial profiles $E = E(2r/d)$ in the cross sections discussed, however, is identical so as it is in planes of axial coordinates $z = H_{12}$ and $z = H_{22}$: Owing to the increasing viscosity of liquid phase in charge, a significant decay of turbulence and thus even about double decrease of quantity E manifests itself on changing the values of quantity Re_M by one order of magnitude (from region of tens to units of thousands).

CONCLUSIONS

The proposed method of measuring the mean specific kinetic energy of turbulence in terms of the SIM technique makes it possible to determine this quantity in transparent and opaque (e.g., fermented media) mechanically agitated systems liquid–gas unless the mean local gas hold-up $\bar{\varphi}_g$ exceeds 10 vol. %. The spatial distribution of mean specific kinetic energy of turbulence is then, under the turbulent regime of flow of agitated charge, significantly influenced both by the kinematic viscosity of liquid phase and by the magnitude of volumetric flow rate of gas put into the charge.

SYMBOLS

A	constant in Eq. (*14*)
a	exponent in Eq. (*14*)
b	width of radial baffle, m
C	constant in Eq. (*13*)
C_0	constant in Eq. (*14*)

D	inside diameter of cylindrical vessel, m
d	impeller diameter, m
d_1	outside diameter of air distributor, m
E	dimensionless mean specific kinetic energy of turbulence
e	specific kinetic eergy of turbulence, kg m^{-1} s^{-2}
H	liquid height in vessel at rest, m
H_{12}	height of disc of lower turbine impeller above bottom, m
H_{22}	height of disc of upper turbine impeller above bottom, m
H_3	height of checking cross section between impellers above bottom, m
H_4	heigt of checking cross section between upper impeller and liquid level above bottom, m
h	height of impeller blade, m
k	constant in Eq. (*9*), kg m^{-1} s^{-2} V^{-1}
n	impeller frequency of revolutions, s^{-1}
N	number of elements in set
Kp_g	flow rate number of gas
R	dimensionless radial corrdinate defined by Eq. (*15*)
R	correlation coefficient (Table I)
r	radial coordinate, m
Re_M	Reynolds number for mixing
T	time interval of integration, s
t	time, s
$\dot{V}_g$	volumetric flow rate of gas (air), m^3 s^{-1}
u	scanned voltage signal of piezoelectric sensor, V
w	local flow velocity, m s^{-1}
z	axial coordinate, m
η	dynamic viscosity, Pa s
φ	volume fraction
ϱ	density, kg m^{-3}

Subscripts and Superscripts

ax	axial
g	gas phase
i	summation index
l	liquid phase
rad	radial
SIM	measured by stirring-intensity-meter
tg	tangential
′	fluctuation quantity
‾	time-averaged quantity

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Translated by J. Linek.

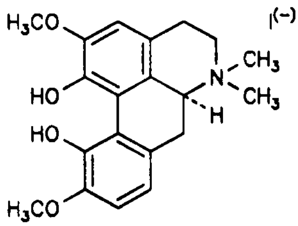
Quaternary Alkaloids from *Thalictrum minus* subsp. *elatum* (JACQ.) STOY. et STEFANOV
Jiří Slavík and Leonora Slavíková
Collect. Czech. Chem. Commun. *57*, 573 (1992)

p. 573, in Papername:
For STOY. read STOJ.

p. 574, in formula *Ie*:
For $R^4 = CH_3$ read $R^4 = CH_2$

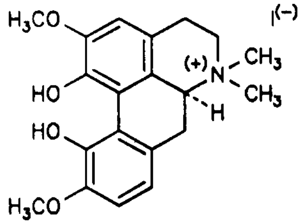
p. 574, in formula *II*:

For



II

read



II

Study of Spatial Distribution of Kinetic Energy of Turbulence in a Cylindrical System with Turbine Impeller and Baffles
Ivan Fořt, Petr Ettler, František Kolín, Juris Vanags and Maris A. Rikmanis
Collect. Czech. Chem. Commun. *57*, 1053 (1992)

p. 1057, Eq. (*11*):
For $E = \bar{e}/[\rho_1 (\pi d n)^2]$ read $E = 2\bar{e}/[\rho_1 (\pi d n)^2]$