PHENOMENON OF TURBULENT MACRO-INSTABILITIES IN AGITATED SYSTEMS

Oldrich BRUHA[a], Ivan FORT[b] and Pavel SMOLKA[a]

[a] *Department of Physics,*
Faculty of Mechanical Engineering, Czech Technical University,
166 07 Prague 6, The Czech Republic
[b] *Department of Chemical and Food Process Equipment Design,*
Faculty of Mechanical Engineering, Czech Technical University,
166 07 Prague 6, The Czech Republic

Received January 17, 1994
Accepted October 20, 1994

Turbulent macro-instabilities in the process of mixing in cylindrical baffled vessel provided with pitched blade impeller were studied. Rules of macro-instability occurrence were investigated in their dependence on physical parameters of three Newtonian liquids mixed and on the regime of mixing. The observations were realized partly visually, partly by means of a specially designed mechanical measuring device connected with an electronic recorder indicating the manifestations of instability in the liquid.

The occurrence of macro-instabilities, i.e. the existence of eddy fields whose space and especially time scales considerably exceed those of current turbulent eddies, represents a well-known reality in mixing systems. This problem has, however, not apparently been treated more deeply as yet. Only recently several papers have appeared describing the principal characteristics of the macro-instability occurrence[1–3].

During the visual observation of the liquid level we may observe only the final phase of this phenomenon usually manifested by an occasional swell of the surface in the area upstream near the baffles in the vessel. The occurrence interval of this type of instability ranges from several up to tens of seconds. As this phenomenon may bring about rather substantial dynamic effects on the parts of industrial agitating equipment and may also influence the entire mixing process, its study is of considerable importance both from the point of view of the equipment design and from that of the mixing process itself. This phenomenon can, on one hand, promote macro-mixing in an agitated charge but, on the other hand, it may cause some mechanical damages via interactions of the large vortices with the baffles, vessel wall and impeller shaft.

Preceding investigations of macro-instabilities (see refs [3,4]) explained their occurrence as a consequence of the appearance of "double-loop" flow in the agitated system besides the classical "single-loop" one (Fig. 1). This knowledge was obtained during mixing water in a cylindrical vessel with four baffles and with two kinds of impellers, both rotating to pump liquid towards the bottom: pitched impeller with four blades[3] and propeller[4]. According to the hitherto known results and to the experiments carried out with a six blade pitched impeller and presented in[5], the frequency of turbulent macro-instability depends approximately linearly on the impeller speed.

The aim of this work was the investigation of regularities of the turbulent macro-instability occurrence in a mixed liquid as a function of impeller speed, liquid viscosity and impeller off-bottom clearance. A pitched impeller with six blades was used in our experiment as this impeller is standardized in the Czech Republic. As the characteristics of the turbulent macro-instability, the shift-over between the single-loop and double loop flow patterns was considered.

EXPERIMENTAL

Arrangement of the Experiments

The experiments were carried out in a cylindrical vessel of diameter $D = 0.3$ m filled with liquid to the height $H = D$ and with four radial baffles at the vessel wall of the relative width $b = 0.1D = 0.03$ m (see Fig. 2). The pitch blade impeller with 6 inclined blades ($\alpha = 45°$) of the relative diameter $d = 0.33D = 0.1$ m rotated to pump the liquid towards the vessel bottom (see Fig. 3) . The impeller off-bottom clearance could be set at three positions, $H_2 = 0.2D$, $0.35D$, and $0.5D$. The liquid temperature was kept always at 23 ± 1 °C, according to the fluctuations of the room temperature. Three different liquids were used for the measurements: water and two aqueous saccharose solutions of mass concentrations 27% and 46%. The physical properties of liquids used are given in Table I. The range of all the applied Reynolds mixing numbers, defined as

$$Re_M = \frac{Nd^2\rho}{\mu} , \qquad (1)$$

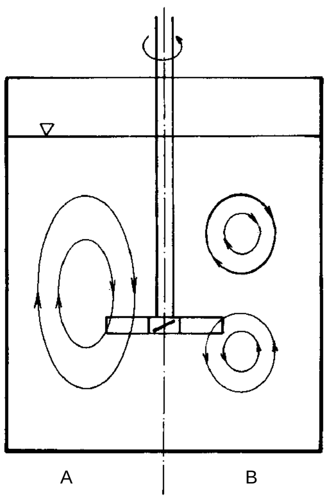

FIG. 1
Flow patterns in a turbulent mixing system. A single-loop regime, B double-loop regime

is presented in Table II. From the given values of Reynolds mixing numbers it is evident that all the measurements took place in the turbulent or at the very beginning of the transition region.

To indicate the shift-over from the single-loop regime into the double-loop flow pattern, an original device named "tornado-meter" was developed. This device (see Fig. 2) consists of a circular

TABLE I
Physical properties of liquids used for measurements (23 °C)

Parameter	Water	Solution 27% saccharose	Solution 46% saccharose
μ, mPa s	0.94	2.2	9.5
ρ, kg m^{-3}	1 000	1 100	1 200

TABLE II
Range of Reynolds mixing numbers

Parameter	Water	Solution 27% saccharose	Solution 46% saccharose
N, s^{-1}	3.33 – 6.67	3.33 – 6.67	3.33 – 6.67
$Re_M . 10^{-4}$	3.3 – 6.7	1.7 – 3.4	0.42 – 0.84

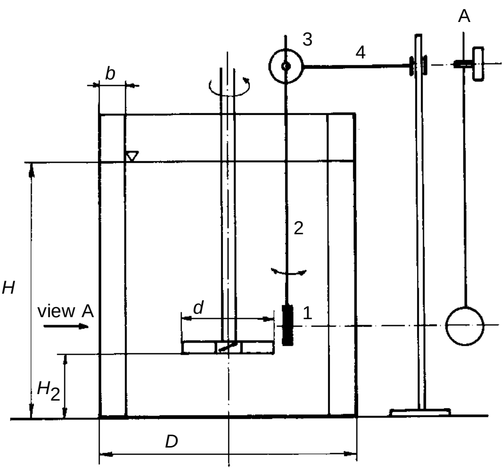

FIG. 2
Experimental arrangement. Parts of tornado-meter: 1 target, 2 swinging arm, 3 electric-resistance sensor, 4 fixed arm (for meaning of letters see Symbols)

target attached to a swinging arm of adjustable depths of immersion between 50 and 200 mm. The axis of the swinging arm rotation is connected with the axis of a swinging electric resistance sensor. A line voltage recorder records – by means of a simple electrical circuit – the movement of the target. The arm of the tornado-meter swings in a vertical plane going through the axis of the impeller shaft. The immersion of the arm is selected in such a way that, under conditions of the single-loop flow pattern, the target lies in the region inside this loop. Here the radial component of the the mean flow is negligible and the tornado-meter records only the radial component of turbulence. During the shift-over of the single loop to the double loop flow pattern, an additional radial flow component appears in the region where the target is located. Although the flow is rather unstable, it is significant enough to cause a conspicuous deflection of the arm if the right position of the target was chosen. This position was established experimentally as the location where the transition between the two flow patterns manifests itself by the most expressive dynamic effects. Besides a lot of experiments with the tornado-meter, a visualization method was used to find the best position for the target, too. According to these experiments it was found that the suitable tornado-meter off-bottom clearance was $Z_t = H_2 + 0.05$ and the radial position $r_t = 0.25D = 0.075$ m (see Fig. 2).

Method of Measurement

For the given geometrical and kinematic conditions of the agitated system, the tornado-meter recording time was always 20 min. This interval was considered to be sufficiently long with respect to the range of values of frequency of macro-instability occurrence f_N. An illustration of a part of the record is shown in Fig. 4. From the record obtained and from the observation made by means of a "light knife" visualization method (a plane slot shaped light beam penetrating through agitated liquid, containing small particles-tracers), it was found out that the so-called shift-over of the single-loop flow pattern to the double-loop one, accompanied by the turbulent macro-instability, manifested itself clearly as an apparent narrow peak in the record.

The procedure of estimating the frequency of the turbulent macro-instability occurrence was as follows: The twenty-minute record was divided into sections, one minute each (see Fig. 4), and, in each section, the number of the above-mentioned peaks (macro-impulses), in the record, n_p, corresponding to the turbulent macro-instability was estimated. From the frequencies of the macro-insta-

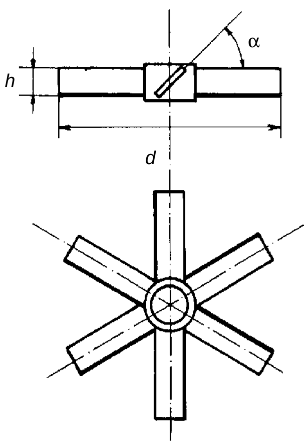

FIG. 3
Impeller characteristics (for meaning of letters see Symbols)

bilities $f_N = n_p/60$ estimated for all the twenty one-minute intervals, an arithmetic mean value $\overline{f_N}$ was then calculated.

This value was taken as the decisive characteristics of the frequency of the macro-instability occurrence at the conditions of the agitated system investigated. The above presented procedure was carried out for each of the above mentioned test liquids at three impeller off-bottom clearances $H_2 = 0.2D$, $0.35D$, $0.5D$ and for five impeller speeds $N = 3.33$, 4.17, 5.00, 5.83, 6.67 s^{-1} (corresponding to 200, 250, 300, 350, and 400 rpm). The experimental technique used did not enable us to distinguish between turbulent eddies and macro-instabilities at impeller speeds higher than 6.67 s^{-1} for all the three liquids tested because of high level of turbulence. The results obtained are summarized in Table III.

RESULTS AND DISCUSSION

Evaluation of Results

Dependences of mean frequency of the macro-instability occurrence on the impeller speed determined always by five points were obtained at three different impeller positions for each liquid measured. These primary dependences have nearly linear character and they can be approximated by straight lines. The analysis of the primary results of the measurements showed that the effect of the impeller off-bottom clearance H_2 manifested itself only in the slope of these straight lines. To obtain a single expression for all the three impeller off-bottom clearances, one of the positions, namely $H_2 = 0.35D$, was taken as the reference position and the so-called impeller off-bottom clearance factors $r_{0.2D}$ and $r_{0.5D}$ were assigned to the remaining two positions ($H_2 = 0.2D$ and $H_2 = 0.5D$). The values of the factors mentioned were determined from relations

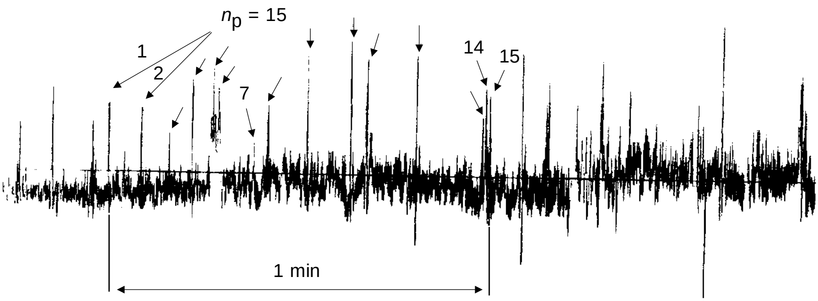

FIG. 4
Example of a part of the output voltage record for water, 23 °C, $H_2/D = 0.2$, $N = 5.0$ s^{-1}. Values of n_p obtained from the whole 20 min record: 15, 17, 13, 16, 15, 16, 15, 17, 17, 14, 14, 15, 16, 14, 15, 13, 12, 17, 16, 16. Corresponding $\overline{f_N} = 0.253$, $\sigma_r = 9.6\%$

$$r_{0.2D} = \frac{1}{5}\sum_{1}^{5} \frac{\overline{f_{N_i}}(0.2D)}{\overline{f_{N_i}}(0.35D)} \ , \quad r_{0.5D} = \frac{1}{5}\sum_{1}^{5} \frac{\overline{f_{N_i}}(0.5D)}{\overline{f_{N_i}}(0.35D)} \ , \qquad (2)$$

where $\overline{f_{N_i}}$ stands for the mean turbulent macro-instability occurrence frequency measured at the impeller speed N_i = 3.33, 4.17, 5.00, 5.83, 6.67 s^{-1}, arguments 0.2D and 0.5D stands for the impeller off-bottom clearance H_2/D = 0.2 and H_2/D = 0.5 and $\overline{f_{N_i}}$(0.35D is the mean macro-instability frequency measured at the reference off-bottom clearance H_2 = 0.35D for the N_i under consideration.

For the different liquids used, the off-bottom clearance factors take the values:

for water:

$$r_{0.2D} = 1.215, \qquad r_{0.5D} = 0.808, \qquad (3)$$

for 27% aqueous saccharose solution:

$$r_{0.2D} = 1.224, \qquad r_{0.5D} = 0.911, \qquad (4)$$

TABLE III

Mean macro-vortex frequencies $\overline{f_N}$, in s^{-1}

N, s^{-1}	H_2/D	Water	Solution 27% saccharose	Solution 46% saccharose
3.33	0.20	0.148	0.155	0.109
	0.35	0.122	0.113	0.102
	0.50	0.092	0.112	0.101
4.17	0.20	0.207	0.213	0.161
	0.35	0.172	0.180	0.158
	0.50	0.139	0.147	0.155
5.00	0.20	0.262	0.253	0.212
	0.35	0.220	0.211	0.192
	0.50	0.182	0.200	0.192
5.83	0.20	0.312	0.266	0.250
	0.35	0.249	0.219	0.237
	0.50	0.211	0.204	0.217
6.67	0.20	0.349	0.322	0.279
	0.35	0.287	0.280	0.267
	0.50	0.230	0.244	0.240

for 46% aqueous saccharose solution:

$$r_{0.2D} = 1.065, \qquad r_{0.5D} = 0.959. \tag{5}$$

(The relative root mean square deviations from the arithmetic mean for all the r-factors were within 0.011 – 0.046).

On multiplying the primary values of $\overline{f_N}$ by the respective r-factor, a reduced frequency $\overline{f_{N,\mathrm{red}}}$ was obtained (for H_2 = 0.35D, $r_{0.35D}$ = 1 by definition and $\overline{f_N} = \overline{f_{N,\mathrm{red}}}$ Then it was possible to express the dependence of this reduced frequency by a single straight line approximating all the measurements obtained for three impeller positions.

The frequencies $\overline{f_{N,\mathrm{red}}}$ are given in Table IV for all the liquids used. The scatter of the reduced values for water is demonstrated in Fig. 5 as an example.

Measurement Accuracy

The main mixing parameters, namely the impeller speed N, the impeller off-bottom clearance H_2 and the liquid viscosity μ were set and maintained so accurate that their deviations had no principal effect on the final result accuracy. Also the accuracy of the experimental data evaluation was supposed to have no significant effect on the final results. It is to say that the systematic error given by the experimental arrangement and by the evaluation method was negligible compared to the random error of the measured quantity.

To obtain data for the random error of the $\overline{f_N}$ estimation, the method of subsequent measurements was used. As already mentioned above, each elementary interval was evaluated separately and besides the mean value $\overline{f_N}$, its standard deviation was calculated, too. The values of the relative standard deviation never exceeded 15%.

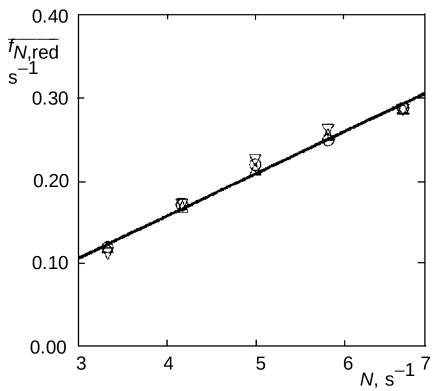

FIG. 5
Reduced frequency of macro-instability occurrence as a function of impeller speed for water at different impeller off-bottom clearances: H_2 = 0.2D (Δ), 0.35D (❍), 0.5D (∇)

Most of measurements were repeated after more than one month period and the differences between the results of the original and repeated measurements did not exceed 15%.

Processing of Results

Processing the $\overline{f_{N,\mathrm{red}}}$–$N$ data by the linear regression, the following relations were obtained for individual liquids tested:

water

$$\overline{f_{N,\mathrm{red}}} = -0.040 + 0.050N, \qquad R_{\mathrm{cor}} = 0.992,$$

27% aqueous saccharose solution

$$\overline{f_{N,\mathrm{red}}} = -0.009 + 0.041N, \qquad R_{\mathrm{cor}} = 0.974,$$

TABLE IV
Mean macro-vortex frequencies $\overline{f_{N,\mathrm{red}}}$, in s^{-1}

N, s^{-1}	H_2/D	Water	Solution 27% saccharose	Solution 46% saccharose
3.33	0.20	0.122	0.126	0.126
	0.35	0.122	0.113	0.102
	0.50	0.114	0.122	0.122
4.17	0.20	0.170	0.174	0.174
	0.35	0.172	0.180	0.158
	0.50	0.172	0.152	0.161
5.00	0.20	0.215	0.207	0.207
	0.35	0.220	0.211	0.192
	0.50	0.225	0.219	0.219
5.83	0.20	0.256	0.217	0.217
	0.35	0.249	0.219	0.237
	0.50	0.261	0.231	0.223
6.67	0.20	0.287	0.263	0.263
	0.35	0.287	0.280	0.267
	0.50	0.285	0.252	0.268

46% aqueous saccharose solution

$$\overline{f_{N,\mathrm{red}}} = -0.026 + 0.044N, \qquad R_{\mathrm{cor}} = 0.978.$$

(Here R_{cor} is the standard correlation coefficient.)

These correlations were obtained each from 60 individual data points, their validity is limited by the range of N from 3.33 to 6.67 s^{-1}.

The graphical illustration of these resulting approximations for all three liquids used is shown in Fig. 6. From this figure, as well as from the values of correlation coefficients, it follows that the assumption about the linear dependence between the frequency of the macro-instability occurrence and the impeller speed is acceptable.

CONCLUSIONS

The measurements proved that within the impeller speed range from 3.33 to 6.67 s^{-1} (the corresponding Re_M range being from 4 200 to 67 000), the dependence of the frequency of macro-instability occurrence $\overline{f_N}$ on the impeller speed N may be considered linear for all the impeller off-bottom clearances measured. By introducing the reduced frequency $\overline{f_{N,\mathrm{red}}}$ related to a chosen reference impeller off-bottom clearance $H_2 = 0.35D$, it was possible to approximate the $\overline{f_{N,\mathrm{red}}}$–$N$ dependence for each of the liquid measured for all the three impeller off-bottom clearances used by only one straight line.

The experiments proved that the macro-instability in its final stage can manifest itself by the level swelling up as described in ref.[5]. But if the intensity of the flow deformation caused by the macro-instability is not high enough, it does not reach the level of liquid at all and only tornado-meter measurement can detect macro-instability occurrence.

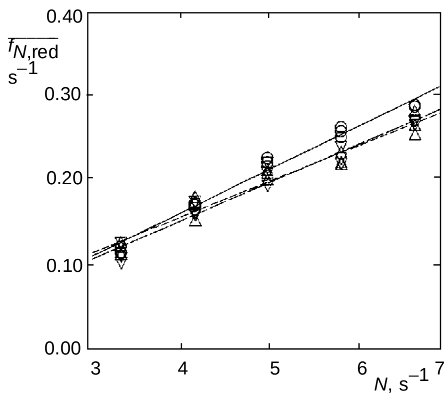

FIG. 6
Reduced frequency of macro-instability occurrence as a function of impeller speed for water (○, ——) and saccharose solutions of concentration 27% (Δ, — — —) and 46% (∇, – – – –) for all three impeller off-bottom clearances (three symbols for each value of N).

The cited authors[3,4] carried out their experiments in devices within the same range of the characteristic dimensions as they were used in the study presented but they used somewhat different types of impellers, as mentioned above. In spite of this, the order of magnitude of the frequencies of macro-phenomena observed by them corresponds fairly well to the frequency of the macro-instabilities encountered in this paper.

The effect of the viscosity of the liquid mixed on the turbulent macro-instability frequencies is not very conclusive in the given range of the impeller speed used and in the examined range of viscosities. There are some differences between the slopes of the lines approximating the dependence of $f_{N,\mathrm{red}}$ on N for the three liquids tested but no quantitative conclusions concerning the viscosity effect can be made up to now.

This research has been supported by the Czech Technical University, grant No. 8166.

SYMBOLS

b	baffle width, m
d	impeller diameter, m
D	vessel diameter, m
f_N	individual value of frequency of macro-instability occurrence, s^{-1}
$\overline{f_N}$	mean value of frequency of macro-instability occurrence, s^{-1}
$\overline{f_{N,\mathrm{red}}}$	mean value of reduced frequency of macro-instability occurrence, s^{-1}
h	width of impeller blade, m
H	liquid height in the vessel, m
H_2	impeller off-bottom clearance, m
n_p	number of peaks in individual, one minute, section of the record
N	impeller revolutions per second, s^{-1}
$r_{0.2D}$, $r_{0.5D}$	off-bottom clearance factors, Eqs (*2*)
r_t	radius of the tornado-meter position, m
R_cor	correlation coefficient
Re_M	Reynolds mixing number, Eq. (*1*)
Z_t	tornado-meter off-bottom clearance, m
α	impeller-blade inclination angle, °
μ	liquid viscosity, Pa s
ρ	liquid density, kg m^{-3}
σ_r	relative standard deviation

REFERENCES

1. Bruha O., Fort I., Smolka P.: *Proc. of Workshop 93: Presentation of the Grant Projects*, part B, p. 59. Czech Technical University, Prague 1993.
2. Ham S., Brodkey R. S.: Ind. Eng. Chem. Res. *31*, 1384 (1992).
3. Winardi S., Nagase Y.: J. Chem. Eng. Jpn. *24*, 243 (1991).
4. Kresta S. M., Wood P. E.: Can. J. Chem. Eng. *71*, 42 (1993).
5. Bruha O., Fort I., Smolka P.: Acta Polytech. Czech Tech. Univ. Prague *27*, 33 (1993).