Prosimy cytować jako: Inż. Ap. Chem. 2009, 48, 1, 124-125

SZYMON WOZIWODZKI
LUBOMIRA BRONIARZ-PRESS

Wydział Technologii Chemicznej, Politechnika Poznańska, Poznań

Transitional mixing in a vessel equipped with triple eccentric impellers

Introduction

Multiple-impeller systems are used in many industries, because of the advantages of the longer residence time, lower decrease of heat exchange area in scale-up treatment, lower power consumption per impeller as compared to single-impeller systems. Moreover, the use of eccentric multiple impeller systems can improve mixing. Eccentricity was found to be equivalent to baffling where eccentric position of the impeller maximized power consumption. Eccentric configurations have been even less studied, but probably they have a wider practical interest, as the off-centre impeller positioning improves the mixing [1]. The effect of impeller eccentricity on mixing has been experimentally investigated in few works [2–5] but knowledge of these systems is still rather incomplete. For the laminar regime, the effect of the shaft position on the flow field has been experimentally investigated by *Alvarez* et al. [6], who found important changes in the flow structure and major enhancement in mixing behaviour even for low eccentricity conditions.

The aim of this work was to determine the impact of the eccentricity ratio on mixing efficiency (mixing time and mixing power) in a vessel equipped with triple turbine impellers.

Experimental part

Experimental set-up consisted of a motor, inverter, speed sensor, PC computers, interface, torquemeter, conductivity probe, conductometer and injection device (*Eppendorf* EDOS 5222). The vessel had diameter $T = 0.19$ m and the height of liquid level was taken $3T$. The three types of impellers ($D = 0.065$ m) were used: *Rushton* turbine (RT), six flat blade turbine (FBT) and six pitched up blade turbine (PBT). The bottom clearance of the lowest turbine was $T/2$ and the spacing between turbines was chosen T, which is the safe distance to prevent hydrodynamic interaction between them in turbulent agitation, according to *Hudcova* et al. [7]. The working viscous *Newtonian* fluid was 75% glycerol solution (η = 0,0345 Pa·s, ρ = 1194 kg/m^3). The mixing time t_m at a 5% deviation from homogeneity was determined by use of the conductivity method. A small part (10 ml) of NaCl solution has been injected into the vessel containing a glycerol solution and after that the conductivity of the solution was measured. The eccentricity ratio was changed as follows: E/R = 0 (centrically mounted), E/R = 0.21, E/R = 0.32, E/R = 0.42 and E/R = 0.52.

Results

It follows from the analysis of data that the shortest mixing time in baffled system was obtained for triple *Rushton* turbines RT-RT-RT. The values of mixing time in relation to an impeller type were arranged as follows:

$$(t_m)_{RT\text{-}RT\text{-}RT} < (t_m)_{FBT\text{-}FBT\text{-}FBT} < (t_m)_{PBT\text{-}PBT\text{-}PBT}.$$

The longest values were obtained for axial impellers. In the range of Reynolds number values Re_m = 299÷1170 the mixing time decreases with increase of E/R, but in range of Re_m = 1170÷3000 this relation progressively decays. This fact can be explained by the peculiarities of transitional flow characteristics. At *Reynolds* number values Re_m > 1170 the turbulence is gradually increasing, and the dependence between the eccentricity and mixing time becomes weaker and finally in turbulent flow regime is negligible. For all impeller systems in the range of *Reynolds* numbers Re_m = 299÷1170 the

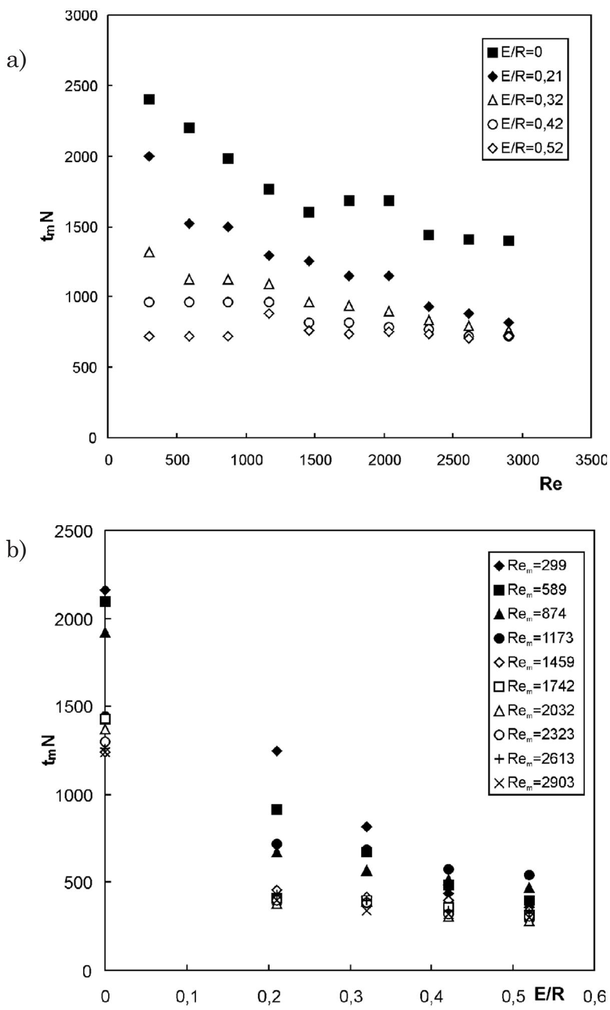

Fig. 1. The relation between dimensionless mixing time t_mN and eccentricy ratio E/R for unbaffled vessel: a) triple PBT, b) triple RT

decrease in mixing time values as a function of E/R was about 61%, and at $Re_m = 1170 \div 3000$ about 20%, respectively. In the unbaffled vessel the shortest mixing time was obtained for triple *Rushton* turbines system RT-RT-RT too.

In an unbaffled tank the greatest values of mixing time were obtained for axial impellers. The reduction of mixing time for all eccentricity ratios was about 75% for RT-RT-RT, 56% for FBT-FBT-FBT and 62% for PBT-PBT-PBT impellers, respectively. At $Re_m < 300$ the mixing time was long. In this part of transitional flow the macromixing is not a convective transport phenomenon. The mechanism of this process is not convection, because the average axial velocity is locally zero. As long as there is turbulence, the mechanism of interstage transport of mass is turbulent but, as laminar flow is approached, mass transport mechanism is based on molecular diffusion, which is an extremely slow process [8]. Therefore the experiments for triple turbine impeller at $Re_m < 300$ systems were abandoned.

The dimensionless mixing time $t_m N$ in triple impeller systems as a function of the *Reynolds* number is presented in Fig. 1, the shape of the curves is in accordance with previous works published [9–11]. It does not seem appropriate to suggest in the transitional regime the relationship $t_m N = A Re_m^B$ with $B < 0$ because the slope of the curve is not constant. One of the most useful relationships to characterize the mixing in transitional flow regime is shown below:

$$Ne_m^{0.33} Re_m Fo_m^m = C \tag{1}$$

where C and m are the constants, dependent on the flow regime. Dimensionless numbers were defined as follows:

$$Re_m = \frac{ND^2\rho}{\eta}, \quad Ne_m = \frac{P}{N^3 D^5 \rho}, \quad Fo_m = \frac{t_m \eta}{T^2 \rho}.$$

According to *Vasconcelos* [11], in the transitional regime $m = 1/2$ and $C = 184$. The analysis of data shows that the constants C and m obtained in this paper and by *Vasconcelos* are different, moreover C depends on eccentricity ratio E/R. The following relationships have been proposed (for unbaffled vessel, valid for $Re_m = 300 \div 3000$):

$$Ne_m^{0.33} Re_m Fo_m^{0.63} = 630 - 642.3\left(\frac{E}{R}\right) \pm 10\% \tag{2}$$

$$Ne_m^{0.33} Re_m Fo_m^{0.73} = 548 - 406.2\left(\frac{E}{R}\right) \pm 15\% \tag{3}$$

$$Ne_m^{0.33} Re_m Fo_m^{0.73} = 861 - 657.1\left(\frac{E}{R}\right) \pm 18\% \tag{4}$$

The above relationships were obtained according to mixing power and mixing time for RT-RT-RT system (eq. (2)), FBT-FBT-FBT system (eq. (3)) and for PBT-PBT-PBT system (eq. (4)) in an unbaffled vessel. The increase of E/R brings about on enlargement of mixing power and will progressively approach its values to the values of mixing power typical of baffled vessel.

Summary

Measurements of mixing time, mixing power in Newtonian viscous solutions in vessel equipped with a triple turbine showed that the dimensionless quantity $t_m N$ is dependent on Reynolds number in the transitional regime. Moreover, this variable is dependent on eccentricity ratio E/R. In unbaffled vessel mixing time decreases with an increase of E/R.

Notatation

A, B, C, m – constant
D – impeller diameter, [m]
E – distance between impeller shaft and stirred tank axis, [m]
E/R – eccentricity ratio
R – radius of stirred tank, [m]
T – inside diameter of stirred tank, [m]
N – agitator speed, [s^{-1}]
t_m – mixing time, [s]
η – viscosity, [Pa·s]
ρ – density, [$kg \cdot m^{-3}$]

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