TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
CHEMISTRY | CHEMIA
2-Ch/2014

SZYMON WOZIWODZKI*, LUBOMIRA BRONIARZ-PRESS*

POWER CHARACTERISTICS OF UNSTEADILY ROTATING RUSHTON TURBINE IN AERATED VESSEL

CHARAKTERYSTYKA MOCY TURBINY RUSHTONA WYKONUJĄCEJ RUCH OSCYLACYJNY PODCZAS WYTWARZANIA UKŁADU CIECZ-GAZ

Abstract

The paper presents an analysis of power requirements for unsteadily rotating Rushton turbine in an aerated vessel. The experiments have shown that the presence of gas phase in liquid results in reduction of power requirements. The effect of oscillation frequency on power requirements for F1 mixing mode was not observed while for FR mode power requirement was inversely proportional to oscillation frequency. The lowest relative power demand (RPD) was equal to 0.49, and the overall power requirements for unsteady mixing modes were higher in comparison to standard unidirectional mixing mode.

Keywords: forward-reverse mixing, oscillations, gas-liquid system, power requirements

Streszczenie

W artykule przedstawiono analizę mocy mieszania turbiny Rushtona obracającej się ze zmienną częstością i kierunkiem obrotów. Zgodnie z oczekiwaniami obecność gazu sprzyja zmniejszeniu zapotrzebowania na moc. Dodatkowo analizowano wpływ częstotliwości zmian częstości obrotów. Stwierdzono, że wpływ ten jest uzależniony od charakteru nieustalonego ruchu mieszadła. W przypadku zmiennej częstości i kierunku obrotów mieszadła moc mieszania była odwrotnie proporcjonalna do częstotliwości oscylacji. Z kolei przy zachowaniu tego samego kierunku obrotów mieszadła nie odnotowano wpływu częstotliwości na moc mieszania.

Słowa kluczowe: mieszanie, oscylacje, gaz-ciecz, moc mieszania

---

* Ph.D. Eng. Szymon Woziwodzki, Prof. Ph.D. Eng. Lubomira Broniarz-Press, Department of Chemical Engineering and Equipment, Faculty of Chemical Technology, Poznań University of Technology.

1. Introduction

Mixing of gas-liquid systems is usually conducted in a baffled vessel equipped with flat blade impeller (i.e. Rushton turbine) or hydrofoil impellers (i.e. BT-6 or A315). In such vessel gas phase is introduced through sparger mounted below impeller. However in some cases use of baffled vessel is not recommended. Resignation of baffles caused decrease in mixing due to formation of central vortex. Therefore new ways to enhance mixing in unbaffled vessels are welcome. One of the methods to improve mixing is use of unsteady mixing. Previous investigations have shown that the use of unsteady forward-reverse mixing with triangular time-course of impeller speed caused enlargement in power requirements [1, 2]. Moreover, it was noticed that mixing time was also greater in comparison to unidirectional standard mixing. This can be explained by presence of disturbance regions behind impeller blades. Such regions are located on both sides of blades because of accelerations and decelerations in impeller revolution.

Unsteady mixing could be successfully applied in laminar and transitional mixing. Use of forward-reverse mixing with triangular time-course of impeller speed causes enlargement of chaotic mixing which is mainly responsible for better mixing. It results in enhancement of mixing up to eight times in comparison to standard mixing mode [3]. Moreover the comparison of mixing times for unsteady mixing and mixing with eccentrically mounted impellers has shown that unsteady mixing generates better mixing for radial impellers [4]. Comparison of both mixing methods for turbulent flow regime showed that power requirement of unsteady mixing is slightly greater [5]. Unsteady mixing generates stronger shear stress in vicinity of impeller. This fact is useful in mixing of shear thinning fluids with shear stress. The use of unsteady mixing results in greater caverns in vicinity of impeller [6, 7].

The gas-liquid mixing plays an important role in many chemical processes, i.e. oxidation, hydrogenation, chlorination, sulfonation. Mixing of air-liquid systems is important especially in food industry. Air incorporation is very important process because many products like bread, beer, champagne, ice cream or chocolate contain air bubbles. The presence of gas causes decrease in power consumption, which affects the mass transfer coefficients [8]. Also the presence of large cavities decreases the efficiency of energy transmission and reduces the mixing performances [9]. Therefore there is a need to propose new method of mixing which differs from standard unidirectional mixing (specifically unsteady mixing).

The purpose of this paper was to study air-liquid power requirements of flat blade turbine impeller – Rushton turbine as well as to compare obtained results with standard unidirectional mixing. Time-course of impeller speed was characteristic to triangle wave form. The effect of a type of time-course (forward-reverse and time-periodic fluctuations of impeller speed) as well as an oscillation frequency have been analyzed.

2. Experimental set-up

Experimental set-up consisted of motor, inverter, speed sensor, PC computer, torque meter, oxidation probe. The vessel with diameter D_T = 0.29 m was equipped with flat bottom. The height of liquid level was taken D_T. One type of impeller was used: Rushton turbine (RT). The ratio of impeller diameter (D = 0.1 m) to vessel diameter was equal to D/D_T = 0.34. The bottom clearance of the impeller was D. The working Newtonian fluid was distilled water (μ = 0.001 [Pa s], ρ = 998 [kg/m^3]). Gas phase (air) was introduced to the vessel through ring sparger of diameter D_s = 0.075 [m] (D_s/D = 0.75), mounted on the vessel bottom, by membrane air compressor Hiblow HP-60. Volumetric flow rate of air ranged from 0.5 to 1.3 [m^3/h], and Reynolds number Re values were changed from 9000 to 80.000. Mixing power was determined with strain gauge technique by measuring torque T on shaft.

Two types of time-course of impeller speed were performed: the forward-reverse mode (FR) with unsteady impeller speed and direction of impeller rotation and the time-periodic fluctuation mode (F1) with unsteady impeller speed and steady direction of impeller revolution (Fig. 1).

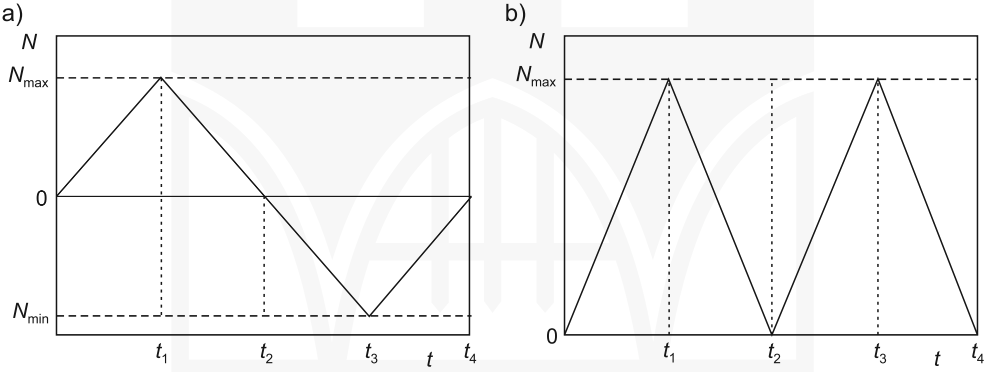

Fig. 1. Time course of impeller speed: a) FR mode, b) F1 mode

Changes in direction of rotation and speed of the impeller were generated by Schneider *p*-Drive MX Eco curve generator.

In the FR mode case the maximal impeller rotational speed $N_{\max}$ and the absolute values of minimal impeller speed $|N_{\min}|$ were the same $N_{\max} = |N_{\min}|$, while for F1 mode $N_{\min} = 0$. The frequency of impeller oscillations was changed from 0.058 Hz to 0.92 Hz.

2.1. Analytical methods

In unsteady flow the fluid force F is changing in time t and for the unsteadily rotating impeller can be expressed by Stokes equation [10]:

$$\frac{dF}{dr} = A'\frac{1}{2}\rho D r^2 \omega|\omega| + B'\frac{\pi}{4}\rho D^2 r\frac{d\omega}{dt} \tag{1}$$

Applying the above equation for mixing, we get:

$$T = C_d\,\rho D^5 \omega|\omega| + C_m\,\rho D^5\left(\frac{d\omega}{dt}\right) \tag{2}$$

where C_d, C_m and ω are drag coefficient, inertia coefficient and angular velocity of impeller, respectively.

According to equation (2) the unsteady fluid force can be expressed by two terms: the viscous drag term depending on velocity and inertia term depending on acceleration. Typical relation between torque T and impeller speed for FR and F1 modes is presented in Figure 2.

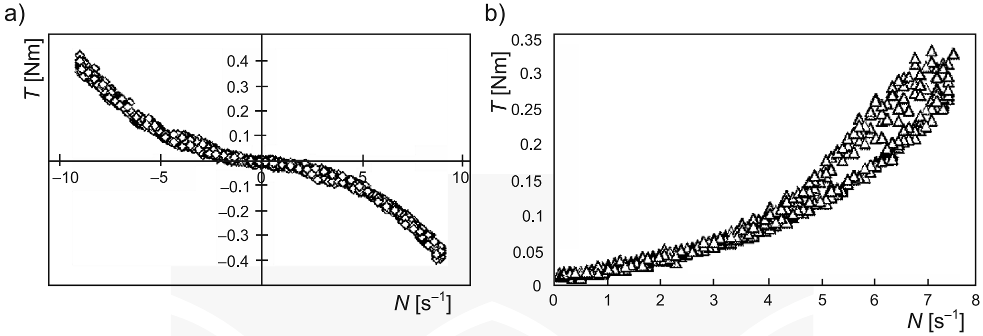

Fig. 2. Relation between torque *T* and impeller speed: a) FR mode, $\mathrm{Re}_{FR} = 47000$, $f = 0.23$ Hz, $Q = 1.3$ [m^3/h], b) F1 mode, $\mathrm{Re}_{F1} = 31713$, $f = 0.058$ Hz, $Q = 0.5$ [m^3/h]

On the basis of changes in torque the average value of *T* as well as impeller speed *N* for unsteady agitation were determined from following equations:

$$T_{FR} \vee T_{F1} = \frac{\sum |T|}{i} \tag{3}$$

$$N_{FR} \vee N_{F1} = \frac{\sum |N|}{i} \tag{4}$$

The torque T was conducted at a frequency from 5 to 50 Hz (it was assumed about 40 measuring points per oscilation cycle) whereas the average value was determined from ten cycles of impeller revolutions.

Next step was the determination of mixing power PFR for forward-reverse oscillations from:

$$P_{FR} = 2\pi N_{FR} T_{Fr} \vee P_{F1} = 2\pi N_{F1} T_{F1} \tag{5}$$

In order to characterize power requirements the power numbers Po_{FR} and Po_{F1} and Reynolds numbers Re_{FR} and Re_{F1} were determined:

$$\mathrm{Po}_{FR} = \frac{P_{FR}}{N_{FR}^3 D^5 \rho} \vee \mathrm{Po}_{F1} = \frac{P_{F1}}{N_{F1}^3 D^5 \rho} \tag{6}$$

$$\mathrm{Re}_{FR} = \frac{N_{FR} D^2 \rho}{\eta} \vee \mathrm{Re}_{F1} = \frac{N_{F1} D^2 \rho}{\eta} \tag{7}$$

3. Results

According to the previous work [1] power number for forward-reverse mixing Po_{FR} in turbulent flow regime was about $Po_{FR} = 7.12$. Moreover power number Po_{FR} was independent of oscillation frequency f (in range of (0.115; 0.46) Hz).

In the first step of power study was to determine power requirements for F1 mixing mode in miscible fluids. Figure 3 presents relation between Po_{F1} and Reynolds number for F1 mixing mode.

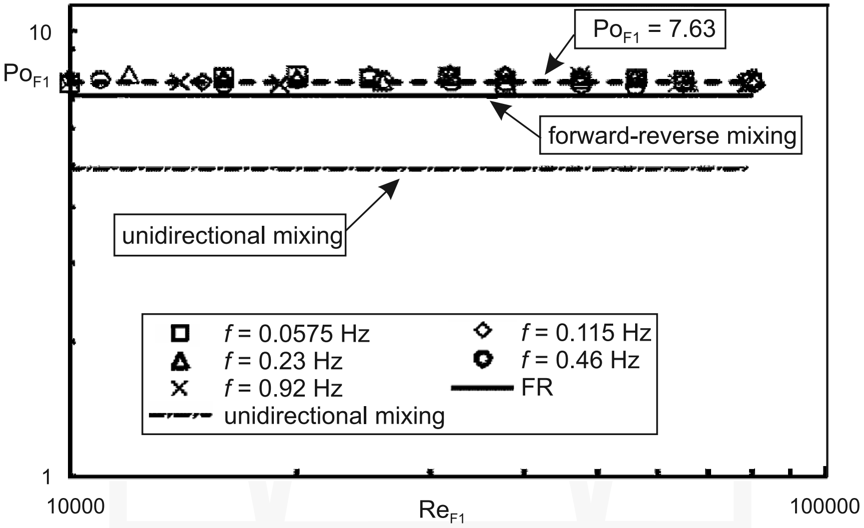

Fig. 3. Relation power number Po_{F1} and Reynolds number for mixing of miscible fluids

Analysis of power requirements for F1 mixing mode has shown that power number was independent of oscillation frequency, similarly to forward-reverse mixing (in oscillation range from 0.0575 Hz to 0.92 Hz). Power number Po_{F1} was equal to $Po_{F1} = 7.63 \pm 3\%$ and was about 7.2% higher from forward-reverse mixing and about 55% from standard unidirectional mixing.

Next step was to investigate power requirements for FR and F1 mixing modes in gas--liquid systems. The volumetric flow rate of gas phase (air) was ranged from 0.5 [m^3/h] to 1.3 [m^3/h] and superficial gas velocity v_s from 0.007 [m/s] to 0.019 [m/s]. Relations between gassed power number for FR mode $Po_{FR(g)}$ and F1 mode $Po_{F1(g)}$ and Reynolds number are presented in Figures 4–5.

It was noticed that for F1 mixing mode presence of gas phase has minor effect on power number in Reynolds number range Re_{F1} from 10000 to about 30000. Above $Re_{F1} = 30000$ the effect of gas presence was observed. Power number was smaller with increase of gas flow rate. The smallest value of gassed power number was achieved for $Q_g = 1.3$ [m^3/h] and Re_{F1} about of 38000 – $Po_{F1(g)} = 3.71$ and was about 52% smaller than power number Po_{F1}. At Q_g =0.5 [m^3/h] the smallest $Po_{F1(g)}$ value, obtained also at $Re_{F1} = 38000$, was equal

$\mathrm{Po}_{F1(g)}$ = 4.51 (40% smaller than Po_{F1}), and at Q_g = 1 [m^3/h] smallest gassed power number was about $\mathrm{Po}_{F1(g)}$ = 3.92 (49% smaller than Po_{F1}). The effect of oscillation frequency was not observed.

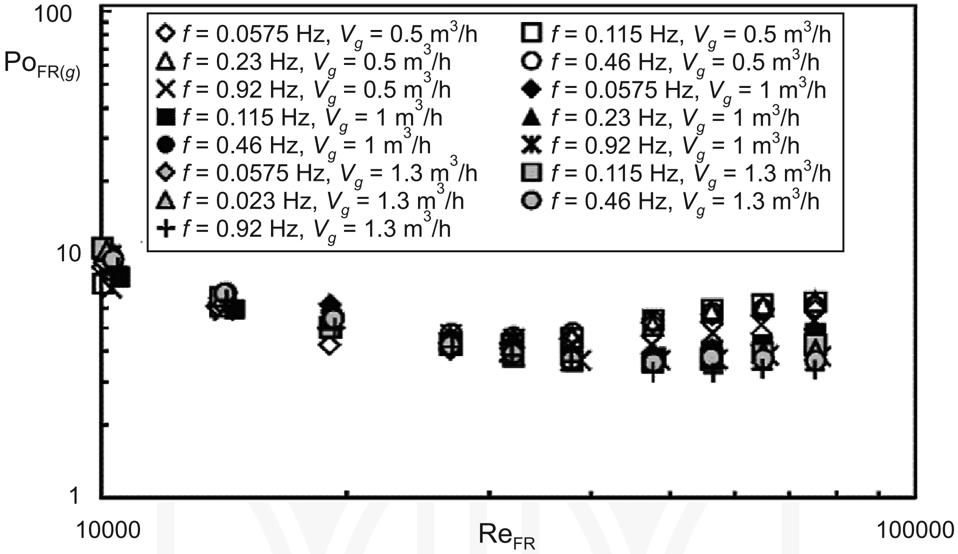

Fig. 4. Relation between gassed power number $\mathrm{Po}_{F1(g)}$ and Reynolds number for F1 mixing mode

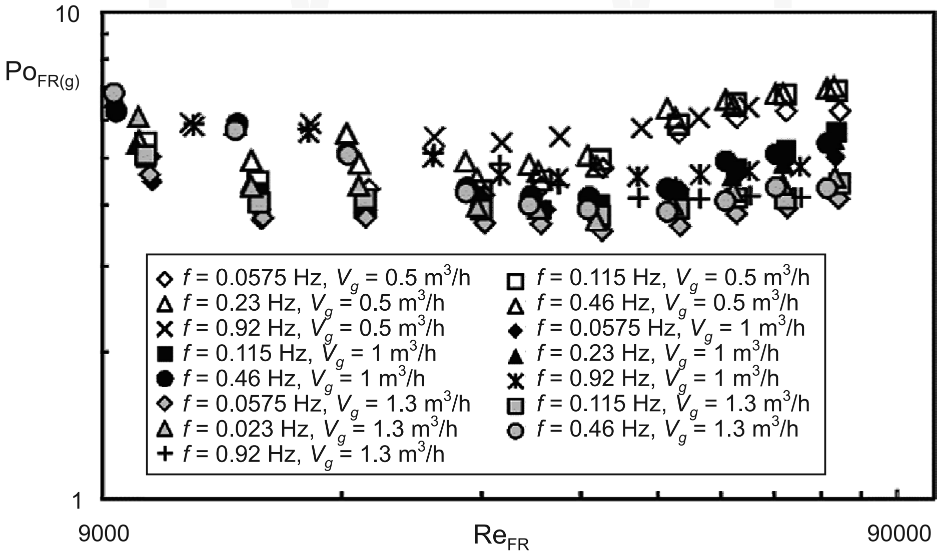

Fig. 5. Relation between gassed power number $\mathrm{Po}_{FR(g)}$ and Reynolds number for forward-reverse mixing

Figure 5 presents power characteristics for forward-reverse mixing. As expected presence of gas caused decrease in power requirements. It was observed that in entire range of Reynolds number gassed power number for forward reverse mixing $\mathrm{Po}_{\mathrm{FR}(g)}$ was dependent of gas flow rate. The smallest values of $\mathrm{Po}_{\mathrm{FR}(g)}$ were obtained for $Q_g = 1.3$ [m^3/h] at $\mathrm{Re}_{\mathrm{FR}} = 38000$. Power number was 51% smaller than power number for liquid phase. For $Q_g = 0.5$ [m^3/h] gassed power number was equal $\mathrm{Po}_{\mathrm{FR}(g)} = 4.14$ and was about 41% smaller than $\mathrm{Po}_{\mathrm{FR}}$. In contrast to time-periodic fluctuation mixing mode F1, an effect of oscillation frequency was observed. It was valid in entire gas flow range. It was found that for constant gas flow rate, at Reynolds number range below $\mathrm{Re}_{\mathrm{FR}} = 40000$, gassed power numbers $\mathrm{Po}_{\mathrm{FR}(g)}$ were greater with increase in oscillation frequency. Highest values of $\mathrm{Po}_{\mathrm{FR}(g)}$ were observed for $f = 0.92$ Hz and $f = 0.46$ Hz, while for remaining oscillation frequencies gassed power numbers were comparable. The effect of oscillation frequency vanished for Reynolds number $\mathrm{Re}_{\mathrm{FR}}$ above 40000. At $\mathrm{Re}_{\mathrm{FR}} = 10000$ as well as at Re = 90000 power requirements in gas-liquid system were comparable with liquid system.

One of the most important parameter for vessels equipped with six-blade turbine impellers is relative power demand (RPD). It depends on the blade shape, gas flow rate as well as on impeller speed N and impeller diameter D [11]. The RPD generally decreases with increased gas flow number defined by follows $\mathrm{Fl}_g = Q_g/ND^3$. One of the most commonly used equation to approximate the gassed power of a single Rushton turbine is the equation proposed by Nienow et al. (1997) [11, 12].

$$\mathrm{RPD} = 0.18\mathrm{Fl}_g^{-0.20}\mathrm{Fr}^{-0.25} \tag{8}$$

The above equations give good approximation of gassed power in the large-cavity regime. Large cavities were developed by Rushton turbine when $\mathrm{Fl}_g > 0.04$.

Figures 6 and 7 present the relation between relative power demand RPD and gas flow number Fl_g for F1 mixing mode (Fig. 6) and forward-reverse mixing (Fig. 7).

For time-periodic fluctuation mode F1 relative power demand RPD decreases with decreased gas flow number Fl_g. At gas flow number $\mathrm{Fl}_g < 0.4$ the effect of gas flow rate Q_g was not observed. In this range of Fl_g gas flow was not swamped by the impeller, but cavities formed caused decreasing in RPD. Further increasing in gas flow rate Q_g caused forming of the large cavities and achieving a minimum of RPD. Comparison of obtained relation between RPD and gas flow number with Nienow et al. equation (8) for $Q_g = 0.5$ [m^3/h] shows good accordance in range of Fl_g from 0.4 to 1.0. Above $\mathrm{Fl}_g = 1.0$ RPD for F1 mixing mode was greater in comparison to values obtained from Eq. (8). For $Q_g = 1$ [m^3/h] good accordance was found for $\mathrm{Fl}_g \in (0.5; 0.15)$ and for $Q_g = 1.3$ [m^3/h] at $\mathrm{Fl}_g \in (0.6; 0.2)$. The effect of oscillation frequency f was not observed.

For forward-reverse mixing mode FR the effect of oscillation frequency and gas flow was noticed. At highest oscillation frequency $f = 0.92$ Hz and $f = 0.46$ Hz the RPD was greatest (at constant Q_g). This can be explained by instability of caverns. For standard unidirectional mixing and turbine impellers with increasing in gas flow number the vortex cavities are transformed into large cavities. At first, they are small and occur behind all blades. As the impeller speed increases, the caverns expand and their number is decreasing. The relative power number RPD decreases until only three large caverns remain. For forward-reverse mode higher oscillation frequency does not allow the expansion and growth of cavities.

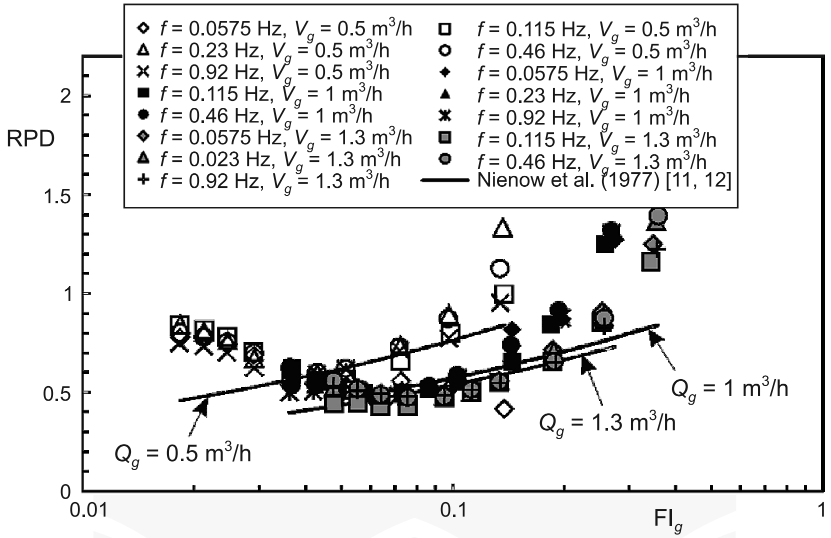

Fig. 6. Effect of gas flow number on RPD for F1 mixing mode

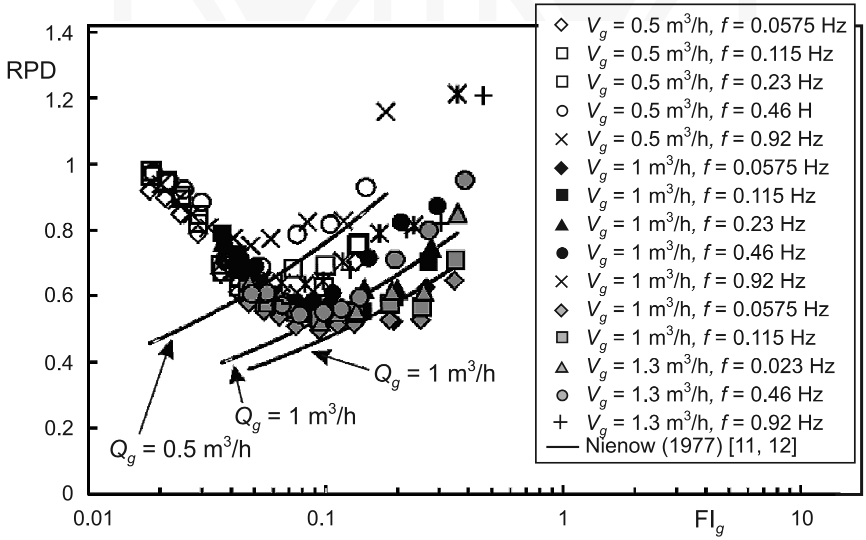

Fig. 7. Effect of gas flow number on RPD for FR mixing mode

Cavities are instable. This effect was observed for all gas flow rates. For remaining oscillation frequencies the effect of f was not so clear. Although it was noticed that an increase of oscillation frequency from 0.0575 Hz to 0.26 Hz causes enlargement in RPD up to 15%. The reason of such difference is also instability of cavities. For frequency ranged from 0.0575 Hz to 0.23 Hz instabilities were smaller than for $f = 0.46$ and $f = 0.92$ Hz.

The comparison of RPD for F1 and FR mixing modes shows that smallest RPD was obtained for F1 mixing mode (RPD = 0.42 at Fl_g = 0.075). For forward-reverse mixing smallest RPD was obtained for Fl_g = 0.1 (RPD = 0.49).

4. Conclusions

In the paper the effect of unsteady mixing on power requirements in gas-liquid system was studied. Two types of unsteady mixing were investigated: forward-reverse mixing and time-periodic fluctuation of impeller speed. For F1 mixing mode the effect of oscillation frequencies was not observed, in contradiction to forward-reverse mixing. In such mixing mode oscillation frequency plays important role in power requirements. Use of oscillation frequencies above f = 0,46 Hz is not recommended due to instabilities of cavities and enlargement of relative power demand RPD. The smallest RPD was found for F1 mixing mode.

The author is indebted for financial support to the Polish Ministry of Science and High Education under the auspices of Grant PUT No. ICT-32/368 and ICT-32/442.

References

[1] Woziwodzki S., *Unsteady mixing characteristics in a vessel with forward-reverse rotating impeller*, Chemical Engineering & Technology, vol. 34, 2011, 767-774.

[2] Woziwodzki S., *Turbulent forward–reverse mixing characteristics in vessel with multiple-turbine impellers*, Journal of Chemical Technology & Biotechnology, vol. 88, 2013, 483-490.

[3] Woziwodzki S., *Mixing of viscous Newtonian fluids in a vessel equipped with steady and unsteady rotating dual-turbine impellers*, Chemical Engineering Research and Design, in press, 2013, DOI: 10.1016/j.cherd.2013.09.013.

[4] Woziwodzki S., Broniarz-Press L., Jędrzejczak Ł, Zaworska K., *Porównanie sposobów zwiększenia efektywności mieszania płynów lepkich w mieszalniku z dwoma mieszadłami*, Inżynieria i Aparatura Chemiczna, vol. 52(4), 2013, 378-379.

[5] Woziwodzki S., Szatkowska K., *Wpływ stopnia niecentryczności na moc mieszania mieszadeł ze zmiennym w czasie kierunkiem obrotów*, Przemysł Chemiczny, vol. 90(9), 2011, 1702-1704.

[6] Woziwodzki S., Słowiński J., *Power Requirements for Yield Stress Fluids in a Vessel with Forward-Reverse Rotating Impeller*, Procedia Engineering, vol. 42, 2012, 1437-1444.

[7] Woziwodzki S., Broniarz-Press L., *Mixing of shear-thinning fluid with yield stress in a vessel with unsteadily rotating impeller*, 14th European Conference on Mixing, Warszawa, 10–13 September 2012, 515-520.

[8] Nienow A.W., *Gas-liquid mixing studies: a comparison of Rushton turbine with some modern impellers*, Chemical Engineering Research and Design, vol. 74, 1996, 417-423.

[9] Yoshida M., Watanabe M., Yamagiwa K., Ohkawa A., Abe M., Tezura S., Shimazaki M., *Behaviour of gas-liquid mixtures in an unbaffled reactor with unsteadily forward-reverse rotating impellers*, Journal of Chemical Technology & Biotechnology, vol. 77, 2002, 678-684.

[10] Stokes G.G., *On the effect of the internal friction of fluids on the motion of pendulums*, Cambridge Philosophical Society Transactions, vol. 9, 1851, 8-106.

[11] Middleton J.C., Smith J.M., *Gas-liquid mixing in turbulent systems*, [In:] E.L. Paul, V. Atiemo-Obeng, S. Kresta, *Handbook of industrial mixing: science and practice*, John Wiley & Sons, Hoboken, 2004, 585-639.

[12] Nienow A.W., Wisdom D.J, Middleton J.C., *The effect of scale and geometry on flooding, recirculation and power in gassed vessels*, Proceedings 2nd European Mixing Conference, Cambridge, 17-34.