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Chemical and Process Engineering 2013, 34 (4), 427-434
DOI: 10.2478/cpe-2013-0035

BLENDING CHARACTERISTICS OF HIGH-SPEED ROTARY IMPELLERS

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This paper presents a comparison of the blending efficiency of eight high-speed rotary impellers in a fully baffled cylindrical vessel under the turbulent flow regime of agitated charge. Results of carried out experiments (blending time and impeller power input) confirm that the down pumping axial flow impellers exhibit better blending efficiency than the high-speed rotary impellers with prevailing radial discharge flow. It follows from presented results that, especially for large scale industrial realisations, the axial flow impellers with profiled blades bring maximum energy savings in comparison with the standard impellers with inclined flat blades (pitched blade impellers).

Keywords: high-speed rotary impeller, turbulent flow, impeller power input, blending time, impeller blending efficiency

1. INTRODUCTION

Blending (homogenisation) is a common operation in chemical and process industries. Until now 80% of application processes have consisted of blending, usually under the requirement of minimisation of energy consumption (Seichter and Pešl, 2005). In chemical and allied industries mainly high-speed rotary impellers are introduced for blending process (Fořt et al., 2001; Grenville and Nienow, 2003; Khang and Levenspiel, 1976; Kramers et al., 1953). Such impellers (in comparison with low-speed impellers) are used above all when the character of flow of agitated charge is turbulent or transitional and their geometry usually holds conditions of relative impeller diameter $D/T \leq 1/2$ and impeller tip speed $\pi Dn > 2\text{ms}^{-1}$.

Characteristic parameter of the blending process is blending time τ related to the chosen homogeneity degree I (usually 95%). However, at practical realisations this characteristic time parameter is not often provided or it is required the total time consumption for blending including time intervals of addition of the individual reaction components or other process items, *e.g.* heating or cooling of agitated batch. Then practical knowledge of the blending time serves for the determination of the efficiency of the mixing process under different arrangements of an agitated system, above all the impellers.

It follows from up to date published studies (Kramers et al., 1953, Rieger et al., 2011; Rieger et al., 2011a; Tatterson, 1991) that under the turbulent flow regime of an agitated liquid the dimensionless blending time is constant:

$$n\tau = const. \tag{1}$$

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Equation (1) is valid for values of the impeller Reynolds number

$$\mathrm{Re}_M = \frac{nD^2\rho}{\mu} > 10^4 \tag{2}$$

when the effect of gravitational forces is eliminated by the introduction of radial baffles in a mixing vessel.

The value of the dimensionless blending time depends, however, on the geometric arrangement of an agitated system (type of impeller, size and position of rotor) and on the degree of homogeneity of the charge. This quantity is defined by the formula (Grenville and Nienow, 2003)

$$I(\tau) = \frac{\langle c(\tau)\rangle - c_0}{c_\infty - c_0} \tag{3}$$

Quantities c_0 and c_∞ express the initial and final concentration of the dissolved matter in an agitated batch, respectively, and the quantity $<c(\tau)>$, depending on time τ, is defined as an average value of the concentration in the whole volume of the agitated batch, except for added volume being homogenised in the batch during blending process (Fořt and Jirout, 2011). Usually the homogeneity degree is considered at the level of 95%, although for a different degree I_A it is possible to recalculate the dimensionless blending time $(n\tau)_{95}$ for the level I_A (in %) according to the relation (Fořt and Jirout, 2011)

$$(n\tau)_A = (n\tau)_{95}\left[\frac{\ln\left(1-\frac{I_A}{100}\right)}{\ln(1-0.95)}\right] \tag{4}$$

For comparison of the blending efficiency of various rotary impellers it is necessary to know their energy consumption. Impeller energy consumption per unit time – impeller power input P; can be expressed in dimensionless form (Beshay et al., 2001; Bujalski et al., 1987; Medek, 1980; Tatterson, 1991)

$$Po = \frac{P}{\rho n^3 D^5} = const. \tag{5}$$

Equation (5) is similarly as Eq. (1) valid for fully turbulent regime of flow of agitated liquid ($Re_M > 10^4$) when the effect of gravitational forces is eliminated by the introduction of radial baffles in a mixing vessel. Values of the power number in Eq. (5) depend on the type of rotary impeller and the geometric arrangement of an agitated system.

For determination of the blending efficiency of various rotary impellers the dimensionless criterion characterising energy consumption for homogenisation was derived (Rieger et al., 2011a; Rieger et al., 2011b; Rieger et al., 2012)

$$E = Po(n\tau)^3\left(\frac{D}{T}\right)^5 \tag{6}$$

Quantity E expresses in a dimensionless form the impeller power consumption for blending of liquid in vessel of the given diameter T at the given blending time τ under the chosen degree of homogeneity of the charge I. Consequently the higher the value E, the higher the power consumption of a rotary impeller necessary for reaching selected homogeneity degree I.

With the help of the above mentioned relations, this study presents a comparison of the blending efficiency of various high-speed rotary impellers based on an experimental determination of the time course of the blending process with the investigated impellers under a turbulent flow regime of an agitated batch, and on the basis of determining their power characteristics in the same pilot plant system.

2. EXPERIMENTAL

The experiments were carried out in a pilot plant flat bottomed cylindrical vessel (diameter $T = 590$mm) equipped with four radial baffles at its wall (width $b/T = 1/10$) when the liquid aspect ratio $H/T = 1$ (see Fig. 1). Tests were performed on five high-speed axial flow impellers and two high-speed radial flow impellers of the same size (impeller off-bottom clearance $C/D = 3/4$, for CVS 27: $C/D = 1/10$) – see Tables 1 and 2. In addition a hyperbolic Invent Hyperclassic impeller ($D/T = 0.42$) was tested (*www.invent-vv.de*). Nonstandard tested impellers are shown in Figs. 2 – 6.

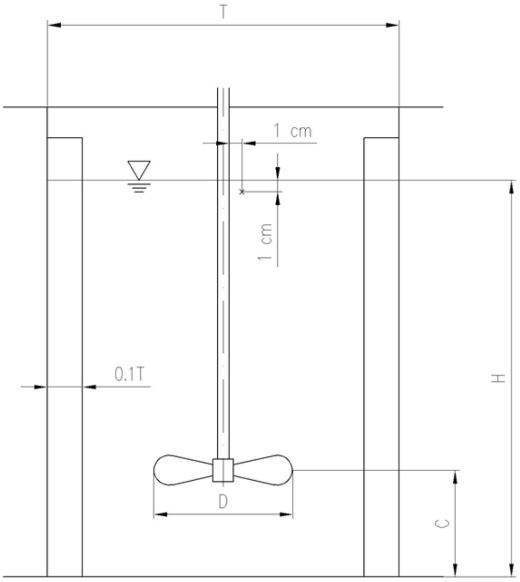

Fig. 1. Sketch of a pilot plant agitated system; *x* - position of sample addition

Table 1. Tested high-speed impellers

Impeller	Abbreviation
Down pumping 4-blade pitched blade impeller ($\alpha = 45°$, $h/D = 1/5$)	4PBT45
Down pumping 6-blade pitched blade impeller ($\alpha = 45°$, $h/D = 1/5$)	6PBT45
Down pumping 4-curved blade impeller of high solidity ratio ($\alpha = 35°$)	TX335
Down pumping 4-trapezoidal broken blade pitched blade impeller ($\alpha = 45°$)	TX445
Down pumping 4-blade modified propeller ($\alpha = 35°$, $(h/D)_{aw} = 1/5$)	TX535
Hyperbolic (diagonal) impeller	HPB
Radial 3-blade impeller (Czech Standard 691027) ($h/D = 1/10$)	CVS27
Standard Rushton turbine impeller	RT

Table 2. Results of impeller power input and blending time experiments ($D/T = C/T = 1/3$, $H/T = 1$, $Re_M > 10^4$, $I = 95\%$)

Impeller	RT	CVS27a	HPB	6PBT45	4PBT45	TX335	TX445	TX535
Po	5.4	0.9	0.35	1.65	1.29	0.9	0.9	0.65
$n\tau$	42.9	79.2	74.1	30.1	35.8	34.4	35.3	39.8

Notes:
1. In view of different D/T relation for HPB impeller its value of $n\tau$ was recalculated according to Eq. (8).
2. Impellers CVS27a and HPB were located close to the bottom ($C/T = 0.1$).

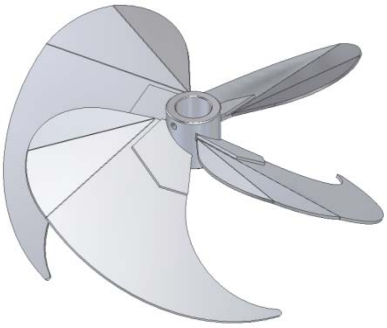

Fig. 2. Impeller TX335

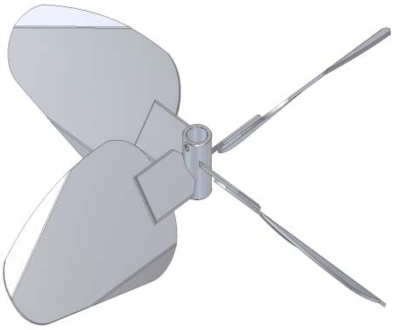

Fig. 3. Impeller TX535

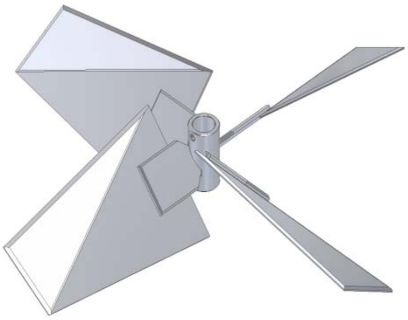

Fig. 4. Impeller TX445

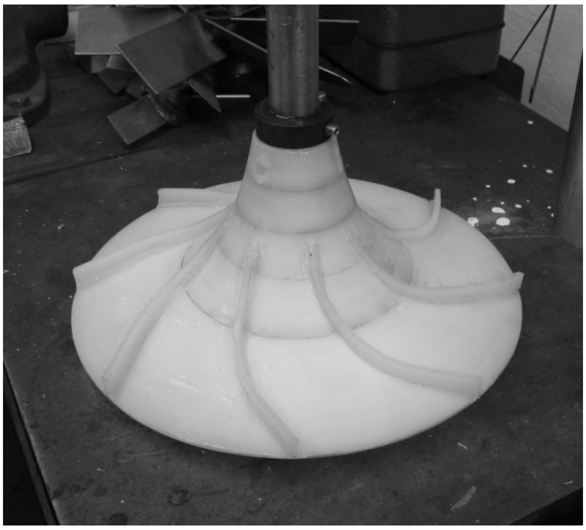

Fig. 5. Hyperbolic Impeller HPB

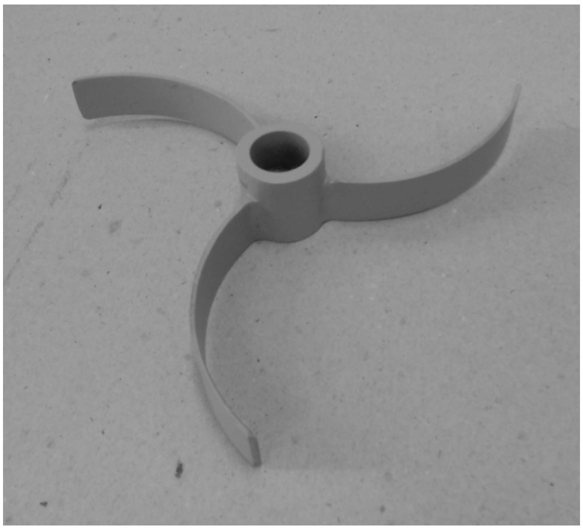

Fig. 6. Radial 3-blade impeller CVS27

2.1. Blending time measurements

The conductivity method was used for measurement of monitoring changes of electrical conductivity with the mixing liquid. Since the method is rather simple and controllable, we preferred it in comparison with more advance techniques (e.g. multipoint sampling or PLIF). Changes of electrical conductivity were caused by adding a sample of a concentrated solution of sodium chloride into the liquid. In owr experiments the injected sample of the liquid had approximately the same density and viscosity as the mixed liquid, and thus the effect of the Archimedes number was eliminated. After adding the tracer into the agitated liquid just below (ca. 1cm depth) the surface of the agitated charge in the vicinity of the impeller shaft (see Fig. 1), the time change of the conductivity was measured and recorded. Then the blending time (the time of homogenisation) was determined at the moment when the fluctuation of the measured electrical voltage U was ±5% (see examples of records of blending time course in Fig. 7 and 8). The addition time of the tracer (less than 1 sec) was negligible in comparison with recorded blending time. Under the same conditions (impeller, agitated system, charge, and impeller speed) blending experiments were repeated 10 times and resulting blending time was an average value from all ten repetitions. Additional details of experiments as well as an estimation of accuracy of determination of all independent variables were described elsewhere (Fořt and Jirout, 2011).

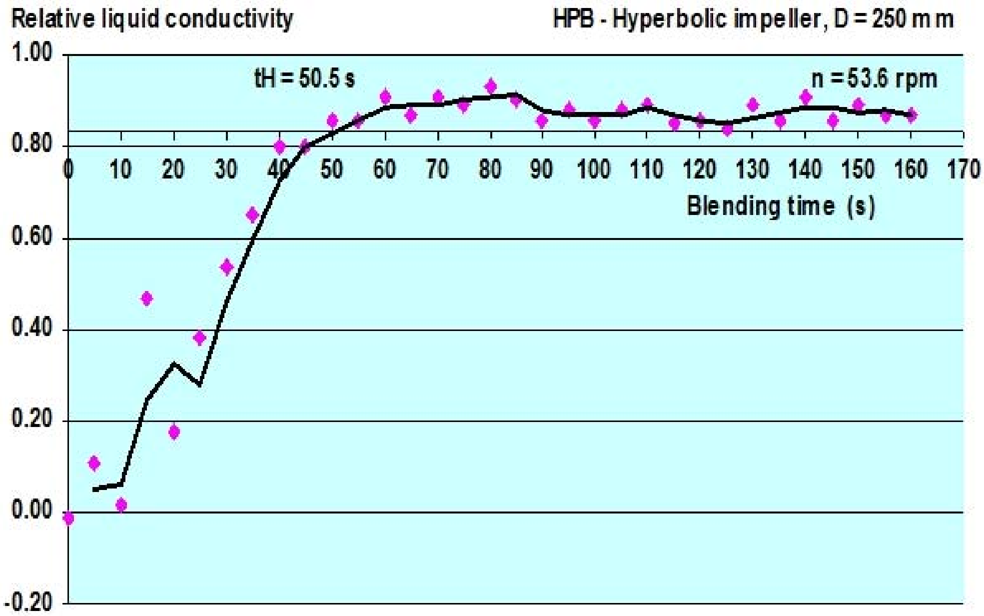

Fig. 7. Course of homogenization (HPB, $T = 590$mm, $D = 250$mm)

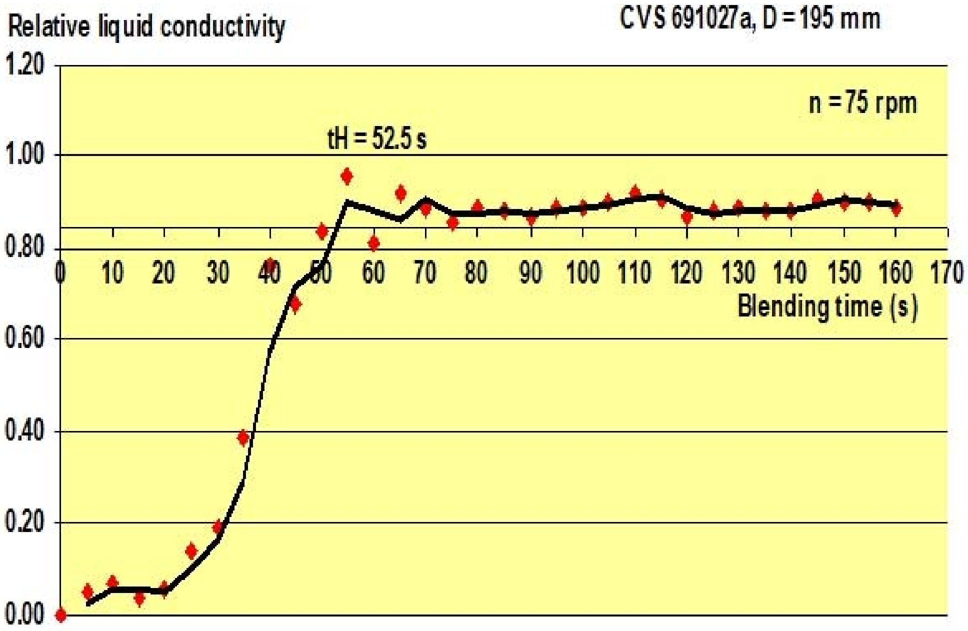

Fig. 8. Course of homogenization (CVS27a, $T = 590$mm, $D = 250$mm)

2.2. Impeller power input measurements

The power input of the investigated impellers was calculated from an experimental determination of the torque and impeller speed. A strain gauge torquemeter, mounted on the motor shaft, was used to measure the torque, and the signal was fed into the data acquisition system. The impeller speed was measured by photoelectric cell and a notched disc mechanism. This quantity was kept constant within ±2rpm during the measurements. Therefore, the maximum experimental error encountered in measuring the speed was 1%. Under the selected technique of measuring the torque (Fořt and Jirout, 2011) the relative standard deviation of the measured impeller power input was calculated and found to be in the range 2.3 – 10%.

3. RESULTS AND DISCUSSION

Table 2 contains a set of calculated values of dimensionless blending time $n\tau$ and power number *Po* of all eight tested impellers following from carried out experiments as well as from the experiments made by Fořt and Jirout (2011) in a mixing vessel T = 300mm geometrically similar to the system investigated in this study. Results of Fořt and Jirout (2011) valid for homogeneity degree 98% were recalculated to the chosen value I = 95% by means of Eq. (4).

With respect to a rather nonstandard geometry of the hyperbolic impeller HPB (see Fig. 5) measured values of the power input of this impeller taken from 26 industrial realisations were considered. Thus the average value of the power number and corresponding standard deviation from the set of industrial data were calculated:

$$Po = 0.43 \pm 0.11(HPB) \tag{7}$$

The found value of *Po* seems to be in a good agreement with the corresponding value in Tab. 2. Further in accordance with a greater ratio *D/T* of impeller HPB (*D/T* = 0.424) than the value of this quantity in all tested cases (*D/T* = 1/3), the value of the dimensionless impeller blending time found in our experiments was recalculated to the geometry of other investigated impellers according to relation (Fořt and Jirout, 2011) – see Note 1 bellow Table 2

$$(n\tau)\left(\frac{D}{T}\right)^2 = const. \tag{8}$$

Cavadas and Pinhol (2004) also investigated the flow characteristics of an agitated system with a hyperbolic impeller. Results of their measurements of the power number

$$Po = 0.81 \text{ (hyperbolic impeller)} \tag{9}$$

differ both from the results of experiments made in this study, and from the results collected from industrial realisations, probably due to the differences of geometry of their impeller compared to the geometry of used HPB impeller.

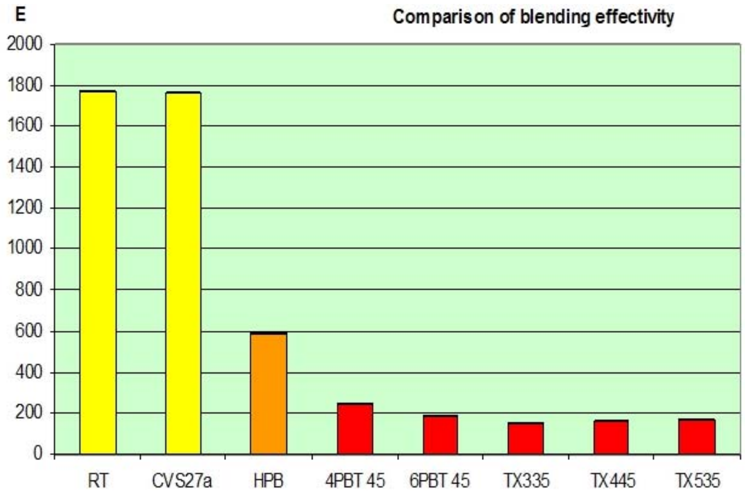

Fig. 9. Comparison of blending efficiency of high-speed rotary impellers (I = 95%, Re_M > 104)

Energetic and blending characteristics of all the tested impellers were generalised by means of Eq. (6). Fig. 9 illustrates a comparison of blending efficiency of all the impellers described in Table 1 and shown in Figs. 2 – 6 (more sophisticated design, only). It follows from Fig. 9 with a set of tested impellers that those exhibiting the radial discharge flow seem to be quite ineffective for blending, while all the tested axial flow impellers are almost one order of magnitude better than the former. Among them a more sophisticated design of impellers TX shows an additional improvement of the impeller blending efficiency. A hyperbolical impeller is generally more energetically saving than impellers with the radial discharge flow, but its blending efficiency is worse (approx. three times) than quantity E of the axial flow down pumping impellers.

4. CONCLUSIONS

Under a turbulent regime of an agitated liquid the axial flow down pumping rotary impellers exhibit blending efficiency of almost one order of magnitude higher than the rotary impellers with radial discharge flow. Among the former mixers the axial flow impellers with profiled blades introduce maximum energy savings in comparison with the standard impellers with inclined plane blades (pitched blade impellers).

The authors of this paper appreciate financial support of the Technology Agency of the Czech Republic, No. TA 02010243 and of Ministry of Education of the Czech Republic grant INGO LG 13036.

SYMBOLS

b	width of radial baffle, m
C	impeller off-bottom clearance, m
c	concentration, kg m^{-3}
D	impeller diameter, m
E	impeller blending efficiency according to Eq. 6
H	height of agitated charge above vessel bottom, m
h	impeller blade width, m
I	degree of homogeneity according to Eq. 3
n	impeller speed, s^{-1}
P	impeller power input, W
Po	Power number
Re_M	impeller Reynolds number
U	electrical voltage, V
T	mixing vessel diameter, m

Greek symbols

α	pitch angle of blade, °
μ	dynamic viscosity, Pa·s
ρ	density, kg m^{-3}
τ	blending (homogenisation) time, s

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Received 17 April 2013
Received in revised form 02 August 2013
Accepted 20 September 2013