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Relation between the rate of erosion wear of axial high-speed impellers and their process characteristics

Introduction

In all areas of particulate technology where solid particles are handled, structures in contact with the particles exhibit wear. In some applications this wear may be so severe as to limit the life of a component or plant, while in others it may be negligible [1]. Since the erosion wear of impeller blades during mixing of solid-liquid suspension can lead to the determination or even collapse of a technological process with impellers [2], knowledge of the erosion wear rate of impeller blades in dependence on their shape and the physico-chemical properties of the agitated suspensions seems to be critical for the proper design of industrial plants provided with mechanical stirrers. Successful estimation of the lifetime of impellers in such systems also depends on this knowledge.

The aim of this study is to discover the influence of the erosion wear rate of the blades of pitched blade impellers on a solid-liquid suspension on their process characteristics – off-bottom suspension of solid particles in a liquid and the blending of liquid phase in suspension.

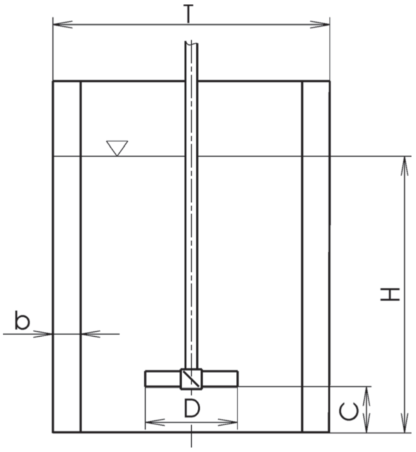

Fig. 2. Geometry of the pilot plant mixing vessel ($T = 300$ mm, $H/T = 1$, $D/T = 1/3$, $C/D = 1$, $b/T = 1/10$)

Theoretical

Let us consider solid-liquid suspension agitated by the down pumping pitched blade impeller (Fig. 1) axially located in cylindrical vessel provided with baffles at the wall (Fig. 2) under turbulent regime of flow of agitated batch. Such an arrangement is especially efficacious for the so called *flow-sensitive operations* [3], *i.e.* homogenization (or blending) of miscible liquids or suspension of solids in liquid. They include batch and continuous operations, homogeneous reactions, crystallization, and dissolution of the solid phase. The term *flow-sensitive* used to describe such process suggests that they depend mainly on the bulk flow conditions of the mixed charge, *e.g.* on the impeller pumping capacity or the total volumetric flow rate of agitated batch.

The erosion of a pitched blade impeller caused by particles of higher hardness (*e.g.* corundum or sand) can be described by an analytical approximation of the leading edge of the worn blade [4] (Fig. 3)

$$H(R) = 1\text{-}C\exp[k(1\text{-}R)] \tag{1}$$

where the dimensionless transversal coordinate H along the width of the blade is

$$H = y(r)/h \tag{2}$$

and the dimensionless longitudinal (radial) coordinate R along the radius of the blade r is

$$R = 2r/D \tag{3}$$

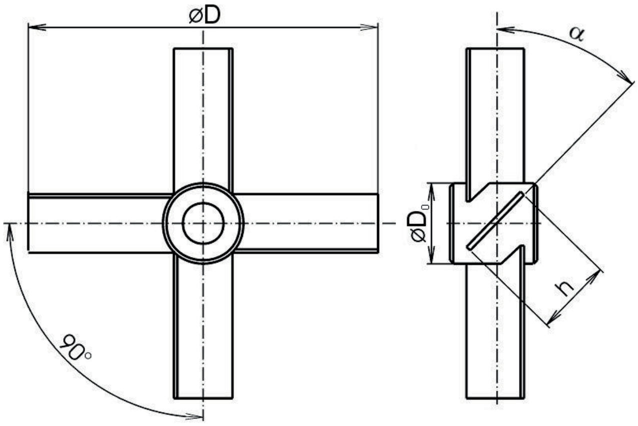

Fig. 1. Design of the pitched blade impeller with four inclined plane blades ($D = 100$ mm, $D_0/D = 0.2$, $h/D = 0.2$, $\alpha = 30°$)

Parameters h and D characterize the blade width and diameter of the impeller, respectively. The values of the parameters of Eq. (1) – the wear rate constant k and the geometric parameter of the worn blade C – can be calculated by the least squares method from the experimentally formed profile of the worn blade (see example in Fig. 4). It follows from experimental studies published recently [4], that while the wear rate constant exhibits a monotonous dependence only on hardness and shape of the solid particles and on the pitch angle α the geometric parameter of the worn blade is dependent on the pitch angle, hardness and

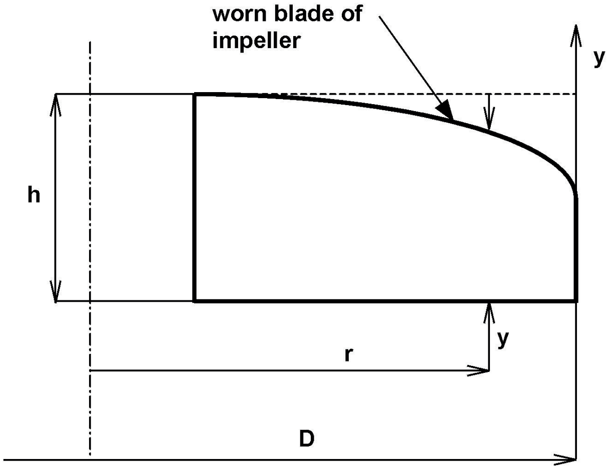

Fig. 3. Radial profile of the leading edge of the worn blade of a pitched blade impeller

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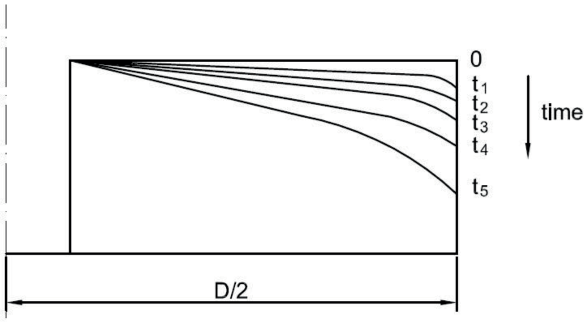

Fig. 4. Profiles of the worn blade of a pitched blade impeller at the process of erosion ($t_{i+1} > t_i$)

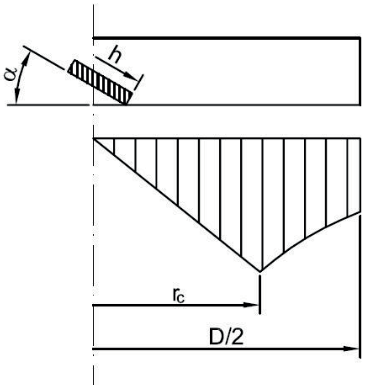

Fig. 5. Velocity profile in discharge flow leaving a pitched blade impeller

thickness of impeller blades, impeller speed, suspension properties and, in a linear form, on time.

Radial profile of the mean velocity in the impeller discharge flow in the system defined above (Fig. 5) exhibits two parts – ascending and descending one with boundary radius r_c [5], where the considered velocity profile reaches its maximum value. Under the assumptions that the impeller discharge stream considered as axisymmetric and the blade lift of the pitched blade impeller can be neglected the axial volumetric flow rate of the given type of impeller can be obtained by integration of the velocity profile over the radius of discharge flow $D/2$. Then we have [5]

$$Q_{p,ax}=\frac{\pi^2 c^2}{2}\sin 2\alpha\left(\frac{1}{2}-\frac{c}{3}\right)nD^3 \tag{4}$$

and correspondingly for the radial volumetric flow rate (if the ratio of the blade width to impeller diameter $K = h/D$) one obtains

$$Q_{p,rad}=\pi^2 c^2 K\sin^3\alpha nD^3 \tag{5}$$

Quantity α in Eqs. 4 and 5 is pitch angle and parameter c is defined as

$$c = 2r_c/D \tag{6}$$

Impeller pumping capacity in dimensionless form (the flow rate number) is given by the sum of axial and radial flow rates

$$N_{Q_p}=\frac{Q_{p,ax}+Q_{p,rad}}{nD^3}=\frac{\pi^2 c^2}{2}\left[\sin 2\alpha\left(\frac{1}{2}-\frac{c}{3}\right)+2K\sin^3\alpha\right] \tag{7}$$

Outside the cylindrical body of rotating impeller (*the impeller rotor region*) we can define the induced flow rate [3] as the liquid its motion results from the momentum transfer between the flow through the impeller rotor region on the fluid surrounds it. The induced volumetric flow rate is located in the hollow cylinder between radius of the impeller $D/2$ and the coordinate r_C where the flow of agitated charge changes its direction from downwards to upwards:

$$Q_i=\frac{\pi^2}{4}c^2\sin 2\alpha\,(c_D-1)\,nD^3 \tag{8}$$

where parameter c_D is defined as

$$c_D=\frac{2r_C}{D} \tag{9}$$

Then the total flow number, the sum of the flow rate number and the induced flow rate number, is

$$N_Q=\frac{Q_p+Q_i}{nD^3}=\frac{\pi^2 c^2}{2}\left\{\left[\sin 2\alpha\left(\frac{1}{2}-\frac{c}{3}\right)+2K\sin^3\alpha\right]+\frac{1}{2}\sin 2\alpha\,(c_D-1)\right\} \tag{10}$$

The worn blade modifies the velocity field in the impeller discharge stream. Under the assumption that the worn blade affects predominantly the outer part of the velocity profile in the impeller discharge stream ($r \geq r_c$) the axial volumetric flow rate of the worn pitch blade impeller is [6]

$$Q_{p,ax,er}=\frac{\pi^2 c^2}{2}\sin 2\alpha\left\{\frac{1}{2}\left[1+\frac{C}{k}\left(1-\exp[k(1-c)]-\frac{c}{3}\right)\right]\right\}nD^3 \tag{11}$$

Radial volumetric flow rate of the worn impeller is affected via parameter C of Eq. (1) corresponding to the reduction of the impeller blade at its tip:

$$Q_{p,rad,er}=\pi^2 c^2 K(1-C)\sin^3\alpha nD^3 \tag{12}$$

The worn impeller pumping capacity in dimensionless form is again given by the sum of the right hand sides of Eqs. (11) and (12)

$$N_{Q_{p,er}}=\frac{Q_{p,ax,er}+Q_{p,rad,er}}{nD^3}=$$

$$=\frac{\pi^2 c^2}{2}\left(\sin 2\alpha\left\{\frac{1}{2}\left[1+\frac{C}{k}(1-\exp[k(1-c)])\right]-\frac{c}{3}\right\}+2K(1-C)\sin^3\alpha\right) \tag{13}$$

Initial conditions of the erosion process correspond to the original shape of impeller and its flow number (Eq. 10).

Induced flow rate depends for the given geometry of agitated system on the impeller pumping capacity, only [3]. Then this quantity decreases its value with respect to the ratio

$$Q_{i,er}/Q_i=Q_{p,er}/Q_p \tag{14}$$

under the assumption that the flow pattern of agitated batch does not change significantly when erosion of the impeller blades takes place.

Effect of the blade erosion on the process characteristics of the pitched blade impeller

Relation between the blending time Θ of miscible liquids in an agitated system and the mean time of the liquid circulation τ_t holds [3]

$$\Theta/\tau_t=A\,(T/D)^a\log[B/I(\Theta)] \tag{15}$$

In Eq. (15) quantity I (depending on time Θ) defines the degree of homogeneity of agitated batch:

$$I=\frac{\langle x(\Theta)\rangle-x_k}{x_0-x_k}\,\varepsilon\langle 1;0\rangle \tag{16}$$

when the average concentration of the mixed component of liquid phade in agitated batch $<x>$ changes from initial value x_0 to the final one x_k. Under conditions of fully turbulent flow of agitated liquid when there is no "dead space" in volume of agitated charge V the following relation holds

$$\tau_t = V/Q_t\,. \tag{17}$$

Eq. (17) can be rewritten to the form

$$\tau_k=\frac{\pi}{4}\left(\frac{T}{D}\right)^3\frac{D^3}{Q_t} \tag{18}$$

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where volume of agitated batch V is considered as a volume of cylinder with the same height H and diameter D. Then the left hand side of Eq. (15) can be rearranged to the form

$$\frac{n\Theta}{n\tau_t}=\frac{4}{\pi}\left(\frac{D}{T}\right)^3 n\Theta\frac{Q_t}{nD^3} \tag{19}$$

and after combination of Eq. (19) with the right hand side of relation (15) with following rearrangement we have finally

$$(n\Theta)N_{Q_t}=\frac{\pi}{4}A(T/D)^{3+\alpha}\log[B/I(\Theta)] \tag{20}$$

It follows from the resulting equation derived from initial relation (15) that the product of the total flow number N_{Q_t} (Eq.10) and dimensionless blending time $n\Theta$ is constant for the given geometry of agitated system (type of impeller, geometric simplex T/D) and chosen homogeneity degree $I(\Theta)$. When decreasing (owing to the erosion wear of impeller blades) the total volumetric flow rate (at the given level of impeller speed n) the dimensionless blending time as well as quantity Θ increases. Thus, erosion wear of the impeller, blades can result in decrease of the rate of the blending process and becoming longer the process necessary to reach required degree of homogeneity of agitated batch.

The critical impeller speed for just off-bottom suspension n_{js} is defined as the speed at which a settled bed of solid particles was just discerned as the impeller speed was reduced from a condition of full suspension [7]. This quantity is rather important for designing of mixing apparatuses with solid-liquid suspensions, *e.q.* crystallizers, dissolution tanks, solid-liquid reactors, *etc.* Wu and Pullum [7] published a semiempirical relation

$$N_{Q_p}n_{js}=const \tag{21}$$

where quantity N_{Q_p} the flow rate number (Eq. 7). For the given type of impeller and geometry of agitated system (position and size of impeller), and for the given properties of the solid-liquid suspension the product of quantities N_{Q_p} and n_{js} must be the same irrespectively of the erosion level of the impeller blades:

$$N_{Q_p,er}n_{js,er}=const \tag{22}$$

Then a reduction of the impeller pumping capacity owing to the erosion process increases the critical impeller speed for just off-bottom suspension to avoid the origin of sediment at the mixing vessel bottom and increases significantly required impeller power input [8]. It is necessary to point out that the above introduced relations are valid for turbulent regime of flow of agitated batch.

Experimental

Measurement of the wear rate of impeller blades was carried out in a pilot plant mixing vessel made from stainless steel (Fig. 2), with a water as a working liquid (density ρ_l = 1000 kg/m^3, dynamic viscosity μ = 1 mPa.s) and particles corundum (mean volumetric particle diameter d_p = 0.21 mm and mean volumetric concentration of particles c_v = 5 %). Pitched blade impeller (Fig. 1) with four adjustable inclined plane blades made from construction steel, pumping downwards was investigated in a fully baffled flat bottomed cylindrical agitated vessel.

The impeller speed was held constant n = 900 min^{-1} within accuracy ± 1% corresponding to complete homogeneity of the suspension under a turbulent regime of flow of agitated batch. It follows from preliminary experiments made visually in a Perspex mixing vessel under the same conditions as for the erosion wear experiments, that there was 90% homogeneity of the suspension at impeller speed n = 700 min^{-1}.

During the experiments, the shape of the blade profile was determined from magnified copies of the worn impeller blades scanned to a PC. The parameters of the blade profile for the given time of the erosion process were determined from each curve of four individual worn impeller blades. The selected time interval from the very beginning of each experiment was not to exceed the moment where the impeller diameter began to shorten. Then the values of the parameters of Eq. (1) – the wear rate constant k and the geometric parameter of the worn blade C – were calculated by the least squares method from the experimentally found profile of each worn blade at the given time interval t of the erosion process. Each curve regression coefficient was better than R = 0.970. The resulting values of parameters k and C were the average values calculated from all individual values of these parameters from each blade. It can be mentioned that the chosen shape of the regression curve $H = f(R)$ fits best to the experimental data among other possible two-parameter equations (e.g. an arbitrary power function or second power parabola).

The time course for homogenization of agitated batch was determined in the same pilot plant mixing vessel and system configuration (Figs. 1 and 2) as the measurement of the impeller blades wear rate described above. The standard technique for measuring electric conductivity of batch with unworn or worn impeller in dependence of time from the moment of adding a sample of different conductivity (solution of NaCl) from the initial one was used. Dynamic viscosity of agitated liquid μ = 1 m Pa.s was chosen so the regime of flow of agitated batch was always turbulent. For the given conditions (impeller speed, worn (or unworn) impeller, kinematic viscosity of the batch) 5 repetitions of the time course of blending process were realized. The average value of the blending time from results of all repetitions was considered as a representive value for the given conditions. The degree of homogeneity I (Eq. 16) was chosen 0.05 (5%).

The critical impeller speed for just off-bottom suspension was measured again in the same pilot plant mixing vessel and system configuration (Figs. 1 and 2) as determination of the impeller blade wear rate described above. The electrochemical (EDD) technique [8] used for indication of quantity n_{js} consists of application of nonconducting solid particles in conducting liquid. Then the presence (or absence) of the particles is detected by electrodes located at the corresponding boundary of solid body, *e.g.* at the vessel bottom. Then it is possible from dependence of the measured signal (current) of the electrode on the impeller speed to detect the step wise change of this signal corresponding to escape of the nonconducting particles from the vicinity of the electrode and their replacement by the conducting liquid. Electrolyte composed 5 wt. % aqueus solution of NaCl and the chosen solid phase was glassy beads (density ρ_s = 2460 kg/m^3, mean volumetric particle concentration c_V = 2.5 % and 10 %). With the aim to confirm a validity of Eq. (22) experiments were carried out with worn and unworn blades of investigated pitched blade impeller.

Results and discussion

Results of all calculations and experiments are summed up in Tables 1–3. Parameters of radial profile of the axial component of the mean velocity in impeller discharge stream c (Eq. 6) and c_D (Eq. 9) were taken from the original study [9]. Flow rate numbers N_{Q_p} and total flow rate number*s* N_{Q_t} in the tables were calculated for unworn blades (parameter C in Eq. (1) is equal zero), from Eq. (7) and (10) and corresponding quantities for worn blades were calculated from Eq. (13) with taking in consideration relation (14), *i.e.* that the induced flow rate $Q_{i,er}$ is lower than the same quantity calculated for original unworn impeller.

Tab. 1. Influence of the wear of impeller blade on the blending time (α = 30°, c = 0.634, cD = 1.533, k = - 4.33 ± 0.16, I = 0.05)

t [h]	C [-]	N_{Q_t} [-]	$(n\Theta)_{av}$ [-]	$N_{Q_t}(n\Theta)_{av}$ [-]
0	0	0.987	45.0 ± 2.0	44.4
20	0.0362	0.976	46.8 ± 4.0	45.7
40	0.1095	0.949	50.0 ± 3.8	47.5
60	0.1705	0.923	54.0 ± 4.2	49.8
84	0.3093	0.881	55.0 ± 3.4	48.8

Ø: 47.0 ± 3.0

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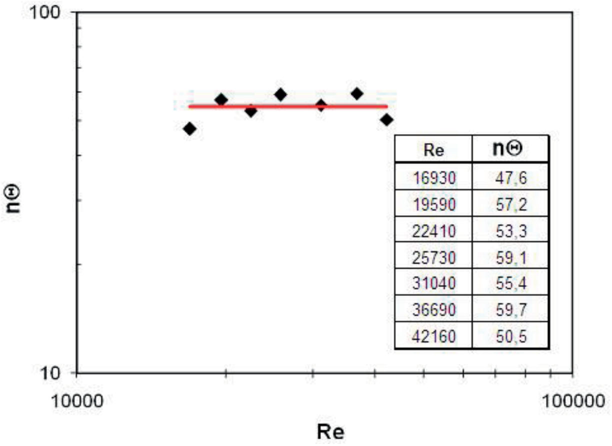

Fig. 6. Dependence of the dimensionless blending time on the impeller *Reynolds* number ($C = 0.1705$, $k = -4.33 \pm 0.16$, $I = 0.05$)

It follows from results in tables that both dimensionless flow rates decrease significantly during erosion process and further that the total volumetric flow rate is approx. twice as much than the impeller pumping capacity.

Average dimensionless blending time $(n\Theta)_{av}$ was calculated from found dependence of the quantity $n\Theta$ on the impeller *Reynolds* number within the internal $1.0 \cdot 10^4 - 5.0 \cdot 10^4$. It was confirmed a few times [10] that for the impeller Reynolds number Re greater than one thousand the dimensionless blending time is constant independent of the impeller Reynolds number. Example of such a dependence is shown in Fig. 6. Values $(n\Theta)_{av}$ were calculated under this assumption and their oscillations are less than ± 8%. It follows from Table 1 that its last column confirms the validity of Eq. (20), *i.e.* that the erosion of the impeller blades lengthens the blending time of miscible liquids in agitated batch.

Tab. 2. Influence of the wear of impeller blade on the critical impeller speed for just off-bottom suspension ($\alpha = 30°$, $c = 0.634$, $k = -4.33 \pm 0.16$)

$d_p = 0.25$ mm			$c_V = 2.5\%$		$c_V = 10\%$	
t [h]	**C** [-]	**N_{Q_p}** [-]	**n_{js}** [s^{-1}]	**$N_{Q_p} n_{js}$** [s^{-1}]	**n_{js}** [s^{-1}]	**$N_{Q_p} n_{js}$** [s^{-1}]
0	0	0.521	9.55	4.98	11.07	5.77
20	0.0362	0.513	10.05	5.16	11.93	6.13
40	0.1095	0.501	9.90	4.96	12.47	6.25
60	0.1705	0.487	9.70	4.72	12.73	6.20
84	0.3093	0.465	10.22	4.75	12.93	6.01

Ø: 4.912±0.25 Ø: 6.070±0.30

Tab. 3. Influence of the wear of impeller blade on the critical impeller speed for just off-bottom suspension ($\alpha = 30°$, $c = 0.634$, $k = -4.33 \pm 0.16$)

$d_p = 0.724$ mm			$c_V = 2.0\%$		$c_V = 10\%$	
t [h]	**C** [-]	**N_{Q_p}** [-]	**n_{js}** [s^{-1}]	**$N_{Q_p} n_{js}$** [s^{-1}]	**n_{js}** [s^{-1}]	**$N_{Q_p} n_{js}$** [s^{-1}]
0	0	0.521	13.30	6.93	18.72	9.86
20	0.0362	0.513	14.45	7.44	19.72	10.15
40	0.1095	0.501	14.43	7.23	20.42	10.23
60	0.1705	0.487	14.60	7.11	19.53	9.51
84	0.3093	0.465	15.35	7.14	22.68	10.55

Ø: 7.17 ±0.30 Ø: 10.05 ±0.50

Tables 2 and 3 illustrate an experimental confirmation of Eq. (22). It follows from calculated values of the product $N_{Q_p} n_{js}$ that for the worn impeller blades (parameter $C > 0$) values of this product practically do not differ from the values valid for unworn blades (parameter $C = 0$). It means that this decrease of the flow rate number must be compensated by the increase of the critical impeller speed for just off-bottom suspension n_{js}. Found dependence is valid for coarse solid particles up to their mean volumetric concentration $c_V = 10$ %.

Conclusions

Pitched blade impellers under turbulent regime of agitated batch affect the *flow-sensitive operations* – blending of miscible liquids and suspension of solid particles in liquid with significant effect of the wear rate of their blades.

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