SURFACE AERATION THRESHOLD IN AGITATED VESSELS

Kamil WICHTERLE[a] and Tomas SVERAK[b]

[a] *Institute of Chemical Process Fundamentals, Academy of Sciences of the Czech Republic, 165 02 Prague 6-Suchdol, Czech Republic; e-mail: kwich@icpf.cas.cz*

[b] *Research Institute for Macromolecular Chemistry, 656 49 Brno, Czech Republic*

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Violent agitation of liquids in mixing vessels may result in the regime of surface aeration being attained when the bubbles formed at the liquid surface enter the impeller region. Analysis of data on surface aeration for different liquids in a set of geometrically similar agitated vessels is presented. Data on the just aerated state as observed visually in transparent liquids, and data for the efficient aeration as determined from the break on the power number curve are considered. A simple model is developed for correlation of the data which enables the threshold of aeration to be predicted from the value of the recirculation number $Nc = Nd\,(\rho/\sigma g)^{1/4}$. The possibility of interpreting various literature data for the aeration threshold and for the power input with use of Nc is demonstrated. Similar modelling rules hold also for the correlation of beginning of the efficient liquid–liquid dispersion.

Key words: Agitation; Gas–liquid; Bubbles.

Many textbooks and monographs present agitation as a process where increasing the impeller speed improves any effect of agitation, which is paid for only by increased power input. But every practitioner knows that increasing the impeller speed beyond a certain limit results also in a disturbance of the liquid level and onset of surface aeration. The surface aeration may be useful when we are interested in the mass transfer between liquid and gas, but more frequently it is undesirable because it may be accompanied by foam formation. The gas cavities which appear at the impeller blade may cause noise, shaft vibrations, and promote corrosion. Flooding the impeller by entrapped bubbles can also suppress the amount of pumped liquid which reduces, e.g., heat transfer or solid suspension.

If a function of the mixing equipment with a given liquid is studied, there are some characteristic ranges of the impeller speed from the viewpoint of the aeration regime. In a transparent liquid, we can distinguish separate regimes also by visual observation. The first problem is to define the just aerated state by the critical impeller speed N_{JA}. van Dierendonck et al.[1], Bujalski et al.[2], and Tanaka and Izumi[3] identified this point by random appearance of the first bubbles under the liquid surface. A state when the bubbles are regularly driven to the impeller region, and a cloud of dispersed gas remains visible which can be indicated by turbidity in transparent liquids, was preferred by Sverak and Hruby[4], Greaves and Kobbacy[5], or Solomon et al.[6]. Another characteristic impeller speed N_{EA} can be assigned to the beginning of efficient aeration. It can be determined from specific changes in any quantity affected by the presence of bubbles in the agitated batch. There appears a significant break in the plot of measured power numbers versus the rotation speed when the aeration becomes important[2,4,7]. Westerterp et al.[8] also found significant increases in the absorption rate when the surface aeration began to be important, and characterized the process by the speed where such a transition occurs. Another possibility was suggested by van Dierendonck et al.[1], who measured the gas holdup as a function of impeller speed, and identified the threshold of aeration by characteristic speed obtained by linear extrapolation of this function to zero gas holdup.

The aim of this paper is to analyze experimental data on the onset of surface aeration, and to determine how the critical impeller speed depends on liquid properties and on the equipment size.

THEORETICAL MODEL

Observation of the process at the liquid surface indicates that the regular surface aeration begins when the recirculating liquid can pull down bubbles from the surface. At higher *Re*, the downstream velocity U_D is, like any other component of the velocity field in the circulatory flow, proportional to the impeller tip speed

$$U_D \propto Nd \quad . \qquad (1)$$

The characteristic diameter of the bubble or drop in a cloud is usually proportional[9] to the Laplace's characteristic length, L. According to Peebles and Garber[10], such objects have, in low viscosity liquids, terminal velocity $U_P \approx 1.2\, U_C$. Assuming $U_D = U_P$ just for $N = N_{JA}$ then the onset of downstream motion of bubbles or drops corresponds to a specific value of the dimensionless group

$$Nc^* \equiv Nd/U_C = Nd[\rho^2/(|\Delta\rho|\sigma g)]^{1/4} \quad . \qquad (2)$$

In particular, the ratio of the impeller tip speed to the terminal rising velocity of bubbles (where $\Delta\rho \approx \rho$), given by the recirculation number

$$Nc \equiv Nd[\rho/(\sigma g)]^{1/4} = (We\, Fr)^{1/4} \quad , \qquad (3)$$

may be assumed to control the process of surface aeration. A similar grouping of variables was recommended by Westerterp et al.[8] for the description of the threshold of intensive absorption of gas through the surface of agitated liquids.

If admitted that there may be also some effect of the liquid viscosity and vessel size, according to dimensional analysis, two other dimensionless criteria should be taken into consideration. We prefer to use ratio $Bs \equiv d/L = d(\rho g/\sigma)^{1/2}$ as a scale parameter, and the group $Rp \equiv LU_C\rho/\mu = (\sigma^3\rho/g)^{1/4}/\mu$ as a viscosity parameter. Our hypothesis that the function $Nc = f(Bs,Rp)$ is weak in geometrically similar situations is tested.

EXPERIMENTAL

Four Blade Impellers in Baffled Vessels

Experiments were performed by Sverak[11] as a part of program investigating the scale-up rules in agitated vessels. Particular results which estimate the effect of the vessel size and of viscosity on the threshold impeller speed were presented in the paper by Sverak and Hruby[4]. The measurements were performed with a set of liquids of different viscosities and densities in a set of 10 strictly geometrically similar mixing equipments covering volumes from 160 cm^3 to 0.780 m^3. The power data for unaerated systems were used for interpretation of a so-called scale effect at high Reynolds numbers[12]. Simple four blade turbine impellers without discs were used during the investigation of the scaling up, see Fig. 1.

The geometrical simplexes of the impellers were:

$$d/D = 0.333 \pm 0.8\%;\ w/d = 0.200 \pm 1.9\%;\ x_L/d = 0.022 \pm 18\%$$

$$d_H/d = 0.170 \pm 5.2\%;\ d_S/d = 0.124 \pm 30\%.$$

The simplexes of the tanks were:

$$b/D = 0.100 \pm 1.6\%;\ x_B/D = 0.0095 \pm 42\%;\ n = 4.$$

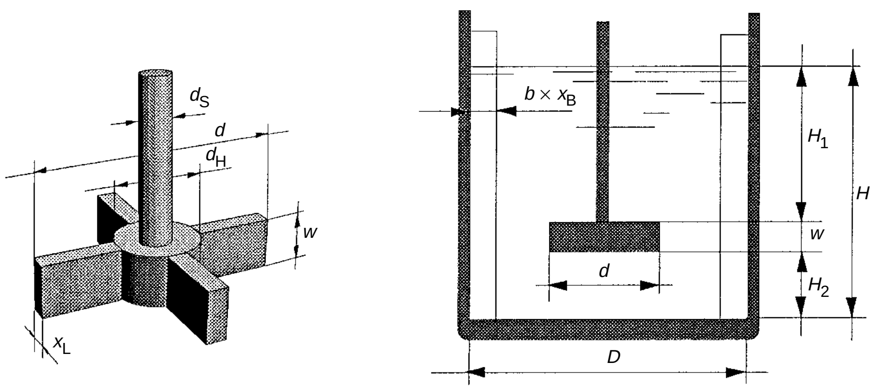

FIG. 1
Four-flat-blade impeller and tank configuration

The position of the impeller and the liquid level was adjusted to keep just

$$H/D = 1 \text{ and } H_2/D = 0.333.$$

The liquid properties are presented in Table I.

The torque measured at varying rotation speed were interpreted in terms of power numbers *Po*. Simultaneously, the regime on the liquid surface and in the agitated batch was observed. From visual observations, it was found that the emergence of first bubbles formed at the surface could hardly be defined in a reproducible manner. Thus, the threshold of just aerated state N_{JA} has been defined as the minimum speed when the systematic and regular entrapment of the bubbles in the impeller area takes place, and when the medium in the respective area stays opaque. Another critical speed N_{EA} has been determined as a value at which the decrease of *Po* with respect to the value assumed for the systems unaffected by surface aeration stays significant. Here, the point where 10% decrease in *Po* has been observed, is assigned to N_{EA}.

RESULTS AND DISCUSSION

Four Blade Impellers in Baffled Vessels

By regression of the variables we have obtained

$$N_{JA} \approx d^{-0.936\pm0.022}\,\sigma^{0.255\pm0.160}\,\rho^{0.035\pm0.291}\,\mu^{0.060\pm0.014}\ . \tag{4}$$

It is apparent that it is closed to

$$N_{JA} \approx d^{-1}\,\sigma^{0.25}\,\rho^{-0.25}\,\mu^{0.0}$$

TABLE I
Properties of liquids at 20 °C

Liquid	Density ρ kg m^{-3}	Viscosity μ m Pa s	Surface tension σ N m^{-1}	Impeller diameters *d* mm
Water	998	1.01	0.0727	19 ÷ 333
Glycerine 25% w/w in water	1 050	2.095	0.0689	19 ÷ 187
Glycerine 44% w/w in water	1 117	4.47	0.0677	19 ÷ 151
Glycerine 74% w/w in water	1 178	32.0	0.0660	19 ÷ 98
Glycerine 91% w/w in water	1 224	62.2	0.0640	19 ÷ 98
Tetrachloromethane	1 584	1.018	0.0265	19 ÷ 80
Ethyl iodide	1 911	0.625	0.0275	19 ÷ 37
Mercury	13 545	1.554	0.476	30

which is identical with the assumption Nc_{JA} = const. Nevertheless, possible minor additional effects of viscosity and linear scale was tested studying correlation of Nc_{JA} with criteria *Rp* and *Bs*, respectively, as apparent in Figs 2 and 3. By regression of all the relevant data[11], covering the range $7 < Bs < 125$, $6 < Rp < 2\,500$, we have obtained

$$Nc_{JA} = (9.336 \pm 0.767)\ Bs^{0.064\pm0.022}\ Rp^{-0.064\pm0.012}\ . \tag{5}$$

As shown in Fig. 2, the effect of *Rp* is mostly given by scattered data for high-viscosity liquids (low *Rp*). However, for low-viscosity liquids, the effect of viscosity can be neglected and prevailing volume of data can be interpreted in usual range *Rp* as

$$Nc_{JA} - 6.6\ Bs^{0.06}\ . \tag{6}$$

Similarly, for N_{EA},

$$Nc_{EA} = (8.211 \pm 0.765)\ Bs^{0.141\pm0.023}\ Rp^{-0.036\pm0.012} \tag{7}$$

has been found and for low-viscosity liquids,

$$Nc_{EA} = 6.7\ Bs^{0.14}. \tag{8}$$

Relevant data are presented in Figs 4 and 5.

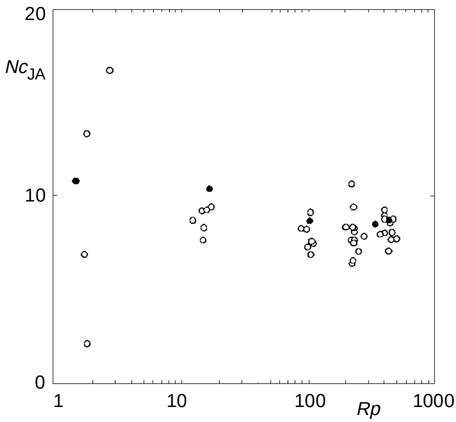

FIG. 2

First surface aeration threshold Nc_{JA}, effect of liquid viscosity. ● d = 0.1 m, ❍ other diameters

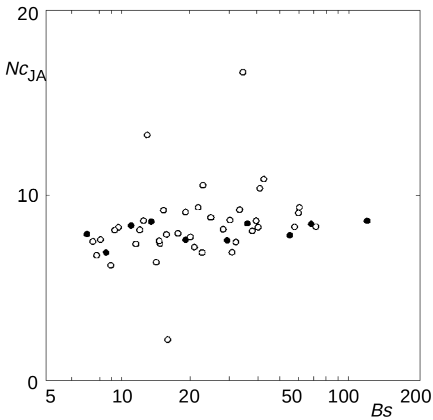

FIG. 3

First surface aeration threshold Nc_{JA}, effect of tank size. ● Water, ❍ other liquids

For standard geometry of the disc mounted turbine, $d/D = 1/3$ in a baffled vessel, the aeration has been studied by a number of authors[1,2,5,8,9,13]. However, such an extended set allowing to apply statistics like that one mentioned above, is not at hand. Therefore, only the critical values of *Nc* were calculated and discussed from the viewpoint of the similar hypothesis.

Results for 5 sets of measurements done by Sverak[11], with water and 44% glycerine can be interpreted for a standard impeller position as $Nc_{JA} = 4.4 \div 5.3$, and $Nc_{EA} = 5.5 \div 6.8$. These values depend significantly on the proximity of the impeller to the liquid level, $H_1 = H - H_2 - w$, and indicate that *Nc* is nearly proportional to the simplex H_1/D, while van Dierendonck et al.[1] and Greaves and Kobbacy[5] reported a weaker dependence.

Bujalski et al.[2] observed the appearance of first bubbles at the liquid surface and their critical rotation speeds can be interpreted as $Nc_{JA} = 0.4\ (D/d)\ Bs^{0.3}$. Of course, it predicts somewhat lower speeds than necessary for the appearance of a bubble cloud. The decrease of presented functions $Po(Re)$ corresponds to $Nc_{EA} \approx 2\ Nc_{JA}$.

Westerterp et al.[8] determined, from the transition point in mass transfer between liquid and gas, that $Nc_{EA} = 1.22 + 1.25(D/d)$ for standard turbines.

van Dierendonck et al.[1] suggested on the basis of the characteristic plot of hold-up vs rotation speed, the correlation

$$Nc_{JA} = 1.55\ (D/d)(H_1/D)^{1/2} \text{ and } Nc_{EA} = 2.0\ (D/d)(H_1/D)^{1/2}\ .$$

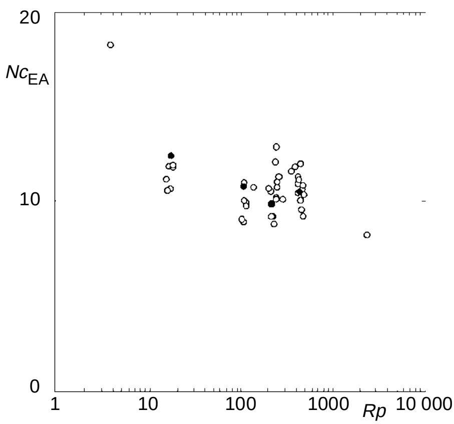

FIG. 4
Efficient surface aeration threshold Nc_{EA}, effect of liquid viscosity. ● d = 0.1 m, ❍ other diameters

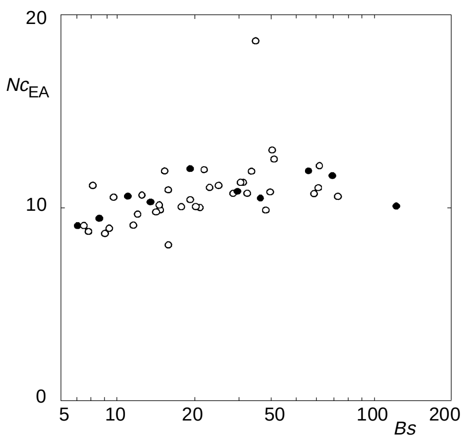

FIG. 5
Efficient surface aeration threshold Nc_{EA}, effect of tank size. ● Water, ❍ other liquids

Similar results were presented by Greaves and Kobbacy[5]. If the terminal velocity of bubbles according to Peebles and Garber[10] is used in their correlation, the critical values are Nc_{EA} = 7.2 and Nc_{JA} = 3.1.

To be able to compare data from different sources, we present in Table II the critical values of *Nc* predicted for the case of water agitated by an impeller d = 0.1 m in a standard position. Though different, and sometimes very subjective methods of critical point estimation has been used by various authors, all the results are close to the values $Nc_{JA} \approx 3.5$, and $Nc_{EA} \approx 6$.

Turbine Impellers in Unbaffled Vessels

Tetamanti et al.[7] studied the impeller power for viscous liquids in baffled vessels. These data allow us to determine the values of Nc_{EA}, which can be interpreted by the function $Nc_{EA} = 9.2\ Rp$ for $0.05 < Rp < 10$. Apparently, there is no essential difference between the onset of surface aeration in baffled and unbaffled vessels. Of course, such a conclu-

TABLE II
Critical recirculation numbers (predictions for air–water system, and for impeller d = 0.1 m in standard position)

Impeller	Ref.	Nc_{JA}	Nc_{EA}
4-Blade paddle	4,11	8.0	11.0
in baffled vessel	17		9.0
Rushton turbine			
in baffled vessel	2	3.5	7.1
	8		5.0
	11	4.5	5.8
	1	3.6	4.6
	5	3.1	7.2
	13	4.2	
liquid–liquid (Nc_{ED})	15		6.8
in unbaffled vessels	16		8.3
	7		(4.5)
Propeller 3 blades	18	9.4	
Axial 6-blade impeller			
in baffled vessel	18	7.2	
in unbaffled vessel (eccentric position)	14	5.2	

sion has to be considered cautiously for systems with higher d/D and lower H_1/D, where the central vortex may actually reach the impeller region.

The effect of tank scale and impeller position has also been investigated by Novak et al.[14] for six blade axial turbines in unbaffled tanks. The result for water could be simply rearranged to

$$Nc_{\mathrm{EA}} = 1.22\ Bs^{0.28}\ (D/d)^{0.58}\ (H_1/D)^{0.37}\ .$$

Lower power at the ratio (D/d) in comparison with the correlations[1,2] holds for the central position of the impeller. With the impeller in eccentric position, the liquid behaves like a liquid in a baffled tank.

Application to Liquid–Liquid Systems

The process of forming the dispersion on the interface of immiscible liquids is analogous to the formation of bubbles at the liquid level. We have studied the critical values Nc^{*}_{ED} calculated from the data by Godfrey et al.[15] who presented 35 efficient-dispersion speeds for different L–L systems in two sizes of standard tanks with Rushton turbine impellers. Though the material properties (σ from 0.008 to 0.052, and $\Delta\rho$ in the range from ±20 to ±250 N m^{-1}) were significantly different from those for G–L systems, the whole volume of the dispersed phase was broken into drops at $Nc^{*}_{\mathrm{ED}} = 6.8 \pm 1.5$, i.e. close to the value Nc_{EA} observed for the efficient gas–liquid dispersion.

Results of several other authors have been recently considered by Skelland and Kanel[16] who recommended a correlation, which can be interpreted for tanks with turbine impellers $d/D = 1/3$ in terms of our criteria as $Nc^{*}_{\mathrm{ED}} = 8\ (H_1/D)\ Bs^{0.29}\ Rp^{-0.08}$. These results indicate that the mechanism of drop formation on a liquid–liquid interface is similar to the mechanism of bubble capture at the liquid level.

CONCLUSIONS

1. A simple theoretical model of the bubble formation has been developed for predicting the effect of liquid properties. According to this model, the gas entrapment from the surface of agitated liquid is controlled by the value of the dimensionless recirculation number $Nc \equiv Nd\ [\rho/(\sigma g)]^{1/4}$.

2. The data on the critical impeller speed at the first threshold of surface aeration (observed visually), and the speed corresponding to the beginning of the efficient aeration (assigned to the point of a 10% decrease in the impeller power), have been analyzed. It was found that both the Nc_{JA} and Nc_{EA} for aeration are nearly independent of the impeller size and of the liquid viscosity which proves validity of the model suggested.

3. The threshold values Nc_{JA} and Nc_{EA} for Rushton turbine impellers were determined also from various literature data. For low-viscosity liquids agitated in the standard tank configuration, the first aeration threshold corresponds to the value $Nc_{JA} \approx 3.5$, and the impeller flooding due to entrapped gas becomes significant for $Nc_{EA} > 6$.

4. Whenever the scale effect was studied, minor increase of the threshold aeration numbers with increase in the equipment size (increasing *Bs*) was apparent. Similarly as for the four-blade impeller, the effect of increasing viscosity (decreasing *Rp*) was nearly negligible.

5. If we compare different configurations of agitated vessels, it is apparent that the surface aeration emerges at lower values *Nc* when impellers with higher downstream pumping capacity are applied and when the impellers are placed closer to the liquid level.

6. In unbaffled vessels, there may prevail another mechanism of the first bubble formation if the central vortex enters the impeller region. However, even in this case, just the recirculation of entrapped bubbles can control the power input decrease, which explains why no striking difference was found in the critical values Nc_{EA} either for baffled, or asymmetric and unbaffled cylindrical vessels.

7. The modified recirculation number Nc^*, taking into account the density of the dispersed phase, can characterize also the threshold conditions for dispersion of liquids, and its threshold value is nearly identical with that one for gas–liquid systems.

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SYMBOLS

b	baffle width, m
d	impeller diameter, m
d_H	hub diameter, m
d_S	shaft diameter, m
D	tank diameter, m
g	gravity acceleration, m s^{-2}
H	height of level, m
H_1	impeller to level distance, m
H_2	impeller to bottom clearance, m
L	Laplace's characteristic length, $L \equiv (\sigma/(\Delta\rho g))^{1/2}$, m
N	impeller speed, s^{-1}
n	number of baffles
P	impeller power, W
U_C	characteristic bubble or drop velocity, $U_C \equiv (\sigma g|\Delta\rho|/\rho^2)^{1/4}$, m s^{-1}
U_D	characteristic liquid circulation velocity, m s^{-1}
U_P	sedimentation velocity of particles, m s^{-1}
w	impeller blade width, m

x_B	baffle thickness, m
x_L	impeller blade thickness, m
μ	liquid viscosity, Pa s
ρ	liquid density, kg m^{-3}
$\Delta\rho$	density difference, kg m^{-3}
σ	surface (interface) tension, N m^{-1}

Dimensionless numbers

Bs	scale parameter, $Bs \equiv d(\rho g/\sigma)^{1/2}$
Fr	Froude number, $Fr \equiv N^2 d/g$
Nc	recirculation number for bubbles, $Nc \equiv Nd(\rho/(\sigma g))^{1/4}$
Nc^*	generalized recirculation number, $Nc^* \equiv Nd(\rho^2/(\|\Delta\rho\|/\sigma g))1/4$
Po	power number, $Po \equiv P/(\rho N^3 d^5)$
Re	Reynolds number, $Re \equiv Nd^2\rho/\mu$
Rp	viscosity parameter, $Rp \equiv (\sigma^3\rho/g)^{1/4}/\mu$
We	Weber number, $We \equiv N^2 d^3\rho/\sigma$

Subscripts

JA	just aerated state
EA	efficient aeration state
ED	efficient drop dispersion state
P	particle (bubble or drop)

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