AERATION OF LIQUIDS IN A VESSEL EQUIPPED WITH MULTISTAGE IMPELLERS*

Václav MACHOŇ and Jiří VLČEK

Prague Institute of Chemical Technology,
Department of Chemical Engineering, 166 28 Prague 6

Received January 21st, 1985

The paper deals with the influence of the number of impellers and the mode of aeration on the mechanical power input in a stirred gas–liquid dispersion using two impellers on the same shaft. Gas has been supplied either under the lower impeller or under both impellers. The power input was measured in the water–air system. A six-blade turbine impeller of the Rushton type and/or impellers with six inclined blades (with downward or upward pumping effect) were used. Experimental results have been obtained for a single impeller in a tank where the depth of liquid was equal to the tank diameter, and for different combinations of two impellers located on a single shaft where the distance between the impellers was equal to the tank diameter and the liquid depth was twice this diameter. It has been found that the power input data for the two-impeller system of two turbines can be correlated adequately by a simple equation. An estimate was made of the amount of gas supplied below the lower impeller which was transported into the region of the upper impeller.

Aeration of liquids in mechanically agitated contactors is often used in chemical and biochemical processes, in flotation and elsewhere. One of the basic quantities characterizing the mixed batch is the power input. Knowledge of the dependence of the power input on operating conditions gives useful information on the mechanism of the process. The most valuable information for industrial purposes is an optimal utilization of the energy supplied. Power inputs to industrial equipment are sometimes fairly high and energy savings are desirable inasmuch as some of the processes (*e.g.* fermentation) last long.

The investigation described in this paper is devoted to the systems with geometrical configuration commonly used in large scale gas–liquid contactors (fermentors) *i.e.* systems with mixing equipment consisting of multiple impellers on the same shaft. When the charge is not distinctly non-Newtonian or highly viscous, the distance of impellers is approximately equal to the tank diameter and the liquid depth is two to three times greater than is the tank diameter. The aim of this work was to compare the power inputs of a single impeller and of a two-stage impeller for two impeller types and for various modes of aeration. Gas introduction into the contactor during

* Part LXV in the series Studies on Mixing; Part LXIV: This Journal *50*, 2545 (1985).

mixing causes a decreas of the power input. This decrease can reach up to 70% of the value of power input in the absence of aeration. Aerated systems are sometimes characterized by the ratio N_g/N_0, where N_g and N_0 are the power input of the aerated and the non-aerated system, respectively[1], under otherwise identical conditions. The usual approach is to correlate the relative power input N_g/N_0 with the gas flow number Kp:

$$N_g/N_0 = f(\mathrm{Kp}) = f(\dot{V}/nd^3)\,. \tag{1}$$

Kudrna[2] has demonstrated for radial stirrers that the relation (*1*) is well suited for the correlation of power input data in aerated systems, and derived the equation:

$$N_g/N_0 = 1 - \frac{1}{K}\left[1 - \left(1 + \frac{K\mathrm{Kp}}{q\sqrt{(N_g/N_0)}}\right)^{-1}\right]. \tag{2}$$

By introducting new variables

$$Y = (1 - N_g/N_0)^{-1} \quad \text{and} \quad X = \sqrt{(N_g/N_0)}/\mathrm{Kp}$$

the equation (*2*) is converted to the form

$$Y = K + qX\,. \tag{3}$$

Equation (*3*) holds for $\mathrm{Kp} > 10^{-3}$ under conditions where the stirrer is not flooded[2]. The values of the constants K and q are dependent on geometrical configuration. The validity of Eq. (*3*) was verified in gas–liquid contactors of up to 100 m^3 capacity[3].

Only a few papers contain data on power inputs in contactors with multiple impellers[4–6], indicating that the power input of a multiple impeller is approximately equal to the sum of the power inputs of individual impellers as long as the spacing of the impellers is greater than 1·5 times the impeller diameter. Hicks and Gates[7] proposed the following equation for computing the power input of an aerated multiple stirrer:

$$(N_g/N_0)_m = 1 - \varepsilon_H\,, \quad m > 1\,, \tag{4}$$

where ε_H is the gas hold-up and m is the number of impellers. Nienow and Lilly[8] presented equations for the power input of the upper and the lower impellers in an aerated system with two impellers, of the form

$$(N_g)_{m=2} = N_{01}(1 - \varepsilon_H)$$

for a singly acting upper impeller, and

$$(N_g)_{m=1} = N_{01}\,(N_g/N_0)_1$$

for a singly acting lower impeller. By combining these two equations they obtained the following equation for the simultaneous action of both impellers:

$$(N_g/N_{01})_2 = 0{\cdot}5[(N_g/N_0)_1 + (1 - \varepsilon_H)]\,. \tag{5}$$

Our experimental work was aimed at verifying the validity of Eq. (3) for the system with more impellers on the same shaft, with the distances between them equal to the vessel diameter. Furthermore, we have compared our data with values resulting from the equation by Nienow and Lilly[8] and have checked the relation between the power inputs of individual stirrers and the power input of a multistage mixer in absence of aeration. Finally we have attempted to estimate what part of the gas introduced under the lower stirrer is redispersed by the upper one.

EXPERIMENTAL

The power input was measured in a cylindrical tank made of organic glase having an interior diameter $D = 0{\cdot}29$ m and a height of 0·7 m (Fig. 1). The tank was fitted with four radial baffles 0·7 m high and 0·03 m wide. The bottom of the tank was fixed in a cylindrical vessel of 0·41 m in diameter. This vessel, suspended in two oil bearings, was free to rotate about its vertical axis. The shaft with stirrers was located in the tank axis and was conected at the top end to the driving system composed of the motor, gear, and stirrer frequency controller. This system, including the shaft with impellers, was vertically adjustable. The gas was supplied to the vessel by pairs of sparging rings located beneath each stirrer. The diameter of the sparging rings was 0·067 m and each ring had six orifices 0·002 m in diameter uniformly spaced atop the ring. The torque was measured by balancing the rotational movement of the vessel, as described in detail by Procházka

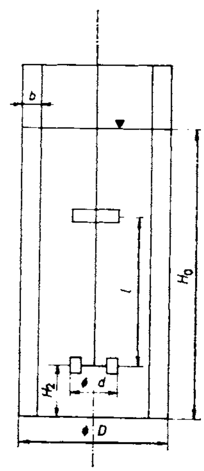

FIG. 1
Diagram of the tank

and Landau[9]. Power input was measured in an air–water dispersion. Two impeller types were used: a six blade Rushton turbine (type A) and a turbine mixer with six inclined blades pumping either downward (B) or upward (B′). The diameter of all impellers was 0·1 m, approximately one third of the tank diameter D. The liquid height was equal to the tank diameter $H_0 = D = 0{\cdot}29$ m in experiments with one impeller, and twice as much $H_0 = 2D = 0{\cdot}58$ m in experiments where two impellers were used. The lower impeller was always located at a distance $H_2 = D/3$ above the bottom, and the distance between impellers in experiments involving two impellers was equal to the tank diameter $l = D = 0{\cdot}29$ m. A summary of the experimental configurations used is given in Table I. The stirrer frequencies were in the 250–500 rpm range and the air flow rates were varied from 2 to 60 litres per minute (one impller aerated) and/or from 2 to 30 litres per minute for each impeller (two impellers aerated). Experiments were performed at room temperature and the physical properties of water were taken at 19°C.

RESULTS AND DISCUSSION

The relative power inputs N_g/N_0 were calculated from experimental data for each configuration and plotted against the gas flow numbers Kp (Figs 2–10). The experimental data for the configurations 1, 2 and 3 were correlated by Eq. (*3*) by linear regression. The calculated values of the constants K, q and correlation coefficient r are in Table II. The calculated curves are plotted in Figs 2–4.

We tried to apply Eq. (*3*) to systems with inclined blades stirrers (axial flow pattern). It is clear from Figs 5 and 8 for configurations 4 and 7, that the relative power input data cannot be fitted by Eq. (*3*). In accordance with this finding it is seen that the relative power input data for configurations with two impellers (of which one has inclined blades, *i.e.*, configurations 5, 6, 8 and 9) cannot be fitted by Eq. (*3*).

Table I

Experimental configurations and measured power numbers without aeration (turbulent region, $Re_M > 10^4$)

Configuration number	Impeller		Eu_M
	lower	upper	
1	A	—	4·78
2	A	A	9·45
3	A	A	9·45
4	B	—	1·43
5	A	B	6·17
6	A	B	6·17
7	B′	—	1·42
8	A	B′	6·13
9	A	B′	6·13

Let us now describe the principle of the method used to estimate the amount of gas introduced under the lower stirrer which is redispersed by the upper stirrer. This redispersed gas is responsible for the decrease of power input of the upper impeller. To estimate the amount of redispersed gas it is necessary to know the dependence of the relative power input N_g/N_0 on the gas flow number Kp for the stirrer in question. This is why we were able to apply this procedure to the configurations 2 and 3, where the constants of Eq. (3) had been determined.

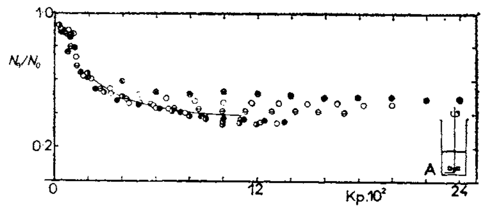

FIG. 2

Relative power input *vs* gas flow number for configuration 1; captions to Figs 2–10: ⊙ 250 min^{-1}, ◑ 350 min^{-1}, ○ 450 min^{-1}, ◒ 300 min^{-1}, ● 400 min^{-1}, ◐ 500 min^{-1}

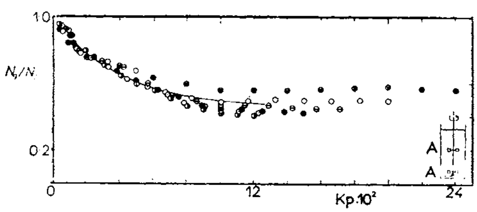

FIG. 3

Relative power input *vs* gas flow number for configuration 2

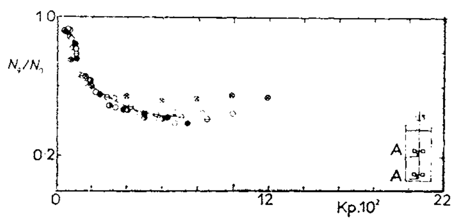

FIG. 4

Relative power input *vs* gas flow number for configuration 3

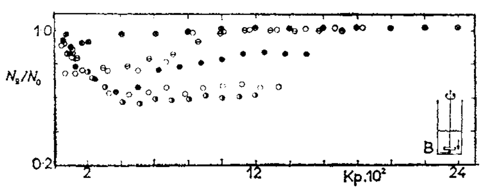

FIG. 5

Relative power input *vs* gas flow number for configuration 4

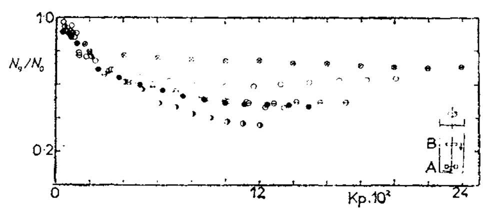

FIG. 6

Relative power input *vs* gas flow number for configuration 5

A model is proposed for the configuration 2 assuming that the system is formed by

a) one turbine without aeration (upper turbine of configuration 2)

b) one turbine with aeration (lower turbine of configuration 2).

This situation is shown schematically in Fig. 11. We assumed the power input of the lower turbine with aeration of configuration 2 to be equal to that of one turbine with aeration. The power input N_2 and the value of N_{g1} can be compared at the same

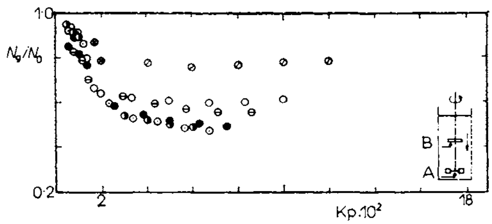

FIG. 7

Relative power input *vs* gas flow number for configuration 6

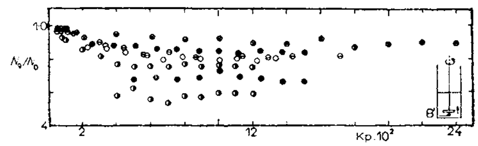

FIG. 8

Relative power input *vs* gas flow number for configuration 7

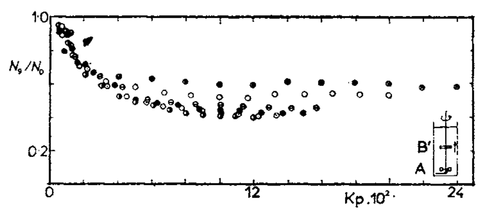

FIG. 9

Relative power input *vs* gas flow number for configuration 8

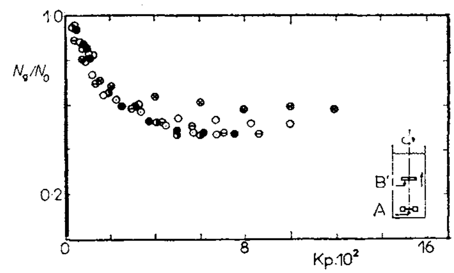

FIG. 10

Relative power input *vs* gas flow number for configuration 9

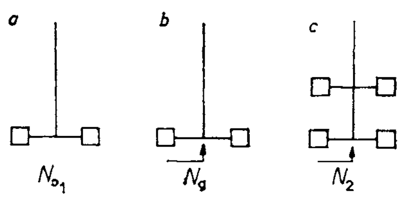

FIG. 11

Splitting of configuration 2: *a*) configuration 1 without aeration (power input N_{01}); *b*) configuration 1 with aeration (power input N_{g1}); *c*) configuration 2 (measured power input N_2)

gas flow rate and rpm. The difference of these two quantities is the power input of the upper turbine, always smaller than the power input of the single turbine without aeration N_{01}. This decrease of power input is caused by the gas being transfered from the lower turbine region to that of the upper turbine; it is a function of the gas flow number Kp, of the form (*1*):

$$(N_2 - N_{g1})/N_{01} = f(\mathrm{Kp}) . \qquad (6)$$

Here it is possible to use Eq. (*3*) with constants given in Table II which represents the line drawn trough Fig. 2. Using Eq. (*3*) or Fig. 2 the relative power input value fromf Eq. (*6*) can be used to determine the value of Kp and thus to estimate the fictious gas flow rate in the region of the upper stirrer, $\dot{V}_f$. The ratios of this flow rate and the overall flow rate for every experimental conditions are approximately constant. The mean of this ratios is 0·291 with standard deviation 0·070. We concluded that with configuration 2, some 30% of the gas were transported to the region of the upper stirrer causing a power input reduction.

The same procedure was used to estimate the amount of gas sparged below the lower stirrer and reaching the region of the upper stirrer in an arrangement where the gas was supplied beneath both stirrers (configuration 3). Provided that N_3 is the measured power input for this case, the difference $2N_{g1} - N_3$ is the decrease of power input caused by redispersed gas. In a situation where redispersed gas alone would approach the upper stirrer, the power input of this stirrer would be $N_{01} - (2N_{g1} - N_3)$. Relative power inputs can be used to calculate redispersed gas flow rates using the relation

$$[N_{01} - (2N_{g1} - N_3)]/N_{01} = 1 - [(2N_{g1} - N_3)/N_{01})] = f(\mathrm{Kp}) \qquad (7)$$

in a way similar to that which was used for configuration 2. The mean of ratios of fictious gas flow rate is in this case 0·098 with standard deviation 0·034.

It is concluded that when both impellers are aerated, the upper impeller will redisperse approximately 10% of the gas supplied under the lower impeller.

TABLE II

Constants K, q and correlation coefficient r of Eq. (*3*)

Configuration	K	q	r
1	1·48	0·0302	0·922
2	1·48	0·0731	0·956
3	1·51	0·0260	0·887

The average power number values for all the configurations in absence of aeration are listed in Table I. Data on power inputs of one impeller and two impellers (configurations 2 and 3) without aeration show that the power input of a system with more impellers (with the distance between them equal to the tank diameter) is equal to the sum of the power inputs of single impellers (Table I).

A comparison of our experimental results with values from Eq. (*5*) introduced by Nienow and Lilly[8] is given in Table III. Equation (*5*) is not suitable for our geometrical arrangement where $H_0 = 2D$. We account for it by the fact that the equation was verified by the authors[8] in a vessel, where H_0 was equal to D and where the distance between impellers was equal to their diameter, *i.e.*, for the configuration which is recommended for mixing of viscous or non-Newtonian liquids.

Interesting results were obtained for a single impeller with inclined blades and downward pumping effect with gas supply-configuration 4 (Fig. 5). The values of the ratio N_g/N_0 decrease at low Kp (low gas flow rates) and then, with increasing gas flow rate, they increase up to $N_g/N_0 = 1$. This dependence is more definite at low rpm (250, 300, 250 min^{-1}). This phenomenon can be explained by the fact that the stirrer pumps the liquid downwards and thus pushes the gas dispersion out, so that the gas bubbles rise along the vessel walls. Hence, no gas reaches the region of the impeller. At higher rpm the impeller sucks from above the gas rising along the wall, which causes a decrease of the power input to some constant value.

TABLE III

Comparison of our results with Eq. (*5*)

Stirrer frequency min^{-1}	$\dot{V}$ $l\ min^{-1}$	ε_H[a]	$(N_g/N_o)_1$ measured	$(N_g/N_o)_2$ measured	$(N_g/N_o)_2$ calculated from Eq. (*5*)
300	10	0·014	0·549	0·730	0·767
300	15	0·020	0·512	0·688	0·746
300	25	0·025	0·477	0·509	0·742
350	30	0·027	0·428	0·535	0·700
350	60	0·040	0·420	0·449	0·690
400	10	0·021	0·550	0·726	0·764
400	15	0·024	0·486	0·680	0·730
400	25	0·031	0·442	0·573	0·705
450	60	0·050	0·345	0·410	0·647
500	10	0·029	0·645	0·801	0·807
500	15	0·029	0·523	0·715	0·747
500	25	0·041	0·478	0·600	0·719

[a] Values of ε_H were taken from Balek[10].

When an impeller with inclined blades and downward pumping effect is combined with a turbine impeller (Figs 6 and 7) the value of N_g/N_0 decreases with increasing gas flow rate. This is due to the dominant influence of the turbine impeller in both these configurations.

For the system with one upward-pumping impeller with inclined blades (type B′) the decrease of power input is due to a small amount of gas present in impeller region at low rpm. However, at higher rpm this decrease is slight (Fig. 8). This can be explained by this impeller sucking the gas from below, thus dispersing only a small portion of this gas. On raising the rpm, the amount of gas that will be dispersed is increased.

The comparison of results obtained with configurations 5 and 6 (Figs 6 and 7) in contrast to those with configurations 8 and 9 (Figs 9, 10) revealed that in the case where the upper stirrer has inclined blades and pumps downwards (configurations 5 and 6) the system is flooded by the gas at lower gas flow rate numbers Kp. This means that the N_g/N_0 ratio is independent of Kp. This finding is in agreement with the analysis of results for configuration 4, *i.e.*, one impeller with inclined blades pumping downwards. We conclude that the axial impeller with downward pumping effect is not suitable for aerated systems, even in combination with other impellers.

CONCLUSIONS

1) It has been found that Eq. (*3*) is adequate for correlating the power input data for a two-impeller system incorporating two turbines and various modes of aeration *2*) In a configuration, where two turbine impellers are employed and the gas enters the vessel below the lower impeller, approximately 30% of the gas are transported to the region of the upper impeller. *3*) When the gas is supplied below both impellers of a two-stage turbine impeller, the upper impeller redisperses approximately 10% of the gas introduced below the lower impeller. This is not true when the impeller is flooded. *4*) The power input to non-aerated charges of all configurations with two impellers is equal to the sum of the power inputs of single impellers. *5*) A single impeller with downward pumping effect (B) pushes the incoming gas out of the impeller at low rpm and, thus, no gas is dispersed. The power input is not reduced by the presence of gas. At higher rpm, some of the gas rising along the wall is sucked by the impeller from above, which causes a small decrease in power input. *6*) A downward-pumping impeller with inclined blades combined with a turbine in multistage configurations is not recommended for aerated systems.

LIST OF SYMBOLS

b	baffle width,	[L]
D	tank diameter,	[L]
d	stirrer diameter,	[L]

H_0	surface level elevation in the tank at rest,	[L]
H_2	clearence of impeller above the base,	[L]
K	constant in Eq. (*3*), dimensionless	
l	distance between stirrers,	[L]
m	number of impellers, dimensionless	
N	power input,	$[L^2MT^{-3}]$
N_0	power input without aeration,	$[L^2MT^{-3}]$
N_g	power input with aeration,	$[L^2MT^{-3}]$
n	stirrer frequency,	$[T^{-1}]$
q	constant in Eq. (*3*), dimensionless	
r	correlation coefficient, dimensionless	
$\dot{V}$	gas flow rate,	$[^3T^{-1}]$
$\dot{V}_f$	fictitious gas flow rate,	$[L^3T^{-1}]$
X	variable in Eq. (*3*), dimensionless	
Y	variable in Eq. (*3*), dimensionless	
ε_H	gas hold-up, dimensionless	
η	liquid viscosity	$[ML^{-1}T^{-1}]$
ϱ	liquid density	$[ML^{-3}]$
Eu_M	Power (Euler) number for mixing, $N/n^3d^5\varrho$, dimensionless	
Kp	gas flow number, $\dot{V}/(nd^3)$, dimensionless	
Re_M	Reynolds number for mixing, $nd^2\varrho/\eta$, dimensionless	

REFERENCES

1. Warmoeskerken M. M. C. G., Smith J. M.: Proc. 4. European Conference on Mixing, P. 237, Netherland, April 1982.
2. Kudrna V.: *Thesis*. Prague Institut of Chemical Technology, Prague 1965.
3. Vlček J., Fořt I., Kudrna V., Hejl V., Mlčoch A.: Paper presented in 7-th Int. CHISA Congress, Prague, September 1981.
4. Bates R. L., Fondy P. L., Corpstein R. P.: Ind. Eng. Chem. *2*, 310 (1963).
5. Takeda K., Hishino T., Taguchi F.: Kagaku Kogaku *32*, 376 (1968).
6. Richards J. W.: Brit. Chem. Eng. *8*, 158 (1963).
7. Hicks R. W., Gates L. E.: Chem. Eng. *19*, 141 (1976).
8. Nienow A. W., Lilly M. D.: Biotechnol. Bioeng. *21*, 2341 (1979).
9. Procházka J., Landau J.: This Journal, *28*, 1103 (1963).
10. Balek F.: *Thesis*. Prague Institute of Chemical Technology, Prague 1979.

Translated by the author (V. M.)