Increasing Gas-Liquid Mass Transfer in Stirred Power Law Fluids by Using a New Energy-Saving Impeller

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The gas-liquid mass transfer performance of a stirred vessel equipped with a novel impeller, has been studied. The device is presented as means to increase gas-liquid mass transfer rate in stirred non-Newtonian media of fermentation vessels. The impeller is of the fluid foil type that is suitable for power law fluids. Mass transfer rates for power law liquids are determined by measuring K_La in model pseudoplastic CMC and xanthan gum solutions at moderate shear. The effects of geometry, gas flow rate, rheology, and impeller speed are illustrated. The results are compared with similar data reported for the disc-style flat blade Rushton (RT) turbine, used conventionally in industrial vessels. The mass transfer coefficient is correlated with gas linear velocity and specific mixing power. An equation for K_La is proposed. In comparison with the conventional case, significant energy saving is demonstrated.

Key words:
Mass transfer; stirred vessel; fluid foil impeller; pseudoplastic media

Introduction

Chemical and biochemical production technology is largely based on two-phase gas-liquid systems with increased viscosity and complex-rheology. With regard to their diversity, such systems require good mixing for homogenization, phase dispersion and enhancement of mass transfer across the interfaces. Because of the high viscosity and complex flow conditions, mixing in such systems is carried out often by impeller-induced agitation. However, it is highly energy consuming. In order to reduce power, while maintaining high performance, fluid foil impellers are employed.[1] In addition to the complex design[2-5] of the blades, these impellers have also high solidity ratios, e.g. 0.9 to 1.2. Due to their specific shape, they generally save power.

Our recent practice has led us to a new blade shape (termed Narcissus, abbreviated NS) that saves considerable power.[6, 7] This specific shape has been found[8] suitable for processing of non-Newtonian fluids, as it ensures low degree of drag-reduction generally associated with such systems.[9] On the other hand, the gas hold-up in pseudoplastic dispersions generated by this impeller, is relatively high.[10] Consequently, enhancement of mass transfer has been expected.

In this paper, the mass transfer of the stirred system involving the new device is considered.

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Experimental

Equipment

The equipment employed (Fig.1) consisted of stirred vessel 1 equipped with impeller 2, gas supply lines 3, and measurement units 4 and 5. A baffled stirred vessel of standard geometry, i.e. D/D_v = 0,33, H/D_v = 1 and h/D = 1, with diameter D_v = 0,4 m, was used. Its liquid volume was 50 liters.

Two types of impellers were used (Fig. 2): the specific NS turbine and the conventional Rushton (RT) flat-blade disc style turbine. The NS-turbine is shown schematically in Fig. 2b. It contains[7] of a supporting disc with attached even number of con-

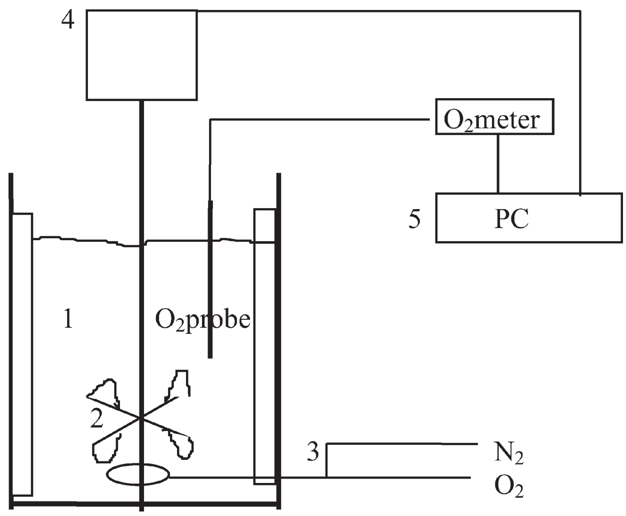
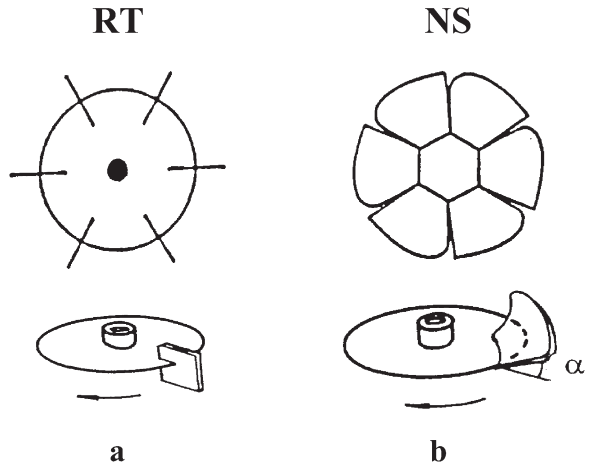


Fig. 1 – *Experimental set-up*



F i g . 2 – *Impeller schematics: (**a**) RT (**b**) NS*

cave, equal-surface blades. Each pair of neighbour blades is positioned symmetrically over and under the supporting disc plane. The blades are positioned in a way as to conclude acute angle α with the supporting disc plane. The angle and blade shape can be selected in a way as to ensure changes of, both, power consumption and gas dispersion capacity.

In this paper, the mass transfer properties of a wide-blade version with solidity ratio 0.9 suitable for transitional mixing, are presented. Two versions of NS with different blade angle α, namely, 30° and 60°, were tested. The RT impeller has been used as comparative basis.

The gas supply lines contained gas cylinder for nitrogen, air compressor, flow rate meter, control valves and gas sparger. The gas sparger was a tube with nine holes, each one of i.d. 0.8 mm. The gas was introduced through the holes into the liquid bed under the impeller at a distance equal to half of the impeller off-bottom clearance.

Model fluids

Runs with aqueous solutions of carboxymethylcellulose (CMC) and xanthan gum (XG), were accomplished. CMC was used as model of a weak pseudoplastic liquid, i.e. $n > 0.6$, and XG was used as a strong pseudoplastic one, i.e. $n > 0.5$.

Table 1 contains the viscometric parameters of the model liquid employed. For the shear stress τ

T a b l e 1 – *Viscometric Data and Power-Law Quantities for the Polymer Solutions*

Fluid System	Fraction w/%	τ* Pa	μ_a* mPa.s	K Pa.s^n	n
CMC	2	1.94	16.0	0.086	0.65
Xanthan gum	0.5	6.84	56.4	2.27	0.23

* Valid for γ = 121 s^{-1} at n_s = 15 rps, 20 °C

and the apparent viscosity μ_a in the Table, power law was assumed, as follows: $\tau = K\,\gamma^n$ and $\mu_a = K\,\gamma^{n-1}$, where $\gamma = k\ n_s$ stands for shear rate. The Metzner constant k required in this equation has been determined elsewhere.[11] It has been found to be $k = 8.1$ close to the value reported for axial flow double-pitch marine propellers.[12]

Measurement technique

The mass transfer rates were determined by the dynamic measurement technique. The studies involved preliminary tests of the probe response in gas phase to unit step change to confirm linearity of the measurement probe characteristic. The probe response in these experiments has been compared with the computed model response corresponding to the one-layer diffusion model of *Lee* and *Tsao.*[13] This way the probe response time was determined to be 3 s in water. To measure K_La, the probe response in the liquid phase of the gas-liquid dispersion to a step change in gas concentration was followed. In this case, the conventional procedure of experimental analysis has been fulfilled: first, the dissolved oxygen has been removed by nitrogen sparging, then, a step change of gas concentration has been introduced by a sharp increase of oxygen flow rate using a pair of alternating magnetic valves. The dynamic probe response in the liquid phase

$$\Psi = (R_t - R_0) / (R_s - R_0) \qquad (1)$$

was evaluated by the MM (liquid and gas perfectly mixed) model[14]. In this relationship, R indicates probe readings at steady state (R_s), at $t = 0$ (R_0), and at time t (R_t). K_La was determined as the slope of a semi-logarithmic plot ln $(1 - \Psi)$ vs. time. Details of the specific analysis of the probe response are given elsewhere.[15]

Referring to Nocentini model analysis,[14] model selection has low impact for interpretation of experimental data in small-scale low-turbulence gas-liquid contactors. According to this analysis, model MM produces less than 10 % error, provided that $K_La \cdot \varepsilon_G \cdot H/v_G < 0.1$. The validity of this inequality for this study is apparent from the experimental data below. Nevertheless, in advance to our main studies in power law liquids, we checked the performance of the above technique in the case of mass transfer and mixing with a Rushton (RT) turbine in water, for which system data can be found in the literature. Our data for the system have been compared with reference data,[16] e.g. the solid line in Fig. 3. Two gas superficial velocities and nine impeller speeds have been involved in this experiment. The compatibility of the measurement tech-

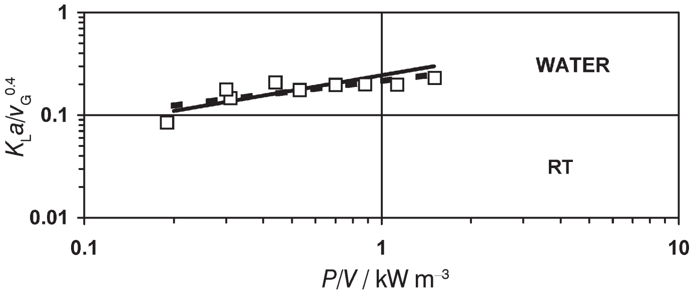


Fig. 3 – *Comparison of K_La-values obtained in this study (the experimental. points) with reference values[16] (the solid line) for the important range (Rushton turbine)*

nique has been confirmed for the important range of specific power 0.5 to 1.5 kWm^{-3}.

During the experimental runs, the torque and the impeller revolutions, were controlled. Power was measured currently by a telemetrical system Electroinvent^R. Viscosity and the flow curves were measured by a Haake rotational viscosimeter (Rheotest 2). On the other hand, gas hold-up was measured locally by a conductivity probe and totally by the liquid displacement method.

Results and Discussion

Initially, in order to determine the effect of different physical parameters, such as impeller geometry, gas flow rate and power law coefficient, the variation of K_La with impeller speed at various conditions, has been studied. Based on the specific power input, some of these results were compared further with similar data measured for the Rushton turbine. Finally, a correlation for K_La has been proposed.

Mass transfer rates versus impeller speed

The effect of blade edge angle

The effect of blade angle α is illustrated in Fig. 4. Mass transfer has been studied for the two impellers in two extreme cases, i.e. in water and in a power law xanthan gum solution. In both cases, the relative gas flow rate was 0.0004 m^3 s^{-1}. One can see that in the power law cases, the small angle is to be preferred. In water, the difference between the two cases is not large. This result coincides with the general concept of keeping low angles for hydrofoils (see *Tatterson*[17]). Consequently, the further studies were based on the 30-degree version.

Effect of gas flow rate and rheology

As seen in Fig. 5, the effect of gas velocity is minor. And yet, one could see the general trend of higher K_La at a higher gas flow rate, due to the par-

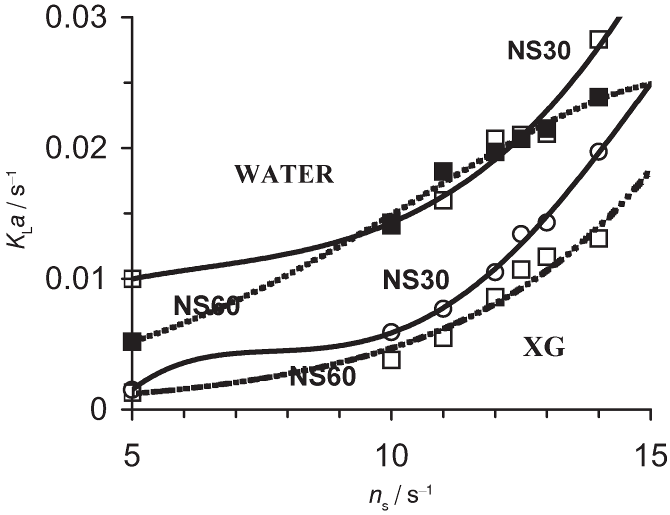


Fig. 4 – *K_La-versus n_s for the NS-impeller in a 30 degree and 60 degree version*

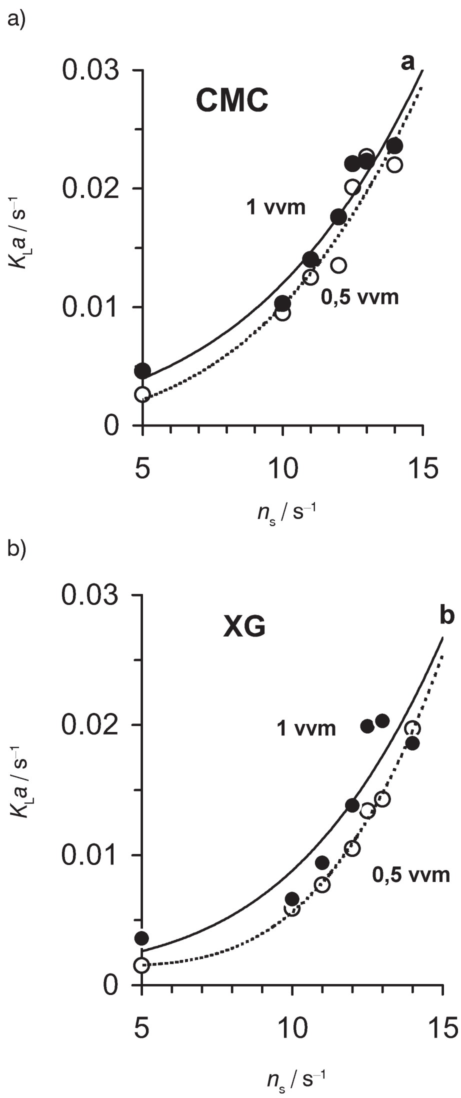


Fig. 5 – *K_La -versus n_s for the NS-impeller in weak (**a**) and strong (**b**) pseudoplastic dispersions at 0.0004 and 0.0008 m^3 s^{-1}, i.e. at v_G ~ 0.33 cm s^{-1} and v_G ~ 0.66 cm s^{-1}, respectively*

allel rise of gas hold-up in the gas dispersion equipment.

The results for the weak and the strong pseudoplastic solutions are rather different. As seen in Fig. 6, the effect of the flow index, n, which is 1 for water, 0.6 for CMC and 0.2 for the XG dispersion, is well pronounced. A systematic decrease of K_La is observed.

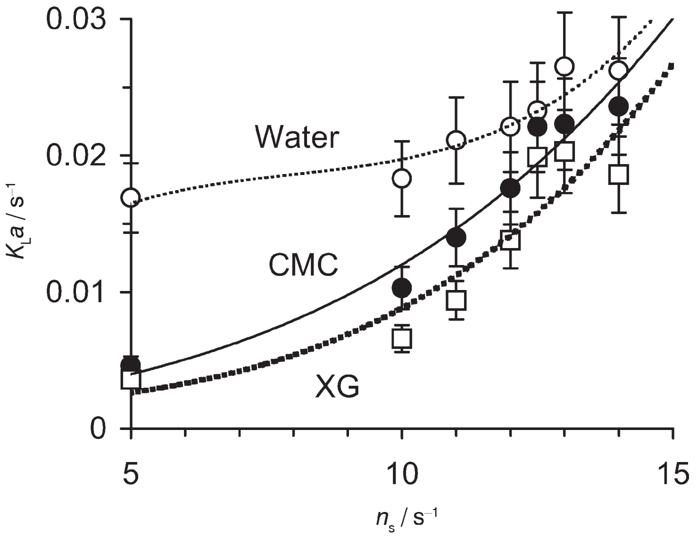


Fig. 6 – *K_La vs. n_s obtained for different rheology liquids: (○) water, (●) w = 2 % CMC solution, (□) 0.5 % XG solution*

In general, introducing polymer into a liquid leads to turbulence suppression plus intact interfacial area that increases the mass transfer resistance. On the other hand, the reduction of power draw, due to polymer presence, lowers the gas hold-up and decreases the interfacial area. Consequently, a drop in the specific mass transfer rate occurs. However, it is essential to compare the rate of decrease to the performance of other well-known impellers, which is illustrated further.

Comparison with the disc-style turbine

The K_La - values determined for the NS turbine are compared with similar data obtained in this study for the RT impeller at equal specific power (Fig. 7). Both weak and strong pseudoplastic fluids have been tested. In the figure, the gas flow rate corresponds to Q = 0.0004 m^3 s^{-1} for XG and to 0.0008 m^3 s^{-1} for CMC.

The plots in Fig. 7 show that the mass transfer coefficients determined for the NS impeller are generally higher. The result can be explained by the gas hold-up behaviour of the impeller. The gas hold-up data corresponding to the cases of Fig. 7 are compared in Fig. 8. One could observe large differences in gas hold-up in favour of the fluid-foil impeller,

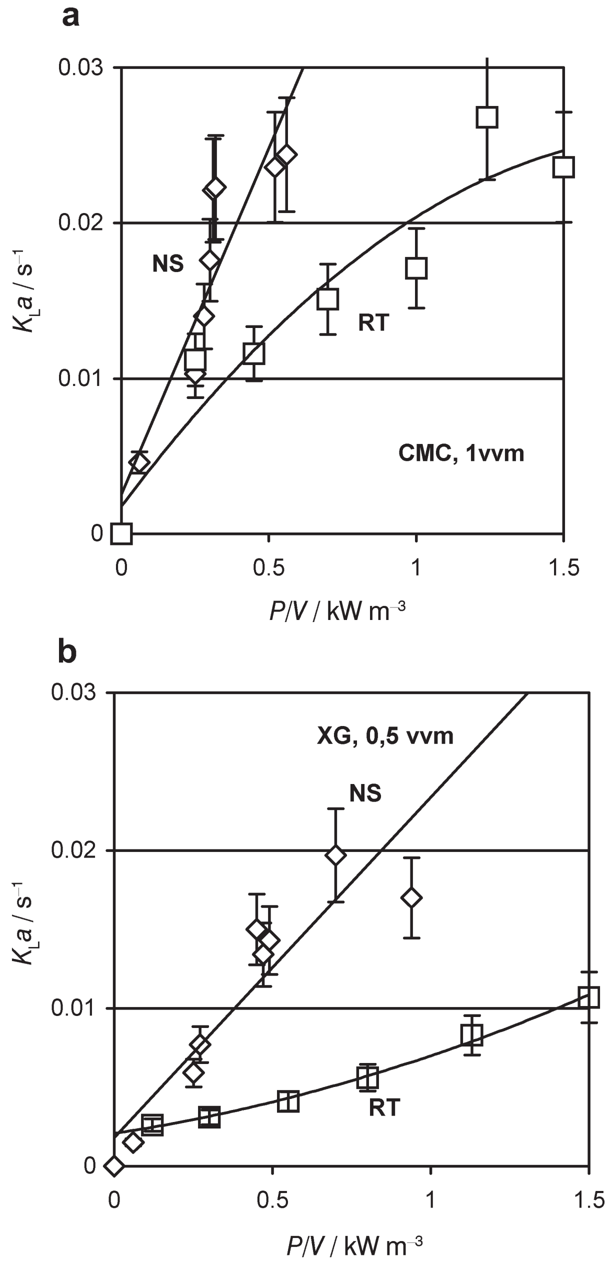


Fig. 7 – *Comparison of K_La-values obtained for NS- and RT-agitated vessels in weak (**a**) and strong (**b**) pseudoplastic dispersions*

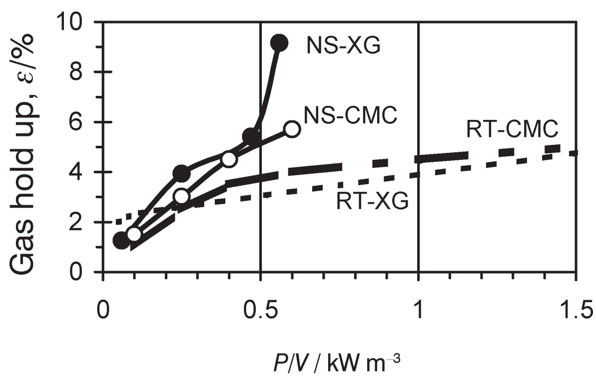


Fig. 8 – *Gas hold-up in the pseudoplastic solutions*

especially in xanthan gum solutions, where the specific power input exceeds 0.5 kW m^{-3}. This has been explained[10] by the uniformity of gas distribution generated by this impeller which helps to avoid cavity formation and increases the gas content around the impeller and in the bulk.

Correlation

The results were correlated with respect to the gas superficial velocity, v_G, and the specific power data, P/V, via equation (2):

$$K_La = A(P/V)^B\ v_G^C \qquad (2)$$

h = 0.4 was assumed by reference to numerous studies.[16] Constants A and B were determined from the logarithmic plots of the experimental data. The correlations for the NS turbine for CMC and XG are plotted in Fig. 9. One can see that the two lines, namely, the line corresponding to CMC and the one describing xanthan gum data, almost coincide with each other.

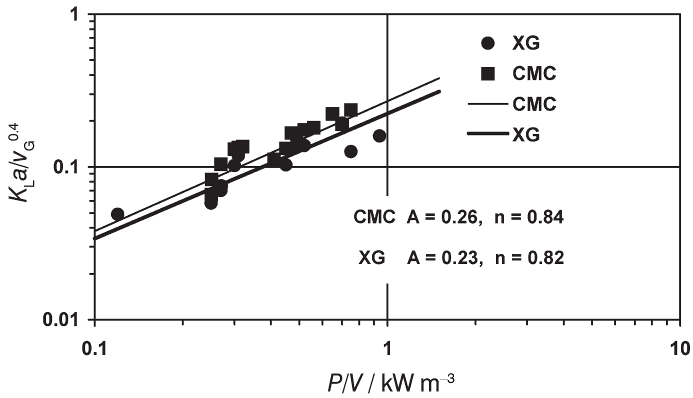


Fig. 9 – *Correlation of gas-liquid mass transfer in power law liquids for the NS impeller*

The following equations are proposed:
for weak pseudoplastic:

$$K_La = 0.26\ (P/V)^{0.84}\ v_G^{0.4}, \qquad (3)$$

for strong pseudoplastic:

$$K_La = 0.23\ (P/V)^{0.82}\ v_G^{\ 0.4} \qquad (4)$$

They are valid for

$$0.1 < P/V < 2 \text{ kW m}^{-3}$$

$$3.3\cdot10^{-3} \text{ m s}^{-1} < v_G < 6.6\cdot10^{-3} \text{ m s}^{-1}$$

$$0.01 < \mu < 0.1 \text{ Pa·s}$$

The corresponding ranges of Re, P_o and Fl are:[8] $1000 < Re < 25\cdot10^{-4}$; $0.5 < P_o < 1$; $0.01 < Fl < 0.04$.

From the relationships obtained one can see that the exponent at P/V is greater than exponent at v_G. Consequently, the significance of the power effect on mass transfer rate is great, i.e. B∼0.8. This result coincides with previous observations due to *Andrew*[18] and *Kawase* and *Moo-Young*[19]. The contemporary survey for mass transfer in non-Newtonian flow[12] puts forward the empirical correlation for K_La due to *Kawase* and *Moo-Young*[19] . This correlation includes a very wide range of power-law parameters. In this correlation, $K_La \sim (P/V)^{(9+4n)/10(1+n)}\ v_G^{0.5}$. Using the n-values of the CMC and XG solutions from this work, one finds exponents 0.7 and 0.8 at P/V for CMC and XG, respectively. These values are close to the exponents determined above.

Because the power law effect on gas-liquid mass transfer is included implicitly in the term of P/V, we believe that, apart from the importance of the input power for the mass transfer rate, the large exponent at P/V shows that the rheology effect upon K_La is high. However, here it has not been determined separately. On the other hand, the dependence of K_La on μ_a found, most often[19] is weak, e.g. $K_La \sim \mu_a^{-0.25}$.

Equations (3) and (4) can be used for interpolation within the range of 20 % relative error. Since the maximum difference of K_La obtained by these equations reaches 15 % comparable with the max deviation of experimental error of 20 %, the difference of parameters A in these equations could be assumed insignificant, so that only one of these equations is used for both fluids. However, using separate equation for CMC and XG could be justified in some ranges of K_La, where the experimental error is lower.

As estimated from equations (3) and (4), and Figs. 7a and 7b, the power per unit volume required by the NS impeller to reach a K_La value similar to the Rushton turbine, is lower. For example, in order to reach $K_La \sim 0.02\ s^{-1}$ in weak psedoplastic medium, RT requires 1 kW m^{-3}, while NS requires 0.4 kW m^{-3} (see Fig. 7a). On the other hand, to reach $K_La \sim 0.01\ s^{-1}$ in strong pseudoplastic fluid the values are 1.5 kW m^{-3} and 0.4 kW m^{-3} for the RT and NS, respectively (see Fig. 7b). Consequently, the same mass transfer rate is obtained by the fluid-foil impeller with a significant energy saving. This fact may look strange on the background of the general conclusion that equal power per unit volume and superficial gas velocity leads to the same K_La regardless of the impeller type[20]. However, this is true for developed turbulent flow conditions. In non-Newtonian flow and transient flow conditions corresponding to higher viscosity, a low power number agitator is driven at a higher speed to give the same specific power and thus gives higher K_La because of the lower apparent viscosity achieved. Regarding recent computational fluid dynamic (CFD) analyses of the NS impeller[21], there is one more reason for producing high gas hold-up and K_La in complex-rheology fluids by means of this impeller. In polymer presence, the NS turbine exhibits lower degree of drag reduction and flat power characteristics compared to the RT and power in Newtonian flow.

Conclusions

The study reveals the gas-liquid mass transfer properties in power law media of a hitherto unknown impeller configuration. It is confirmed, that using impellers with improved fluid-foil blades in stirred vessels, mass transfer could be increased up to 100 % compared to conventional bioreactors equipped with conventional turbines. The increase is believed to be due to the greater uniformity of gas hold-up and hindrance of the power drag reducing property of the impeller-liquid system caused by the specific fluid-foil blade shape NS. Compared to the conventional system, the NS turbine exhibits also significant energy saving.

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Symbols

h – impeller off-bottom clearance, m
D – impeller diameter, m
H – liquid height, m
K – consistency coefficient, Pa s^n
n – flow behaviour index
n_s – impeller speed, s^{-1}
K_La – volumetric mass transfer coefficient, s^{-1}
P – power, W
P/V – specific mixing power, W m^{-3}
D_v – vessel diameter, m
Q – volumetric flow rate, m^3 s^{-1}
v – superficial gas velocity, m s^{-1}
V – liquid volume, m^3
w – mass fraction, %

Greek letters

γ – shear rate, s^{-1}
ε – phase hold-up
ρ – density, kg m^{-3}
μ, μ_a – viscosity, apparent viscosity, Pa. s
τ – shear stress, Pa

Dimensionless numbers

Fl – flow number, $Q/n_s D^3$
Re – Reynolds number, $n_s D^2 \rho/\mu$
P_o – power number, $P/n_s^3 D^5 \rho$

Indices

G – gas phase
L – liquid liquid phase

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