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Volumetric mass transfer coefficient, power input and gas hold-up in viscous liquid in mechanically agitated fermenters. Measurements and scale-up

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ABSTRACT

Transport characteristics such as volumetric mass transfer coefficients, k_La, power input, P and gas hold-up, ε_G, are the key parameters in the design of mechanically agitated gas-liquid contactors. For their successful design, values of the key parameters can be estimated using empirical correlations. The goal of this work is to complete a complex study to investigate the behavior of k_La, P and ε_G in multiple-impeller vessels in non-coalescent viscous batch. We used the dynamic pressure method (DPM).

The experiments were conducted in multiple-impeller vessels of both laboratory and pilot-plant scale, which enabled the scale-up studies. Several impeller types with different diameters and their combinations on a common shaft were used in the vessel, under various impeller tip speeds and gassing rates. For all impeller combinations, the gassed and ungassed power consumption, gas hold-up and volumetric mass transfer coefficient were measured in viscous batch.

The measured transport characteristics were summarized into correlations. Several literature correlations were judged, using these extensive datasets. In addition to this, new correlation shapes were also established. The correlation given by and $\frac{P_g}{V_L} = K_1\left(\frac{P_u}{V_L}\right)^{K_2} \upsilon s^{K_3}$ gave fairly good prediction of the impeller power. The correlation of this shape can also be employed to calculate the power dissipated in the bottom and upper stages of the multiple-impeller vessel.

Correlation $\varepsilon_G = K_1\left(\frac{P_g}{V_L}\right)^{K_2} \upsilon s^{K_3}$, based on the theory of isotropic turbulence was shown to be reliable for various impeller types.

For non-coalescent viscous batch, it is worth using correlation based on power dissipation $k_La = K_1(P_{TOT})^{K_2}\upsilon_s^{K_3}$ This correlation shape can be used to predict transport characteristics in industrial-scale vessels under a wide range of operational conditions.

1. Introduction

Stirred tank reactors are frequently used for the intensification of mass transfer in gas-liquid systems. The main variable describing the intensity of mass transfer in stirred tank reactors is volumetric mass transfer coefficient k_La. These apparatuses are frequently used in chemical, food and biochemical industries as fermenters and as hydrogenation, oxidation or chlorination reactors. However wide the usage of such apparatuses is, their design is not based on chemical engineering data, but is still rather empirical.

For a long time, single-impeller systems were commonly used. These are frequently criticized for non-ideal distribution of shear stresses and power dissipation in the vessel. This phenomenon is highly problematic in fermentation processes, where shear sensitive living cells are used, and especially in the batches with higher viscosity. The next disadvantage of one-impeller systems is the non-ideal distribution of inlet gas into the whole volume of the batch. In the vicinity of the impeller, the shear stresses are high and the apparent viscosity is low. Thus a good mixing and high mass transfer is achieved. But not far away from the impeller blades, the shear stresses start to drop significantly and also the apparent viscosity increases. This leads to inferior mixing intensity and mass transfer. Due to the gradients in the apparent viscosity of liquid, the gas is sucked into the impeller area, which embarrasses gas distribution into the bulk of the liquid. The disadvantages of a

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Nomenclature

Ae	dimensionless aeration number ($= Q/fD^3$) [–]
a	gas-liquid interfacial area per unit liquid volume [$m^2\ m^{-3}$]
D	impeller diameter [m]
D_{blade}	impeller blade width [m]
D_i	diffusivity in layer i, $i = L$ [$m^2\ s^{-1}$]
D_L	diffusivity of gas in solution [$m^2\ s^{-1}$]
f	impeller frequency [s^{-1}]
Fr	dimensionless modified Froude number ($= f^2D^4/(gD_iV^{2/3})$) [–]
g	gravitational constant [$m\ s^{-2}$]
H	vessel height [m]
J	number of experiments [–]
K_i	empirical constants in the correlations of transport characteristics [–]
k_L	oxygen mass transfer coefficient [$m\ s^{-1}$]
k_La	volumetric mass transfer coefficient [s^{-1}]
k_Lai	volumetric mass transfer coefficient characteristic for i-th stage region [s^{-1}]
L	water level elevation under aeration [m]
l	characteristic scale defined as Batchelor's microscale of turbulence [m]
M_{bear}	torque on the impeller shaft in an empty vessel [N m]
M_{tot}	total torque on the impeller shaft in a full vessel [N m]
N_A	dimensionless aeration number ($= Q/(N{\cdot}D^3)$) [–]
N	impeller frequency in former articles referred as f [s^{-1}]
P^N	specific power dissipated by n impeller in the liquid [$W\ m^{-3}$]
P_i	specific power dissipated by impeller in the stage i (i = 1, 2, 3, 2–3) [$W\ m^{-3}$]
P_u	specific power dissipated by impeller under ungassed condition [W]
P_g	specific power dissipated by impeller under gassed condition [W]
P_{TOT}	total dissipated power input [$W\ m^{-3}$]
P_o	impeller power number ($Pu/(\rho{\cdot}N^3{\cdot}D^5)$) [–]
p	pressure [Pa]
Q	gas flow rate [$m^3\ s^{-1}$]
S	vessel cross-sectional area [m^2]
S_{baffle}	baffle cross-sectional area [m^2]
T	temperature [K]
T	vessel diameter [m]
T_{shaft}	shaft diameter [m]
t	time [s]
V_G	gas volume [m^3]
V_L	liquid volume [m^3]
v_s	gas superficial velocity [$m\ s^{-1}$]
v_τ	bubble terminal velocity [$m\ s^{-1}$]

Greek letters

β	parameter correcting term adiabatic gas expansion for position of gas sparger in the vessel [–]
ε	energy dissipation intensity ($=P/\rho$) [$W\ kg^{-1}$]
ε_G	gas hold-up in the dispersion (volume fraction) [–]
μ	dynamic viscosity of liquid [Pa s]
ν	kinematic viscosity of liquid [$m^2\ s^{-1}$]
ρ	density [$kg\ m^{-3}$]
σ	surface tension [$kg\ s^{-2}$]

Abbreviation

CFD	computational fluid dynamics
DO	dissolving oxygen
DPM	dynamic pressure method
LTN	Lightnin A315 impeller
OTR	oxygen transfer rate
PBD	Pitched blade turbine pumping down
RT	Rushton turbine
SD	standard deviation
T30	laboratory scale vessel
T60	pilot-plant scale vessel
TXD	Techmix 335 impeller pumping down

non-ideal balance of energy and non-ideal distribution of gas can be partially eliminated by the use of multiple-impeller systems [1].

Multiple-impeller systems also have other advantages in comparison with one-impeller systems. They have better gas distribution into the liquid batch, longer gas residence time and better liquid flow. In addition, the same power dissipation is achieved at lower impeller frequency and thus at lower values of shear stresses. At the same time, the contribution to the break-up of gas bubbles is the same in both the one- and multiple-impeller configuration. So it can be expected that multiple-impeller systems will leave a smaller fraction of dissipated power on the destruction of microorganisms at the same power dissipation in both systems [1,2].

Scale-up, design and performance optimization of mechanically agitated gas-liquid contactors are based on the knowledge of the mixing intensity of the liquid phase and on the mass transfer between gas and liquid. Both aspects are dependent on many parameters. These parameters may be, according to [3], the physical properties of liquid and gas (viscosity, density, surface tension, coalescence, oxygen diffusivity); process parameters (impeller frequency, gas flow rate, temperature and pressure) and geometry of the system (impeller and vessel size, impeller/vessel ratio, vessel height, number of impellers and their type, the number and type of baffles). Impeller geometry is one of the parameters which has a significant influence on the transport processes. The impeller has to play many roles simultaneously in aerated stirred tank reactors. According to [4], among these are: breakage of gas bubbles to increase the interfacial area for mass transfer; creation of a homogeneous and sufficiently fine dispersion; creation of good macromixing without any dead zones; having a flow so fast along the heat transfer zones that the demanded heat transfer coefficient is achieved.

The influence of impeller geometry, the number of impellers and the type of batch on the mixing intensity and mass transfer was investigated by several authors [4–11]. Based on their results, the authors suggested the processes for which particular impellers are suitable. These authors carried out their experiments mainly in distilled water, a coalescent batch, and using only one scale of an apparatus. However, most of the industrial batches are non-coalescent and sometimes with increased viscosity in comparison with water. The increased viscosity is typical for fermentation batches or in batches containing coalescence-decreasing compounds.

As will be given below, we will gradually follow partial aims to finally create a complete equation series for prediction of process parameters in mechanically agitated fermenters useful in the design of fermentations, where liquid batches of about ten times higher viscosity, compared to water, occur.