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Fluid dynamics of bubble swarms rising in Newtonian and non-Newtonian liquids in flat sheet membrane systems

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ABSTRACT

The bubble swarm behavior in a system comparable to a flat sheet membrane module was investigated. The parameters channel depth, superficial gas velocity, superimposed liquid velocity and viscosity of the continuous phase were varied. Besides water as continuous phase, a non-Newtonian liquid was used with respect to the rheology of real waste water sludge. The gas hold-up was determined for 144 parameter combinations with high speed imaging and the shear stress – important for the fouling mitigation – was determined for 72 parameter combinations with the electrodiffusion method. To the authors' knowledge, this is the first application of the electrodiffusion method in a bubbly flow with a non-Newtonian liquid. For the two properties gas hold-up and the shear stress describing correlations were found taking all parameters into account. In both cases, the strongest influences were found for the gas velocity and the rheology of the continuous phase. Regarding the shear stresses, the median values were up to 3.2 Pa while the maximum values were up to 9.1 Pa. Depending on the parameter combination, a significant influence of the rheology was found disagreeing with the statement of the transferability of the results gained in water to real waste water systems mentioned in some papers.

1. Introduction

Bubble swarms appear in numerous processes in industrial applications. In most cases, bubble columns have a circular cross section. The motivation for this project is the use of flat sheet membrane modules operated with an air lift loop and used e.g. inside membrane bioreactors (MBR[1]) for waste water treatment. Here, aeration is applied to establish a cross flow operation for cleaning purposes. The rising bubble swarms generates liquid flows that detach deposition layers from the membrane surfaces [1–4]. In this case, the bubble swarm rises in the gaps with rectangular cross sections between the membranes. Although circular cross section reactors are most common in the literature, still even in recent years, the investigation of bubble swarms in rectangular cross section geometries (sometimes referred to as 2D-bubble columns) is an attractive topic as a brief literature review reveals (Table 1). Comparisons between these two basic geometries (circular/rectangular) are not easy to draw as in case of circular cross sections, often a diameter of at least 0.15 m is chosen where the conditions are regarded as independent of the geometry while in rectangular cross section the (hydraulic) diameter is in most cases below this critical value and therefore influences the results. In the following, only investigations in columns with rectangular cross sections are discussed.

The depth of the investigated channels went down to 1 mm [5,6] whilst the height was usually less than 1 m. Commercial flat sheet membrane modules are usually in a channel depth (=spacing) range of 6–10 mm with heights between 950 and 1608 mm [7]. The gas flow rate in the bubble swarm experiments ranged from $1.2 \ast 10^{-2}\ \mathrm{m^3/h}$ [8] (with 1 h = 3600 s) to $3.4\ \mathrm{m^3/h}$ [9]. Recalculated as superficial gas velocities, the ranges were between $4.0 \ast 10^{-4}$ m/s [10] and 1.56 m/s [11–15]. In membrane processes, these values lie between 1.25 cm/s and 7.6 cm/s [7]. Actually the aeration is often given as specific aeration demand SAD$_m$ where the aeration rate is divided by the membrane area. Typical values of the SAD$_m$ for flat sheet membrane modules range between $3 \ast 10^{-1}\ \mathrm{m^3/(m^2h)}$ and $1.28\ \mathrm{m^3/(m^2h)}$ [7]. The recalculated SAD$_m$ values for the investigations listed in Table 1 are between $7.0 \ast 10^{-2}\ \mathrm{m^3/(m^2h)}$ [10] and $24.9\ \mathrm{m^3/(m^2h)}$ [16]. In most cases including Yamanoi and Kageyama's investigation [17] which is closest to a real flat sheet membrane system regarding the geometry and operation, Newtonian liquids were used as continuous phase, in parts with added surfactants to influence the surface tension or coalescence behavior [5,6,18]. In MBRs the

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[1] CFD: Computational fluid dynamics; CMC: carboxymethylcellulose; EDM: Electrodiffusion method; MBR: Membrane Bioreactor; SAD$_m$: specific aeration demand

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Table 1
Recent publications dealing with experimental investigations of bubble swarms in bubble columns with rectangular cross section.

Reference	Setup geometry (height × width × depth) (mm³)	Continuous phase	Aerator type	Gas flow rate Q_g (m³/h)	Superficial gas velocity v_g (m/s)	Specific aeration demand SAD_m (m³/(hm²))	Varied parameters	Bubble sizes d_B, bubble velocities w_B, gas hold-ups ε_g
This publication	1500 × 160 × 5–7	Water/Xanthan solution /+different salts	Pipe aerator (15 holes with d=0.7 or 1 mm)	10^{-1}–$6 \ast 10^{-1}$	$2.5 \ast 10^{-2}$–$2.1 \ast 10^{-1}$	$3 \ast 10^{-1}$–1.3	Channel depth, gas flow rate, liquid flow rate, liquid viscosity	$\varepsilon_g=3.4–58.2\%$
[8]	– × 50 × 4	Water/glycerin	Fritted glass	$1.2 \ast 10^{-2}$–$6 \ast 10^{-2}$	$1.6 \ast 10^{-2}$–$8.3 \ast 10^{-2}$	–	Gas flow rate, Liquid flow rate, channel orientation, liquid phase	$w_{B,rel}=5–7$ cm/s
[17]	600 × 211 × 5–10	Water	Nozzle (d=6 mm) and glass ball filter	$7.2 \ast 10^{-2}$–$5.7 \ast 10^{-1}$	$9.4 \ast 10^{-3}$–$1.5 \ast 10^{-1}$	$2.8 \ast 10^{-1}$–2.27	Gas flow rate	$d_B=3.3–21$ mm $\varepsilon_g=2–28\%$
[18]	900 × 120 × 50	Water,+Polyglykol,+n-Pentanol	Slot sparger	–	–	–	Gas flow rate	$d_B=0.5–4$ mm $w_B=19–31$ cm/s $\varepsilon_g=6.1–15.2\%$
[9]	1000 × 240 × 40	Water	Needle injector	$8.6 \ast 10^{-1}$–3.4	$2.5 \ast 10^{-2}$–$1.0 \ast 10^{-1}$	1.8–7.2	Gas flow rate	$d_B=1–8$ mm $w_B \leq 100$ cm/s $\varepsilon_g=6–36\%$
[19]	450 × 150 × 150	Water	Needle injector	–	–	–	Bubble size	$d_B=1.5–4.75$ mm $w_B=12–42$ cm/s $\varepsilon_g \leq 16\%$
[20]	500 × 200 × 15	Water	Needle injector	$2.4 \ast 10^{-1}$	$2.2 \ast 10^{-2}$	1.2	–	$d_B=1–13$ mm $w_{B,rel}=-30$-70 cm/s
[10]	1000 × 100 × 100	Water/glycerin/ +carboxymethyl cellulose /+polyacrylamide	Single hole (d=2 mm)	$1.4 \ast 10^{-2}$–$7.2 \ast 10^{-2}$	$4 \ast 10^{-4}$–$2 \ast 10^{-3}$	$7.0 \ast 10^{-2}$–$3.6 \ast 10^{-1}$	Gas flow rate, liquid viscosity	$\varepsilon_g=5–17\%$
[5,6]	800 × 400 × 1	Water+magnesium sulfate	Capillary tubes	–	–	–	Gas flow rate	$d_B=3.5–6.5$ mm $\varepsilon_g=1.4–13.6\%$
[16]	147 × 70 × 5	Water+different salts	Pipe aerator (12 holes with d=0.5 mm)	$< 5 \ast 10^{-1}$	$< 4 \ast 10^{-1}$	< 24.9	Gas flow rate, liquid flow rate	–
[21]	– × 400 × 32	Water/+methyl cellulose	Pipe aerator (63 holes with d=0.8 mm)	$4.1 \ast 10^{-1}$–1.5	$9 \ast 10^{-3}$–$3.3 \ast 10^{-2}$	–	Gas flow rate, liquid viscosity	$d_B=3–40$ mm
[11–15]	122 × 122 × 1–5	Water/Xanthan solution /+different salts	Pipe aerator (6 holes with d=5 or 6 mm) and slit	$1.8 \ast 10^{-2}$–$6.8 \ast 10^{-1}$	$8.1 \ast 10^{-3}$–1.56	$6 \ast 10^{-1}$–23	Gas flow rate+filtration	–