

Experimental investigation on mass transfer coefficient in airlift reactor involving Boger fluid

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In the realm of aerobic processes, both the average shear rate and mass transfer coefficient play crucial roles, directly influencing the proliferation of microorganisms. Moreover, the behaviour of fluids in biochemical processes may diverge from the typical Newtonian model, thereby impacting the efficiency of airlift reactors. This study delves into the influence of elasticity on the mass transfer coefficient, specifically examining the effects using a Boger fluid comprising glycerol 55% (v/v) and polyacrylamide 0.04% in tap water. Boger fluid is chosen due to the presence of elasticity whereas, its viscosity closely resembling that of a Newtonian fluid composed of glycerol 65% (v/v). The investigation revealed a lower mass transfer coefficient for the Boger fluid compared to both tap water and the glycerol 65% (v/v) solution. Furthermore, an empirical correlation has been proposed to forecast the mass transfer coefficient involving the Boger fluid. The experimental and predicted data comparison demonstrates a strong alignment, with an error margin of approximately $\pm 10\%$.

Keywords: Average shear rate, Boger fluid, Mass transfer coefficient, Newtonian fluid

Introduction

Airlift reactors have emerged as indispensable tools in various industrial processes, including chemical, biochemical, petrochemicals, and wastewater treatment plants. Their popularity stems from their advantageous features such as low cost, low shear, high heat and mass transfer coefficients, perfect mixing, and the absence of moving parts. The driving force behind liquid phase circulation within these reactors lies in the density disparity between the riser and downcomer sections, facilitating efficient mass transfer and reaction kinetics¹⁻⁸. A critical consideration in the design and operation of airlift reactors is the impact of shear rate on the microorganisms involved in aerobic biological processes⁹. High shear rates can detrimentally affect cell integrity and compromise process efficiency¹⁰. The shear rate within airlift reactors is subject to variation due to changes in superficial gas velocity and reactor configuration, as well as fluid properties¹¹.

Fluids encountered in chemical and biological reactors exhibit complex rheological behaviour due to the presence of suspended organics and microorganisms¹². The efficiency of mass transfer, particularly the diffusivity of oxygen from the gas phase to the liquid phase, is influenced by both physical (e.g., density, viscosity, surface tension) and

rheological (e.g., viscoinelasticity, viscoelasticity) properties of the fluids. Consequently, understanding the mass transfer coefficient and shear rate is crucial for optimizing airlift reactor design, especially when dealing with viscoelastic fluids. Viscoelastic fluids, characterized by both viscous and elastic properties, exhibit altered flow behaviour compared to purely viscous fluids, owing to the presence of elasticity¹³. While previous studies have explored the combined effect of viscosity and elasticity on mass transfer coefficient¹⁴⁻¹⁶, the individual contributions of viscosity and elasticity remain unexplored.

Recent investigations by Esmaeili *et al.* have highlighted the influence of elasticity on hydrodynamics in bubble column reactors¹⁷. Given the significance of elasticity in altering fluid dynamics, understanding its impact on the mass transfer coefficient in airlift reactors becomes imperative. To address this gap, we focus on studying the effect of elasticity in airlift reactors using a Boger fluid characterized by constant viscosity with elasticity¹⁸⁻¹⁹.

In this study, we present experimental investigations to elucidate the influence of fluid viscoelasticity, specifically employing the Boger fluid as a model system, on the mass transfer coefficient in airlift reactors. By comparing the performance of

Boger fluid with a Newtonian fluid (glycerol 65% v/v), we aim to develop an empirical correlation for mass transfer coefficient incorporating parameters such as superficial gas velocity, viscosity, and the ratio of storage modulus (G') to loss modulus (G'') in internal loop airlift reactors. Through this research, we seek to enhance the understanding of mass transfer phenomena in complex fluids and contribute to the development of more efficient and reliable airlift reactor designs for diverse industrial applications.

Experimental Section

Experimental setup

The internal loop airlift reactor was made of acrylic material. The experiments were conducted in a 1.8 m high airlift reactor. The schematic of the internal loop airlift reactor is shown in Fig. 1. This reactor features a cylindrical vessel divided into riser and downcomer zones. The reactor has an outer column diameter of 200 mm, a draft tube with an inner diameter of 120 mm, and both the riser and downcomer lengths are 1.5 m each. Compressed air, was introduced at the bottom of the reactor through a perforated plate sparger, which is equipped with 64 holes, each measuring 0.5 mm in diameter^{6,7}. The airflow rate was regulated using an airflow meter.

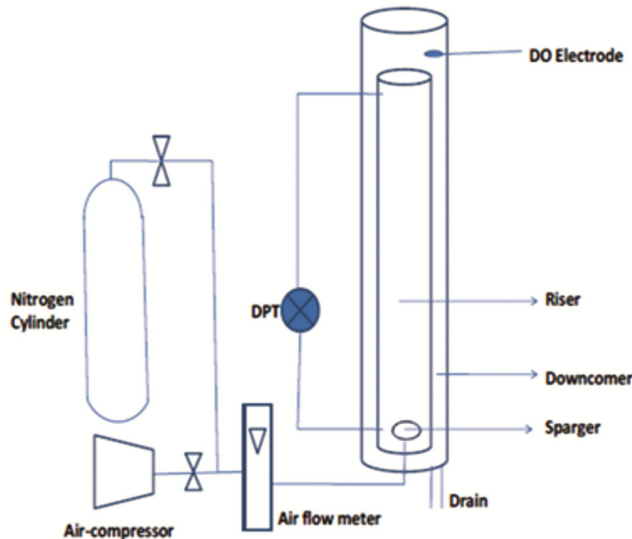


Fig. 1 — Schematics of the internal loop airlift reactor

Test fluids

The tap water is the reference fluid, and the Newtonian fluid and Boger fluids were prepared by dissolving known composition in the reference fluid (tap water). Glycerol 65% (v/v) was chosen as the Newtonian fluid. The glycerol 55% (v/v) solution was first prepared to prepare the Boger fluid. Then, 0.04% (wt.) polyacrylamide was dissolved in the prepared glycerol 55% (v/v) solution and was termed as the Boger fluid. Due to the addition of 0.04 wt% polyacrylamide, it possesses the property of elasticity. The concentration of the polyacrylamide solution was chosen by preliminary studies so that the prepared solution possesses almost similar viscosity as that of glycerol 65% (v/v) solution. To get a consistent solution, the prepared solution was stirred regularly with the help of the glass rod for 24 h. Thus, the prepared Boger fluid is a constant viscosity fluid having the additional effect of elasticity. The apparent viscosity of complex fluids was calculated in terms of shear rate ($\dot{\gamma}$), consistency index (k), and flow behaviour index (n) using the power law model as:

$$\mu_{app} = k \dot{\gamma}^{n-1} \quad \dots (1)$$

The behaviour of Boger fluids is near to Newtonian with variation in flow behaviour index (n) in the range 0.93-1^(Ref. 20,21) whereas for purely Newtonian fluids, it is unity. The fluid rheology was measured with the cone and plate geometry of the Rheometer (MCR-302, Anton Paar). The density and fluid rheology of various fluids at 20°C are presented in Table 1.

Average shear rate

The average shear rate for the Newtonian (Tap water and glycerol 65% (v/v)) and Boger fluid at different superficial gas velocities were evaluated by considering the rheological parameters of the fluid⁶ as:

$$\dot{\gamma}_{av} = \left(\frac{(\rho_L g U_g)}{k \left(1 + \frac{A_d}{A_r} \right)} \right)^{\frac{1}{n+1}} \quad \dots (2)$$

Table 1 — Physical and rheological properties of the fluids at 20°C

Composition of Fluid	Fluid Type	Density (kg m ⁻³)	K (Pa s ^{n})	n (-)	G'/G'' (-)
Tap water (100%)	Newtonian	1009.31	0.0010	1	0
Glycerol 65% (v/v)	Newtonian Viscous	1191.76	0.0160	1	0
Boger fluid (Glycerol 55% + Polyacrylamide 0.04%) (v/v)	Viscoelastic	1163.34	0.025	0.94	0.2

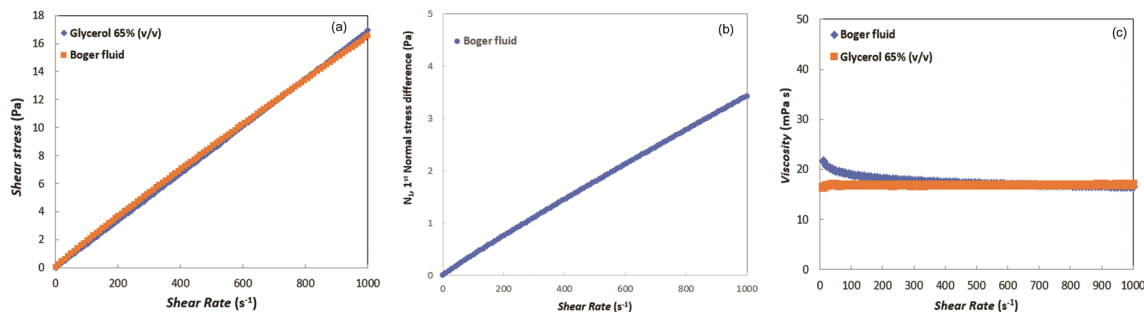


Fig. 2a — Plot of (a) shear stress vs. shear rate for glycerol 65% (v/v) and Boger fluid, (b) 1st normal stress difference (N_1) vs. shear rate for Boger fluid and (c) viscosity vs shear rate curve for glycerol 65% (v/v) and Boger fluids

Volumetric mass transfer coefficient ($k_L a$)

The volumetric mass transfer coefficient in the reactor was measured using dynamic gassing method²²⁻²⁴. The nitrogen gas was sparged through the multiple orifice sparger in the riser part of the reactor to reduce the concentration of dissolved oxygen in the fluid to 1 mg L^{-1} . Thereafter, air at the desired flow rate was introduced into the reactor through the multiple orifice sparger. The dissolved oxygen concentrations with respect to time were measured with a dissolved oxygen meter placed at the top of the reactor until it reaches to the saturation. The experiments were repeated for various fluids by varying the airflow rate at atmospheric conditions. The dissolved oxygen concentration data were used to analyze $k_L a$ as:

$$\ln\left(\frac{C^* - C_L}{C^* - C_0}\right) = -(k_L a)t \quad \dots (3)$$

Results and Discussion

Rheology of test fluids

The rheological characterizations of the test fluids were done with Rheometer (MCR-302, Anton Paar). The shear study was carried out to measure the viscosity of the test fluids in the range of $1-1000 \text{ s}^{-1}$. Fig. 2a shows the dependence of shear stress on the shear rate for glycerol 65% (v/v) and Boger fluid.

From Fig. 2a, it is observed that the shear stress varied linearly with the shear rate for glycerol 65% (v/v) as well as Boger fluids. The Boger fluid shows the presence of 1st normal stress difference in comparison to glycerol 65% (v/v) solution, which confirms its elastic nature along with constant viscosity characteristics. The 1st normal stress difference is not observed in glycerol 65% (v/v) solution only shear stress has been observed (Fig. 2b). The results are in line with the findings of Esmaili *et al.*,¹⁷. Thus, the Boger fluid has shown the effects

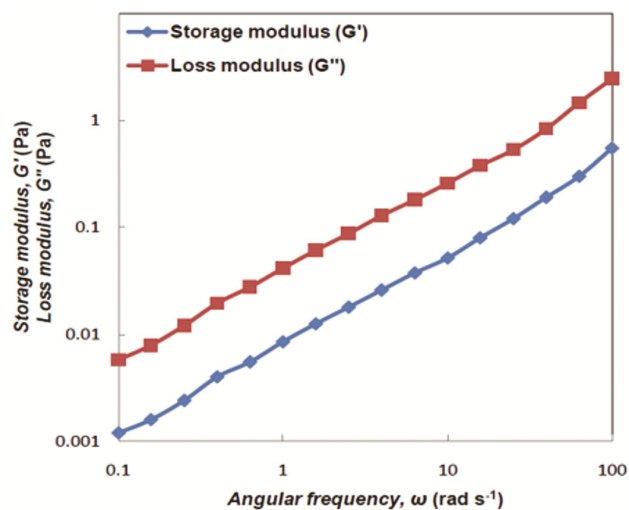


Fig. 3 — Plot of storage modulus and loss modulus vs angular frequency for Boger fluid

of both viscosity and elasticity, whereas glycerol 65% (v/v) shows the effect of viscosity only. The variation of viscosity of glycerol 65% (v/v) and Boger fluid with shear rate is presented in Fig. 2c. The viscosity of glycerol 65% (v/v) and Boger fluid remains nearly constant under shear, mimicking Newtonian behaviour. An oscillatory shear study of the Boger fluid was conducted at 10% of the strain amplitude to understand viscoelasticity of the fluid. The variation of dynamic moduli, i.e., storage modulus (G') and loss modulus (G'') with angular frequency, is presented in Fig. 3 for Boger fluid. The storage modulus and loss modulus represent the elastic and viscous properties of the fluids respectively. With an increase in angular frequency from 0.1 rad s^{-1} to 100 rad s^{-1} , the parallel increase in the storage and loss modulus was observed and the ratio of the storage modulus to loss modulus is found nearly constant i.e., 0.20 for Boger fluid. But for tap water and glycerol 65% (v/v), the ratio was found to be zero because Newtonian fluids do not show elastic properties.

Effect of superficial gas velocity on average shear rate

The average shear rate at varying superficial gas velocities for various test fluids was analysed using Eq. (2) and is shown in Fig. 4. The average shear rate increased with U_g for tap water, glycerol 65% (v/v) and Boger fluid (Fig. 4). As superficial gas velocity increased from 0.00295-0.0235 m/s, the average shear rate was found in the range from 144.08-407.52 s^{-1} for water, 39.14-110.7 s^{-1} for glycerol 65% (v/v) and 34.4-100.48 s^{-1} for Boger fluid, respectively. Tap water shows a maximum shear rate as compared to the glycerol 65% (v/v) and Boger fluids. Glycerol 65% (v/v) is Newtonian fluid (viscous fluid), whereas, Boger fluid is non-Newtonian fluid (viscoelastic fluid). The Boger fluid shows the effect of viscosity and elasticity in the same fluid. Therefore, it is difficult to analyze the effect of viscosity and elasticity separately while handling viscoelastic fluids. To overcome this Boger fluid has been prepared having viscosity nearly similar to Newtonian fluid and elastic property in the same fluid was created by adding polyacrylamide in the Newtonian fluid. A nearly similar average shear rate was observed for glycerol 65% (v/v) and Boger fluids, which isolates elasticity as the primary factor differentiating the two fluids. This allows the study to specifically analyze how elasticity influences the mass transfer coefficient, independent of viscosity or shear rate effects. Further, these average shear rate data were used to calculate the apparent viscosity of Boger fluid and these apparent viscosity data has been used to develop an empirical correlation to find the volumetric mass transfer coefficient. However, Boger fluid also exhibits elasticity, distinguishing it from a purely Newtonian fluid.

Effect of superficial gas velocity on volumetric mass transfer coefficient

The effect of superficial gas velocity on the volumetric mass transfer coefficient for various fluids is shown in Fig. 5. It was observed that the mass transfer coefficient for Newtonian (i.e., tap water and glycerol 65% (v/v) solution) and Boger fluids increased with superficial gas velocity. Further, a lower mass transfer coefficient was observed for highly viscous glycerol 65% (v/v) solution in comparison to tap water. The lower mass transfer coefficient in a highly viscous glycerol solution was may be due to the bubble coalescence phenomenon. The bubble coalescence will form larger bubbles, thereby decreasing the diffusivity of oxygen in the

fluid. The larger bubbles will move at a higher velocity, resulting in decreased residence time of bubbles in the reactor, thereby decreasing the surface area and the contact time available for mass transfer between gas and liquid phases. For Boger fluid, the lower mass transfer coefficient was observed in comparison to glycerol 65% (v/v). This decrease in mass transfer coefficient for Boger fluid, was due to the presence of elasticity in it.

Correlation for volumetric mass transfer coefficient

As seen above, the volumetric mass transfer coefficient for Boger fluid depends on the superficial gas velocity, fluid properties such as viscosity, and

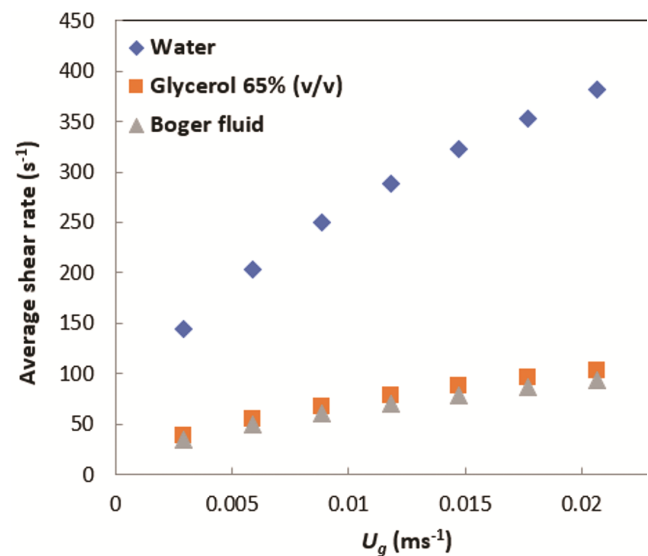


Fig. 4 — Superficial gas velocity vs. average shear rate plot for Newtonian and Boger fluids

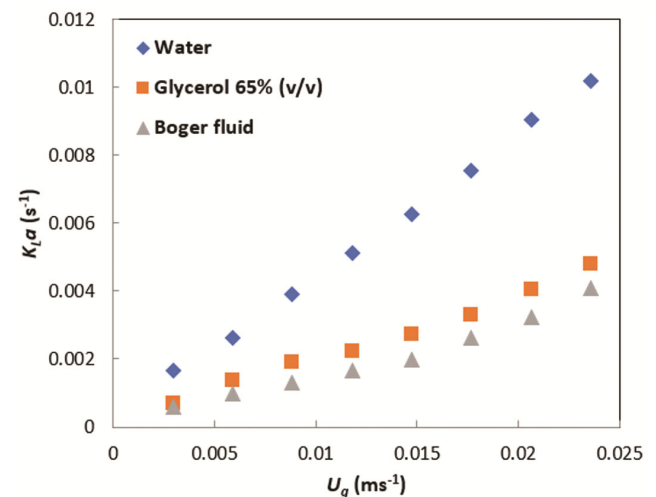


Fig. 5 — Superficial gas velocity vs. mass transfer coefficient for Newtonian and Boger fluids

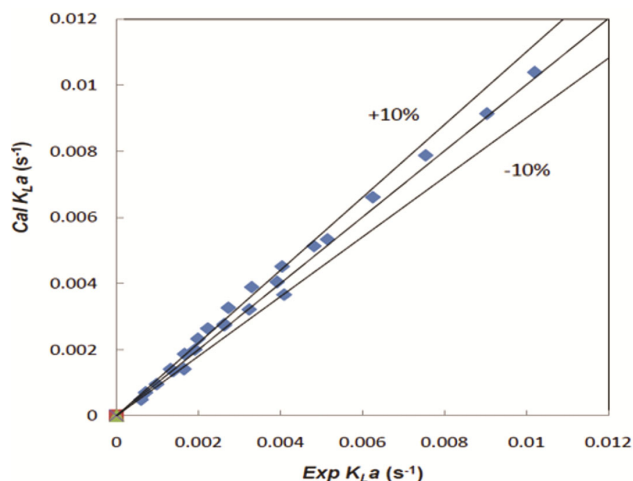


Fig. 6 —Parity plot for experimental and calculated data for mass transfer coefficient

elasticity. In our previous study⁶, we have proposed the correlation for the volumetric mass transfer coefficient in terms of superficial gas velocity and viscosity for Newtonian fluids (i.e. tap water, 25%, glycerol 50% (v/v) and glycerol 65% (v/v) as:

$$k_L a = 0.006 U_g^{0.962} \mu^{-0.254} \quad \dots (4)$$

In order to predict it for Boger fluid, the Eq. (4) has been extended by including the effect of elasticity in terms of the ratio of storage modulus (G') to loss modulus (G'') as:

$$k_L a = 0.066 U_g^{0.962} \mu^{-0.254} \left(e \frac{G'}{G''} \right)^\alpha \quad \dots (5)$$

After regression, the value of α was found to be:

$$\alpha = -1.482 \pm 0.220$$

$$R^2 = 0.987$$

The parity between the experimental and predicted values (using Eq. 5) of the volumetric mass transfer coefficient for Boger fluid is shown in Fig. 6, which shows that the proposed correlation predicts the data well with an error of $\pm 10\%$ for Boger fluid. Thus, the proposed correlation can be used for design and also scale-up of the airlift reactor for viscoelastic fluids.

Conclusion

In this experimental study we have examined how elasticity impacts the mass transfer coefficient in an airlift reactor using Newtonian and Boger fluids. The rheological analysis revealed that glycerol 65% (v/v) and

Boger fluid exhibit nearly constant viscosity, with the Boger fluid displaying additional elasticity alongside viscosity, as indicated by the presence of 1st normal stress difference. The average shear rate for glycerol 65% (v/v) and Boger fluid remained consistent and lower than that of water. The mass transfer coefficient for both Newtonian (tap water and glycerol 65% (v/v)) and Boger fluids increased with superficial gas velocity. However, for Boger fluid, the mass transfer coefficient was lower compared to water and glycerol 65% (v/v). The study shows that elasticity, as exhibited by the Boger fluid, reduces the mass transfer despite similar viscosity with glycerol 65% (v/v). Thus, the presence of elasticity in the fluid influences gas-liquid mass transfer efficiency. An empirical correlation has been proposed to predict the mass transfer coefficient for Boger fluid based on superficial gas velocity, viscosity, and the ratio of storage modulus (G') to loss modulus (G''). The experimental and predicted data exhibited a close match within $\pm 10\%$. The proposed correlation, which incorporates elasticity (via the ratio G'/G''), can be utilized by designers to predict the mass transfer coefficient for viscoelastic fluids.

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Nomenclature

U_g	Superficial gas velocity (m s^{-1})
$k_L a$	Volumetric mass transfer coefficient (s^{-1})
$\dot{\gamma}_{av}$	Average shear rate (s^{-1})
$\dot{\gamma}$	Shear rate (s^{-1})
μ	Dynamic viscosity of the fluid (Pa s)
μ_{app}	Apparent viscosity of the fluid (Pa s)
A_r	Riser area (m^2)
C^*	Concentration of dissolved oxygen at saturation (mg L^{-1})
C_L	Concentration of dissolved oxygen at time t (mg L^{-1})
G'	Storage modulus (Pa)
G''	Loss modulus (Pa)
k	Consistency index (Pa s^n)
n	Flow behaviour index (-)
N_1	1 st normal stress difference (Pa)
t	Time (s)
ρ	Density of fluid (Kg m^{-3})
τ	Shear stress (Pa)
ω	Angular frequency (rad s^{-1})
α	Correlation parameter

References

- 1 Luo L, Liu F, Xu Y & Yuan J, Hydrodynamics and mass transfer characteristics in an internal loop airlift reactor with different spargers, *Chem Eng J*, 175 (2011) 494.
- 2 Gharib J, Moraveji M K & Davarnejad R, Chemical engineering research and design hydrodynamics and mass transfer study of aliphatic alcohols in airlift reactors, *Chem Eng Res Des*, 91 (2012) 925.
- 3 Wei C, Wu B, Li G, Chen K, Jiang M & Ouyang P, Comparison of the hydrodynamics and mass transfer characteristics in the hydrodynamics and mass transfer characteristics in internal-loop airlift bioreactors utilizing either a novel membrane-tube sparger or perforated plate sparger, *Bioprocess Biosyst Eng*, 37 (2014) 2289.
- 4 Behin J & Amiri P, A review of recent advances in airlift reactors technology with emphasis on environmental remediation, *J Environ Manage*, 335 (2023) 117560.
- 5 Drandev S, Penev K I & Karamanev D, Study of the hydrodynamics and mass transfer in a rectangular air-lift bioreactor, *Chem Eng Sci*, 146 (2016) 180.
- 6 Kumar N, Bansal A & Gupta R, Shear rate and mass transfer coefficient in internal loop airlift reactors involving non-Newtonian fluids, *Chem Eng Res Des*, 136 (2018) 315.
- 7 Kumar N, Gupta R & Bansal A, Effect of surface tension on hydrodynamics and mass transfer coefficient in airlift reactors, *Chem Eng Technol*, 43 (2020) 1004.
- 8 Mendes C E & Badino A C, Hydrodynamics of Newtonian and non-Newtonian liquids in internal-loop airlift reactors, *Biochem Eng J*, 109 (2016) 137.
- 9 Wan C, Fu L, Li Z, Liu X, Lin L & Wu C, Formation, application, and storage-reactivation of aerobic granular sludge: A review, *J Environ Manage*, 323 (2022) 116302.
- 10 De-Jesus S S, Neto J M & Filho R M, Hydrodynamics and mass transfer in bubble column, conventional airlift, stirred airlift and stirred tank bioreactors, using viscous fluid: A comparative study, *Biochem Eng J*, 118 (2017) 70.
- 11 Natsume T & Yoshimoto M, A Method to estimate the average shear rate in a bubble column using liposomes, *Ind Eng Chem Res*, 52 (2013).
- 12 Caillet H & Adelaar L, A review on the rheological behavior of organic waste for cfd modeling of flows in anaerobic reactors, *Waste Biomass Valori*, 14 (2023) 389.
- 13 Vélez-cordero J R, Sámano D & Zenit R, Study of the properties of bubbly flows in Boger-type fluids, *J Non-Newtonian Fluid Mech*, 176 (2012) 1.
- 14 Cerri M O, Futiwaki L, Jesus C D F, Cruz A J G & Badino A C, Average shear rate for non-Newtonian fluids in a concentric-tube airlift bioreactor, *Biochem Eng J*, 39 (2008) 51.
- 15 Cartmell E, Water S & Soares A, Gas to liquid mass transfer in rheologically complex fluids, *Chem Eng J*, 273 (2015) 656.
- 16 Neto M, Santana A & Filho R M, Influence of impeller type on hydrodynamics and gas-liquid mass-transfer in stirred airlift bioreactor, *Am Inst Chem Eng J*, 61 (2015).
- 17 Esmaeili A, Guy C & Chaouki J, The effects of liquid phase rheology on the hydrodynamics of a gas-liquid bubble column reactor, *Chem Eng Sci*, 129 (2015) 193.
- 18 James D F, Boger Fluids, *Annu Rev Fluid Mech*, 41 (2009) 129.
- 19 Boger D F, A highly elastic constant-viscosity fluid, *J Non-Newton Fluid Mech*, 3 (1978) 87.
- 20 Chang J C & Denn M M, An experimental study of isothermal spinning of a newtonian and a viscoelastic liquid, *J Non-Newton Fluid Mech*, 5 (1979) 369.
- 21 Poole R J, Inelastic and flow-type parameter models for non-Newtonian fluids, *J Non-Newton Fluid Mech*, 320 (2023) 105106.
- 22 Zedníková M, Orvalho S, Fialová M & Ruzicka M C, Measurement of volumetric mass transfer coefficient in bubble columns, *Chem Eng*, 2 (2018) 1.
- 23 Moraveji M K, Pasand M M, Davarnejad R & Chisti Y, Effects of surfactants on hydrodynamics and mass transfer in a split-cylinder airlift reactor, *Can J Chem Eng*, 90 (2012) 93.
- 24 Han M, González G, Vauhkonen M, Laari A & Koironen T, Local gas distribution and mass transfer characteristics in an annulus- rising airlift reactor with non-Newtonian fluid, *Chem Eng J*, 308 (2017) 929.