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**Impact of gas injection on physicochemical
properties of waste activated sludge: A linear
realationship between the change of
viscoelastic properties and the change of other
physiochemical properties.**

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Abstract

Aeration process in the waste activated sludge treatment accounts
for 75% of total energy consumption of the treatment plant. The
main purpose of the aeration process is to enhance the

22 biodegradation of the liquid waste. Gas bubbles, rising through the
23 liquid, improves mixing, reduces inhomogeneities in the treatment
24 tank and enhances biological reactions. Thus aeration intensity and
25 several physicochemical properties of feed such as viscosity, total
26 suspended solids, and surface charge play a significant role in the
27 biological reaction.

28 This paper examines the impact of the gas injection rate on some
29 physicochemical properties of waste activated sludge namely
30 rheological properties, suspended solids, soluble COD (sCOD),
31 surface tension, and zeta potential. The impact of four different gas
32 flow rates on four different concentrations of waste activated sludge
33 properties was analysed.

34 The results showed that in linear viscoelastic regime the viscous and
35 elastic modulus decreases linearly with an increase in gas flow rate.
36 The amount of stress imposed by gas injection also showed a direct
37 relationship with gas velocity. Gas injection also showed a
38 substantial impact on soluble COD, suspended solids, and zeta
39 potential. Additionally, a linear relationship was observed between
40 the percentage change in the above mentioned physical properties
41 and stress imposed by gas injection. These results confirm that gas
42 injection produces additional shear impacting sludge
43 physicochemical properties and therefore changes its rheological
44 behaviour. The extra stress induced by gas injection can be
45 predicted using a simple model based on sludge concentration and
46 gas velocity

Keywords: waste activated sludge, viscoelastic Properties, suspended solids, soluble COD, zeta potential

1. Introduction

The waste activated sludge process is the most versatile and commonly used biological treatment (Seyssiecq et al. 2008). The efficiency of the waste activated sludge process depends upon an aeration operation. Aeration provides oxygen to the micro-organisms to breakdown the complex organic compounds into carbon dioxide and water and reduces the volume of sludge produced (Bailey et al. 2002). However, the oxygen transfer rate in the aeration tank decreases with an increase in the total solid concentration of sludge and strongly influences the efficiency of the process (Rosenberger et al. 2002). This is because with increasing solid concentration of sludge results in an increased viscosity of sludge that causes variations in system hydrodynamics as and impacts on bubble buoyancy, bubble shape and turbulence (Bajón Fernández et al. 2015).

Waste activated sludge is composed of water, microorganisms, and macromolecules grouped in bioflocs (Laspidou and Rittmann 2002). Hence it's structure depends on many factors and can remarkably change when exposed to shear stress. Therefore, sludge is known to exhibit shear thinning behaviour (Eshtiaghi et al. 2013, Baudez and Coussot 2001, Baudez 2008). Thus, rheology plays a crucial role in optimising and designing the aeration system. Since the sludge characteristics and rheology affect each other, the impact of

72 aeration on rheology and sludge physical properties should be
73 considered when studying the sludge flow behaviour in the aeration
74 tank.

75 Increase in aeration intensity results in a severe breakup of sludge
76 flocs, and promotes the release of colloids and solutes from the
77 microbial flocs to the bulk solution (Meng et al. 2008).
78 Consequently, it influences the sludge physical properties like total
79 suspended solids (TSS), sludge volume index (SVI), etc. and impacts
80 on sludge settleability, filterability, and compressibility (Pollice et al.
81 2007). The impact of shear stress generated by aeration intensity
82 increased the soluble contents of sludge (SMP, EPS) (Menniti et al.
83 2010, Menniti et al. 2009). Moreover, the induced shear stress by
84 microbubbles broke down the sludge that reduced the floc size and
85 released the organic content such as EPS and it also changed the
86 viscosity and surface tension of sludge (Liu et al. 2012). Almost all
87 the studies that have conducted to date have only focused on
88 membrane bioreactor to study the impact of aeration intensity on
89 sludge physical properties and for the solid concentration less than
90 2%.

91 Provided that aeration intensity impacts on sludge physical
92 properties and consequently changes its rheological properties,
93 currently there isn't any study that showed the relationship
94 between sludge rheology (especially in a linear viscoelastic region
95 that can be measured online) and physiochemical properties of
96 sludge.

97 As both the physical and rheological properties simultaneously
 98 change in the aeration process and impact on the efficiency of the
 99 waste activated sludge process, monitoring shear and its effect on
 100 complex physicochemical properties through online tools (e.g.
 101 rheometers) with any minor change provides useful information to
 102 adjust operating conditions accordingly. However, there is lack of
 103 detailed analysis on the change in sludge rheology with anaeration
 104 rate and its impact on the sludge physicochemical properties. This
 105 study wants to elucidate and correlate the stress generated by
 106 aeration intensity with sludge physicochemical properties.
 107 Therefore this research primarily aims at investigating the impact of
 108 gas injection on viscoelastic properties, zeta potential, soluble COD
 109 and surface tension to get the detailed insight of the shear induced
 110 by the gas intensity and its effect on sludge physicochemical
 111 properties. The second objective is to develop relationships
 112 between change in rheological properties and physical properties at
 113 the different gas flow rates.

114 **2. Materials and Methods**

115 **2.1 Sample preparation**

116 Waste activated sludge with 3wt% (TS 30g/l; TSS 26.833g/l; sCOD
 117 3720 mg/l; zeta potential -16.4mv; surface tension 46.04 mN/m)
 118 was collected from a wastewater treatment plant (Mt.Martha
 119 Treatment Plant) in southern region of Victoria, Australia. Sewage
 120 sludge of 600,000 customers after girt removal and primary tank
 121 settling is areated in ambient temperature. The sludge samples

122 were collected after the dissolved air flotation tank before the
123 polymer dosing. The sludge was thickened to higher concentration
124 (6%) using a centrifuge at 7°C and 8000 rpm (i.e., at 12,200g
125 maximum relative centrifugal force) for 30 minutes. The
126 homogeneous samples of 3.0%, 4.0%, 5.0% & 5.5% total solids
127 concentration (TS) were prepared by diluting the 6% concentrated
128 sludge with the original sample.

129 **2.2 Apparatus**

130 Rheological measurements were performed using commercially
131 available hybrid stress controlled (HR3) rheometer from TA
132 Instruments using a grooved bob geometry with an outer diameter
133 of 14.9 mm, and 42 mm length. A custom designed plexiglass cup
134 (inner diameter: 100 mm, length: 100 mm) with a stainless steel
135 porous disk (outer diameter: 100 mm, thickness: 1.6mm, porosity:
136 40%, from SINTEC Australia) at the bottom was used for sparging gas
137 while it connected to rheometer (Bobade et al. 2017). The gas flow
138 rate was varied from 0.001m³/min to 0.007 m³/min using a gas mass
139 flow meter from AALBORG at a pressure of 10 Psi.

140 **2.3 Rheometric technique**

141 To monitor the evolution of structural changes in sludge due to gas
142 injection, dynamic time sweep measurement was carried out. The
143 experimental procedure for the time sweep measurement was
144 carried out in the following pattern:

- 145 • Step 1: Pre shear the sludge at high shear rate (350s^{-1}) for
- 146 900s to ensure that identical condition is achieved before
- 147 each measurement.
- 148 • Step 2: The sludge was allowed to rest for a short time
- 149 (120s) to start the test in the same condition (Baudez 2008,
- 150 Markis et al. 2014).
- 151 • Step 3: The dynamic time sweep test at 0.09% strain and
- 152 1HZ frequency in a linear viscoelastic range was carried out
- 153 for 1500s.
- 154 • Step 4: Preshearing of sludge was repeated (step1) and the
- 155 nitrogen gas was injected for 1500s before repeating the
- 156 time sweep measurement (step 3). Similar experimental
- 157 procedure was repeated for four different sludge
- 158 concentrations (3%, 4%, 5% & 5.5%) at four different gas
- 159 flow rates (1LPM - 7LPM).

160 The experimental procedure to measure the extra stress
 161 induced by gas injection on sludge was carried out as follows:

- 162 • Step 1: Preshearing of sludge at 350s^{-1} for 900s; resting for
- 163 120s;
- 164 • Step 2: Dynamic time sweep measurement at different
- 165 strains and 1 HZ frequency without aeration;
- 166 • Step 3: Compare the viscoelastic response (G' , G'') of non
- 167 aerated sludge with the aerated sludge at 0.09% strain, the
- 168 difference between the two strains showed the extra strain
- 169 imposed. The detailed sketch diagram of the rheological

measurement process is provided else where, Bobade et al.
(2017).

2.4 Physicochemical properties

Soluble COD (sCOD) and Zeta potential were examined to study the sludge solubilisation after gas injection. The sample collected for measuring the sCOD and Zeta potential was centrifuged at 10,000 rpm (i.e., 20913g at maximum relative centrifugal force) for 20 min for separating the liquor from solid. The small volume of obtained liquor was used directly for zeta potential measurement and rest of the liquor was filtered through a 0.45 μ m filter membrane. The collected filtrate was used to determine sCOD following standard American methods (Eaton et al. 2005). All measurements were carried out in duplicate. To avoid any alteration of sludge properties the samples and liquor are stored in a fridge at 4°C.

The zeta potential measurement was performed using zetasizer Nano Range from Malvern Instruments, using disposable folded capillary cells (DTS 1070). The measurement was carried out at 20°C, keeping the time lag of 10s between each set of readings. Each measurement was repeated for three times. The standard maximum deviation is 5%.

A surface tension of fluid changes with any change of formulation at the molecular level and helps to know the dispersibility and adhesion of the fluid (Davies and Rideal 1963). The measurement of surface tension was performed by using Force Tensionmeter (K100) from Kruss (Germany) using plate method. Sludge being a non-Newtonian viscous fluid, the measurement was carried out using

microscope glass slide for 1200s at an immersion depth of 2mm. For precise measurement of surface tension, the glass slide was activated using oxygen flame before each measurement. Different immersion depth and time of run was examined to find an optimum point to obtain reproducible data.

201

202 **3. Result and Discussion**

203 **3.1 Influence of Aeration Intensity on Viscoelastic**

204 **Properties**

The oscillatory time sweep carried out in the linear viscoelastic region at low applied sinusoidal strain helps to understand whether any change in structure is occurring during gas injection. Both the storage modulus (G') & loss modulus (G'') are impacted by gas injection as they are decreasing when the gas flow rate is increasing. At different solid concentrations, viscoelastic modulus [storage modulus (G') & loss modulus (G'')] vs. time was plotted. One sample graph is presented in Fig. 1 (Bobade and Eshtiaghi 2018 Figshare). This figure indicates the impact of different gas flow rates on the modulus of sludge with 3wt% total solids. A similar effect of gas intensity on sludge modulus was observed for all the four concentrations at four different gas flow rates during oscillatory time sweep (Bobade and Eshtiaghi 2018 Figshare) (see the supplementary material, fig. S1-S3). The percentage change of average sludge modulus due to aeration intensity, i.e.,

$$\left(\frac{(\text{Avg of } G' \text{ at without gas} - \text{Avg of } G' \text{ at given gas flowrate})}{(\text{Avg of } G' \text{ at without gas})} \right) * 100$$

220

221 obtained during the measurement for all the four concentrations by
 222 four different gas flow rates is shown in Table 1. This change in
 223 sludge modulus with gas intensity indicates that sludge structure is
 224 impacted by gas injection because the gas injection is applying
 225 additional shear (Bobade et al. 2017). Such modification of sludge
 226 structure may be attributed to the release of soluble components
 227 due to floc dissolution (Meng et al. 2008). Similarly, it was reported
 228 that the increase in aeration intensity enhances the release of
 229 soluble components, which further decreases the oxygen transfer
 230 efficiency (Meng et al. 2007, Menniti et al. 2010) by impacting on
 231 food to microorganism ratio. As more soluble material means more
 232 food and less oxygen available for microorganism to consume.

233 *3.1.1 Amount of Shear strain /stress imposed by* 234 *gas injection*

235 The extra strain imposed by gas injection showed that the imposed
 236 strain increases with increase in gas flow rate but decreases with
 237 increase in concentration as shown in Table 2. Furthermore, the
 238 equivalent shear stress imposed is calculated by using Equation 1
 239 (Mezger 2011).

$$240 \quad \tau = G' * \gamma \quad (1)$$

241 , where,

242 τ = shear Stress, (pa)

243 γ = strain, (%)

244 G' = Average of the modulus of elasticity of unaerated
 245 sludge over 20min measurement time, (Pa)

246 The amount of stress imposed by different gas velocities for
247 different concentrations was plotted in Fig. 2 (Bobade and Eshtiaghi
248 2018 Figshare). The linear increase of stress with gas velocity was
249 observed for the entire concentration range. This result indicates
250 that for a given concentration the stress imposed by gas injection
251 increases linearly. In contrast, for the same gas velocity, the amount
252 of imposed stress decreases linearly with an increase in sludge
253 concentration, i.e., at high solid concentrations of sludge the shear
254 caused by the gas injection decreases. The reduction in imposed
255 stress by gas injection with an increase in solid concentration is
256 because sludge becomes more viscous and possesses a strong force
257 of attraction between particles as the concentration increases
258 (Baroutian et al. 2013). Also, to better understand the stress
259 imposed by gas flow rate at the different concentration of sludge,
260 the obtained data (refer Table 2) is analysed using linear multiple
261 regression method and an equation is derived (Eq. 2). In which its
262 fitting parameters are linked to measurable parameters in the
263 sludge to increase the applicability of this equation 3 to other
264 systems. The equation was also applicable with $\pm 10\%$ error to
265 another waste activated sludge sample collected from Eastern
266 Treatment plant in Eastern region of Victoria. The equation 3 is
267 significant at 95% of confidence level with a P value much less than
268 0.05 and with an R^2 value of 0.88. The estimated error is $\pm 7\%$
269 within the range of concentration studied with 0.5% for lowest
270 concentration and 7% for the highest concentration.

271

$$\sigma_{imposed} = 840.15 * U_g - 10.92 * TS \quad (2)$$

, where,

$\sigma_{imposed}$ = Stress, (N/m²)

U_g = Gas velocity, (m/s)

TS = Concentration of total solids, (g/g)

$$\sigma_{imposed} = \left(\frac{(0.0135 * TS^2)}{T_{ss}^2 * D_p} \right) * \mu_{(water)} * U_g - \left(\frac{10 * TS^2}{T_{ss}} \right) \quad (3)$$

Where,

T_{ss} = Total suspended solids of unaerated sludge (g/g)

TS = Total solids concentration (g/g)

D_p = Diameter of the Pore of the membrane (in this study is 0.00002 m)

$\mu_{(Water @ 20^\circ C)}$ = Viscosity of water = 1Ns/m²

3.2 Influence of Aeration Intensity on Total Suspended Solids (T_{ss})

Suspended solids mostly consist of colloidal and particulate particles (Meng et al. 2017, Trussell et al. 2007). Fig. 3 illustrates the decreasing trend of suspended solids with increasing gas velocity. It means that as the gas velocity increases, the amount of solids that can pass through filter increases, i.e., gas intensity breaks the suspended particles into smaller fragments and a large number of smaller particles settles causing fouling issue. However, it is also

293 clear from Fig. 3, that as the concentration increases, reduction in
 294 suspended solids decreases, i.e., at higher concentration and for the
 295 same gas velocity, the stress imposed by gas velocity is not sufficient
 296 to break down the suspended particles into submicron particles.
 297 Zhang et al. (2004) also found that suspended solids gradually
 298 decrease with increasing aeration intensity. This reduction in
 299 suspended solids due to aeration intensity is the consequence of the
 300 floc breakage and releasing EPS present inside the floc structure
 301 (Chang et al. 2002), which consequently decreases an oxygen
 302 transfer efficiency due to increase in food to microorganism ratio
 303 (Houghton and Quarmby 1999, Meng et al. 2006, Wilén et al. 2003).
 304 Interestingly, there is a linear relationship between stress imposed
 305 by gas injection and the change in suspended solids at given
 306 condition and for given concentration (Eq. 4). This linear relation
 307 has 95% of confidence level and p-value much less than 0.05 with $\pm$
 308 5% error which is the highest related to sludge with the highest
 309 concentration. Utilising an online rheometer and obtaining
 310 viscoelastic properties of sludge and the stress imposed by the gas
 311 injection can give us a better understanding of the influence of
 312 aeration intensity on suspended solids.

$$313 \quad \% \Delta T_{ss} = a^* \sigma_{imposed} \quad (4)$$

314 , where,

315 $\sigma_{imposed}$ = Stress imposed by the gas velocity at any solids
 316 concentration studied (3-5.5%), (N/m²)

317 $\% \Delta T_{SS}$ = Percentage change in suspended solids compared to
 318 non aerated sludge, (%)

319 a = Fitting parameter = 2.01, (m^2/N)

320 This decrease in suspended solids is due to change in floc structure
 321 caused by the aeration was also confirmed by measuring the
 322 viscoelastic properties of aerated sludge immediately after sparging
 323 and after resting the sludge for 40 minute as shown in Fig.4. It is
 324 obvious that after 20 mins of gas injection, G' reduced by (13%) also
 325 after stopping gas injection and giving 40 mins of rest time, the
 326 sludge structure was not returned to original structure as the G' is
 327 8% less than the G' of the non aerated system.

328 **3.3 Influence of Aeration Intensity on Soluble COD** 329 **(sCOD)**

330 The soluble COD is one of the critical parameters for estimation and
 331 optimisation of the performance of the biological treatment process
 332 (Hayet et al. 2016). The sCOD content is also used to determine the
 333 amount of oxygen required for the biodegradation in the aeration
 334 tank (Henze and Henze 1997). Thus the impact of aeration intensity
 335 on the soluble COD (sCOD) of the sludge sample was measured at
 336 different concentrations and at different gas injection rates as
 337 presented in Table 3.

338 A linear increase in sCOD was observed with an increase in gas
 339 velocity over the entire concentration range. Additionally, the
 340 results indicated that at 0.01274 m/s of gas velocity, more organic
 341 matter is released from solid phase to liquid phase. A similar

342 increase in soluble COD with an increase in aeration intensity was
 343 also observed by Meng et al. (2008) and very well explained that the
 344 shear-induced by gas leads to floc breakage and increases the
 345 soluble contents in the sludge. Azami et al. (2012), Ladewig and Al-
 346 Shaeli (2016), Meng et al. (2006) have also highlighted that role of
 347 soluble microbial products (SMP), which is characterized as soluble
 348 chemical oxygen demand (sCOD) on the kinetic activity, flocculating
 349 and settling properties of sludge.

350 The increase in soluble COD, therefore confirms that the shear
 351 induced by gas injection impacts on floc structure releases EPS and
 352 increases the soluble contents causing a decrease in viscoelastic
 353 properties. Hence, it is necessary to consider the impact of shear
 354 force induced by the gas injection on the sludge and increase in
 355 sCOD together for efficient operation of the treatment plant.
 356 Additionally using multiple regression analysis, the percentage
 357 change in sCOD has a linear relationship with stress imposed for all
 358 concentration studied (Eq. 5). This equation has a confidence level
 359 of 95% with R square value of 0.96 and a P value much smaller than
 360 0.05 with an error range of $\pm 15\%$ for lower concentration and
 361 increases upto $\pm 30\%$ at higher concentrations.

$$362 \quad \% \Delta sCOD = b * \sigma_{imposed} \quad (5)$$

363 , where,

364 σ = Stress imposed by the gas velocity at
 365 concentration range studied (3-5.5%),
 366 (N/m²)

367 % Δ sCOD = Percentage change in soluble COD
 368 compared to non-aerated sludge, (%)

369 b = Fitting parameter = 2.75, (m²/N)

370 **3.4 Influence of Aeration Intensity on Zeta potential**

371 The zeta potential, which measures the surface charge /
 372 electrostatic interactions between the particles, represents the
 373 potential drop between the diffuse double layers of the surface. This
 374 analysis helps to get detailed insight into the cause of dispersion,
 375 aggregation, flocculation & sedimentation (Hunter 1981, Vold 1982,
 376 Yuan et al. 2011).

377 The zeta potential of waste activated sludge at given total solids
 378 concentration, linearly decreased (become more negative) with
 379 increasing gas velocity (Fig. 5). The reduction in zeta potential i.e.
 380 the zeta potential value becoming more negative indicates that the
 381 sludge is becoming more stable because the repulsive force is more
 382 than the attractive force (Lu and Gao 2010). Thus the resistance to
 383 aggregation is increasing (Vold 1982). The zeta potential also
 384 increased with increasing total solid concentration and became less
 385 negative. The less negative zeta potential values confer that the
 386 attractive force is exceeding the repulsive force and decreasing the
 387 stability (resistance to aggregation/agglomeration) of the sample
 388 and increasing the coagulation & flocculation behaviour. Similarly,

389 zeta potential value becomes less negative with an increase in solid
390 concentration at a constant aeration rate of $0.2 \text{ m}^3/\text{h}$ as reported by
391 Meng et al. (2006). Interestingly, an increase in zeta potential with
392 an increase in total suspended solids is also reported by (Su et al.
393 2014). Additionally, Sutherland (2001) also showed that EPS plays a
394 crucial role in defining the stability of the system as each structural
395 cell of polysaccharide forms intra-or inter-molecular associations
396 that leads to gelation. However, this gelation varies greatly
397 depending on the type of inter or intramolecular hydrogen bonding
398 which contributes to floc formation, stability, etc.

399 Therefore, the more negative surface charge of sludge with an
400 increase in gas velocity indicates that gas injection modifies the
401 sludge characteristics because of increased solubilisation of loosely
402 bound EPS (LB-EPS)(Zhang et al. 2013). A linear correlation between
403 stress imposed by gas injection and the percentage change in zeta
404 potential as presented in Eq. 6 was found through multiple
405 regression method with a P value less than 0.05 and R square value
406 of 0.92. The percentage error is $\pm 5\%$. Zeta potential crucially
407 reflects the stability of the system and affects the overall
408 performance of the process. Moreover, the knowledge of zeta
409 potential and hydrophobicity is important to understand the
410 electrostatic interaction between SMPs with membrane surface and
411 flocculation potential in activated sludge process (Azami et al. 2012,
412 Chen et al. 2012). Thus the knowledge of a change in zeta potential
413 with stress imposed by gas flow rate will help to optimise the
414 operation of waste activated sludge process.

415 $\% \Delta \zeta = c * \sigma_{imposed} \quad (6)$

416 Where,

417 $\% \Delta \zeta$ = Percentage change in Zeta potential

418 compared to the non areated system (%)

419 $\sigma_{imposed}$ = Stress imposed by gas injection at a

420 given concentration (N/m²)

421 c = Fitting parameter = 2.12, (m²/N)

3.5 Influence of Aeration intensity on surface tension

The change in interfacial surface tension of sludge with gas velocity is shown in Table 4. The interfacial surface tension is observed to increase linearly with increase in gas velocity for all the concentrations studied ($R^2 = 0.9$). (Note: All the surface tension reported here are at the 1200s of the time interval). As the concentration increases the time required by the surface tension curve to reach steady state increases, i.e., the surface tension curve has not reached the stable value at the 1200s and hence shows a large difference in surface tension value even at no gas.) As the concentration increases, the intermolecular force in the sludge increases and results in bubble coalescence, thereby impacting more on surface tension. Hence the percentage change of surface tension is more at high concentration of sludge and low gas flow rate as shown in Figure 6.

Interestingly it was also observed that gas velocity has a linear correlation with the percentage change in surface tension at a given concentration.

The surface tension is closely related to carbohydrates, and protein content of EPS as those are amphiphobic molecules and could change the surface tension of the fluid (Sheng et al. 2010).

Moreover, a direct relationship was reported by Schonhorn (1965) between surface tension and cohesive energy of the molecule. And the cohesion of sludge increases with increasing the polysaccharide content of EPS (Ahimou et al. 2007). In addition,

there is a direct relation between interfacial surface tension and bio flocculation i.e. when the fine dispersed particles are clumped together and a big agglomerated floc is formed, and settling of organic matter takes place more which then results in reducing the interfacial surface tension (Liss and Droppo 2005). Thus, gas injection induces shear and increases the sludge stability which means resistance to aggregation increases (more negative Zeta potential) and results in measuring higher value for surface tension. This understanding of surface tension and gas flow rate at a given concentration will help to understand orientation time and growth time of bubble (Kulkarni and Joshi 2005). During the bubble formation and detachment process, two types of surface tension forces act on a bubble, dynamic and static. At the initial growth phase, the surface tension is dynamic as its contact angle with the orifice changes continuously and in the later part, it reaches to a constant contact angle approaching to static. Thus although the surface tension forces are small, they vary significantly with gas flowrates and impacts on bubble formation. In addition, considering the surface tension change with the strain imposed by gas injection together is important to understand the bubble coalescence phenomena and gas distribution behaviour. This will further help to optimise the hydrodynamics of the system since bubble characteristics depend on the viscous property and the surface tension of the fluid (Sikorski et al. 2009).

4. Conclusion

The impact of gas injection on the physiochemical and rheological properties of sludge is elucidated. The viscoelastic modulus of sludge decreased with an increase in gas flow rate resulting in weakening of sludge structure. The gas flow rate induced shear, and the intensity of shear-induced linearly increased with increasing gas velocity. However, for the same gas flow rate, the shearing intensity decreased with increasing total solids concentration of sludge.

A linear relationship was observed between the change in suspended solids, soluble COD, and zeta potential with an increase in stress induced by gas injection. This change in physiochemical properties is because of break down of floc structure.. The decrease in zeta potential values also proved that gas injection modifies the sludge surface by changing the stability of the system which in turn increases the surface tension linearly with increase in gas velocity. . Thus observing the change in rheological properties due to gas injection intensity is also useful to understand the changes in physicochemical properties of sludge that are responsible for efficient and optimised operation of waste activated sludge treatment.

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Table 1: Change of sludge elastic modulus (G') at four different (3%, 4%, 5%, and 5.5%) total solids concentration of waste activated sludge and at four different gas injection intensities (percentage of change in elastic modulus was calculated in comparison to non-aerated sludge at the similar solid concentrations)

Total solids concentration (%)	Percentage change in sludge elastic modulus (%)			
	1LPM	3LPM	5LPM	7LPM
3%	18%	25%	30%	37%
4%	13%	21%	27%	30%
5%	5%	11%	20%	26%
5.5%	2%	5%	7%	14%

Table 2: Strain and stress imposed by four different gas velocities (1.82E-03 to 1.27E-02) at four different total solid concentrations of waste activated sludge (3%, 4%, 5% and 5.5%)

Total Concentration (TS), (g/g)	Gas flow rate, (L/min)	Gas velocity, (m/s)	Strain imposed (%)	Stress imposed calculated from Eq.1 (N/m²)
0.03	1	1.82E-03	4.00E-02	4.4564
	3	5.46E-03	7.00E-02	7.7987
	5	9.10E-03	9.00E-02	10.0269
	7	1.27E-02	1.30E-01	14.4833
0.04	1	1.82E-03	1.50E-02	2.67855
	3	5.46E-03	3.00E-02	5.3571
	5	9.10E-03	4.00E-02	7.1428
	7	1.27E-02	6.00E-02	10.7142
0.05	1	1.82E-03	5.00E-03	2.42791
	3	5.46E-03	8.00E-03	3.884656
	5	9.10E-03	1.00E-02	4.85582
	7	1.27E-02	2.00E-02	9.71164
0.055	1	1.82E-03	2.00E-03	1.04614
	3	5.46E-03	6.00E-03	3.13842
	5	9.10E-03	8.00E-03	4.18456
	7	1.27E-02	0.01	5.2307

Table 3: Impact of gas velocity on soluble COD (sCOD) at four different total solid concentrations (3%, 4%, 5%, & 5.5%) of waste activated sludge.

Gas velocity (m/s)	sCOD (mg/l)			
	3%Ts	4%TS	5% TS	5.5%TS
0	3720	3960	4740	5090
0.00182	4060	4260	5390	5580
0.00546	4960	5050	6000	6260
0.0091	5340	5500	6520	6740
0.01274	6340	6680	7120	7290

Table 4: Impact of gas velocity on Surface tension at four different total solid concentrations (3%, 4%, 5%, & 5.5%) of waste activated sludge.

Gas Velocity	Surface Tension (mN/m)			
	3%	4%	5%	5.5%
0	46.04	46.4	59.45	60.04
0.00182	49.5	48.91	65.68	65.9
0.00546	52.68	54.43	67.72	67.9
0.0091	54.1	55.33	69.39	70.45
0.01274	56.62	56.32	72.68	73.9

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Highlights of the paper

- Gas injection induces extra shear on sludge and changes its physicochemical properties.
- Developed a model to predict stress induced by gas injection.
- The change of physicochemical properties is proportional to stress imposed by gas injection.