Chemical Engineering Science 141 (2016) 154–165

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Impact of suspended solids on the activated sludge non-newtonian behaviour and on oxygen transfer in a bubble column

C. Durán [a], Y. Fayolle [a,*], Y. Pechaud [a,b], A. Cockx [c,d,e], S. Gillot [f]

[a] Irstea, UR HBAN, 1 Rue Pierre-Gilles de Gennes, F-92761 Antony, France
[b] Université Paris-Est, Laboratoire Géomatériaux et Environnement (EA 4508), UPEMLV, 5, Boulevard Descartes – Champs sur Marne, 77454 Marne-la-Vallée, France
[c] Université de Toulouse, INSA, UPS, INP, LISBP, 135, Avenue de Rangueil, Toulouse, France
[d] INRA, UMR792 Ingénierie des Systèmes Biologiques et des Procédés, Toulouse, France
[e] CNRS, UMR5504, Toulouse, France
[f] Irstea, UR MALY, 5 Rue de la Doua, F-69626 Villeurbanne Cedex, France

HIGHLIGHTS

- Activated sludge rheological behaviour is significantly determined by MLSS content.
- Gas hold-up and k_La are reduced in activated sludge compared to clean water.
- k_La is mainly controlled by the sludge apparent viscosity (μ_{app}) and U_G.
- A dynamic representation of μ_{app} in the bubble column is proposed.
- A model correlating k_La with μ_{app} and superficial gas velocity (U_G) was developed.

ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form
4 August 2015
Accepted 4 October 2015
Available online 21 October 2015

Keywords:
Activated sludge
Non-Newtonian fluid
Capillary rheometer
Hydrodynamics
Oxygen transfer
Bubble column

ABSTRACT

This paper presents the experimental study and analysis performed in order to better understand the link between activated sludge properties, rheological behaviour and oxygen transfer. The experimental set-up consists of a bubble column of 0.3 m^3 continuously fed with activated sludge and a capillary rheometer, installed in two different wastewater treatment plants: a conventional activated sludge plant and a membrane bioreactor. In the bubble column, equipped with a fine bubble diffuser, the overall gas hold-up (ϵ_G) and volumetric oxygen transfer coefficients (k_La) were measured. A fraction of the column outflow was sent to the capillary rheometer where the activated sludge rheological behaviour was investigated. Several properties of the studied activated sludge were characterised (MLSS, MLVSS, soluble COD, surfactants, surface tension, soluble cations) and their impact on rheology and oxygen transfer was examined.

The experimental data showed that the parameters K and n, from the Ostwald-de Waele rheological model, were strongly related to the suspended solids concentration (in terms of MLSS or MVLSS). An increase in k_La was observed as the superficial gas velocity (U_G) was increased. Compared to clean water, the k_La coefficient was lower in activated sludge and still reduced with an increase of the MLSS concentration. This reduction could be partially attributed to a lower gas holdup (ϵ_G) associated with an increase in the sludge apparent viscosity (μ_{app}) leading to a reduction of the specific interfacial area (a). Subsequently, an estimation of the mean shear rate exerted by the bubble swarm in the column allowed to evaluate the sludge apparent viscosity (μ_{app}) of the mixed liquor at a given superficial gas velocity and MLSS concentration. Finally an empirical correlation linking k_La to the superficial gas velocity (U_G) and the sludge apparent viscosity was obtained for both types of sludge. The good agreement between the experimental and the fitted data suggests that k_La can be estimated from the superficial gas velocity and the rheological behaviour.

* Corresponding author. Tel.: +33 1 40 96 60 32; fax: +33 1 40 96 61 99.
E-mail address: yannick.fayolle@irstea.fr (Y. Fayolle).

http://dx.doi.org/10.1016/j.ces.2015.10.016

1. Introduction

In conventional activated sludge wastewater treatment plants, air supply can represent up to 70% in terms of energy expenditure. The process optimization requires a fine understanding of how the different operational parameters impact the aeration efficiency of the system.

Studies performed in clean water have shown that the aeration efficiency depends on design parameters such as the reactors geometry and the characteristics of the aeration system (type, layout and depth) as well as on the operating conditions such as superficial gas velocity or liquid circulation velocity (Gillot et al., 2005). Under process conditions, the activated sludge (AS) properties also have an impact on the oxygen transfer and the aeration efficiency is always lower compared to its value in clean water.

In particular, several investigations performed on activated sludge (AS) systems highlighted that increasing the MLSS (mixed liquor suspended solids) concentration (between 2 and 30 g L^{-1}) reduces the volumetric mass transfer coefficient (Cornel et al., 2003; Krampe and Krauth, 2003; Jin et al., 2006; Germain et al., 2007; Henkel et al., 2009). Actually, the only presence of solids (biological flocs and particulate material) represents an obstacle for the oxygen transfer at the gas–liquid interface (steric effect, Mena et al., 2005).

Concerning the soluble fraction, Germain et al. (2007) have shown in a membrane bioreactor (MBR) that the soluble organic matter (soluble COD) ranging from 54 to 198 mg L^{-1} has a negative impact on oxygen transfer in AS and attributed this effect to the presence of surfactants. Some measurements carried out in clean water have demonstrated that soluble substances such as surfactants (even at small concentrations i.e. 1 mg L^{-1}), salts and glucose interfere with oxygen transfer by accumulating at the gas–liquid interface and generating different overlapping effects: (i) lowering the surface tension (Wagner and Pöpel, 1996; Gillot et al., 2000), (ii) preventing bubble coalescence (Zlokarnik, 1980; Craig, 2004) (iii) or/and reducing the oxygen diffusivity into the liquid (Rosso et al., 2006; Hebrard et al., 2009; Jamnongwong et al., 2010). For Rosso et al. (2005), Gillot and Héduit (2008) and Henkel (2010), the negative impact of the soluble substances on oxygen transfer is reduced at higher sludge retention time (SRT) in relation to a more advanced removing or sorption of soluble substances such as surfactants.

Moreover the coincidence of different characteristics and physicochemical properties of AS determine the fluid viscosity which is a key property governing the bioreactor hydrodynamics and consequently impacting the volumetric oxygen transfer coefficient (k_La). Especially the MLSS concentration has been identified to play a determining role in the rheological behaviour of activated sludge (Rosenberger et al., 2002; Tixier et al., 2003; Mori et al., 2006; Yang et al., 2009). For a given surface tension, viscosity can affect the bubble size at detachment (Kulkarni and Joshi, 2005), their rising velocity and the bubble coalescence phenomena (Mena et al., 2005). As activated sludge is a non-Newtonian fluid (Seyssiecq et al., 2003; Ratkovich et al., 2013) its apparent viscosity depends on the shear rate which can be exerted by the stirring system and by the airflow rate. Although several authors studied the influence of sludge properties on oxygen transfer on one hand, and on rheology on the other hand, Wagner et al. (2002) presented the impact of sludge apparent viscosity at a mean shear rate (40 s^{-1}) on oxygen transfer in two full-scale MBR wastewater treatement plants (WWTP). However, in such processes, the mean shear rate is variable and depends on process operating conditions such as airflow rate or mixing characteristics. Moreover, no studies have until now evaluated, on the same type of activated sludge, the relationship existing between the activated sludge physicochemical properties, its dynamic rheological behaviour, the airflow rate and oxygen transfer.

In this context, the objective of this work was to evaluate the influence of two key parameters of aerated bioreactors (sludge properties and air superficial gas velocity) on the activated sludge rheological behaviour, hydrodynamics (mean shear rate) and on the volumetric oxygen transfer coefficient. The impact of operating conditions on mean shear rate is considered in order to introduce a dynamic representation of the apparent viscosity and its relationship with oxygen transfer. To this aim, the sludge properties and rheology, together with gas hold-ups and oxygen transfer coefficients were determined using an experimental set-up installed on two wastewater treatment plants (WWTPs): a conventional AS plant and a membrane bioreactor (MBR).

2. Materials and methods

The experimental set-up was installed on the WWTPs of the following municipalities: Marolles/Saint Vrain (conventional activated sludge plant, later called CAS) and Briis-sous-Forges (membrane bioreactor, later called MBR). These facilities are designed for 22 000 PE and 17 000 PE respectively, treat mainly domestic effluents and are operated under extended aeration (F/M ratio <0.1 kg BOD_5 (kg VSS)$^{-1}$ d^{-1}). The installation consists of a high cylindrical bubble column (H=4.5 m; D_c=0.29 m; D_c/H=6.4.10^{-2}; S_{cw}/V_C=13.8 m^2 m^{-3}) installed near the aeration tank of the WWTPs. Bubble dynamics in such experimental apparatus, with a liquid height similar than those encountered in full scale aeration tanks, can be considered as representative of full scale gas–liquid dynamics as they induce similar contact time between bubble and sludge. As shown in Fig. 1, activated sludge was continuously drawn out either from the aeration tank, the sludge recirculation loop or the membrane reactor, using a helical rotor pump and fed into the column at the bottom. This recirculation induces a continuous feeding and renewal of the activated sludge during the measurements, hence allowing constant physicochemical characteristics of biological flocs and interstitial liquid during each operating conditions and avoiding endogenous respiration of activated sludge. The superficial liquid velocity (U_L) in the column was maintained low and constant for a given aeration test and ranged between 2.7×10^{-3} and 4.5×10^{-3} m s^{-1}. In the column, the liquid media was aerated by means of two compressors supplying air through a flexible fine perforated EPDM membrane (orifice diameter $\approx0.7\times10^{-3}$ m; S_p=0.024 m^2; S_P/S_c=0.36) installed at the bottom of the column. The injected airflow rate was measured using a volumetric gas metre (dresser). The superficial air velocity (U_G) ranged from 1×10^{-3} to 5×10^{-3} m s^{-1} (comparable to the observed range in full-scale aeration tanks). At a height of 4.42 m from the diffuser, the sludge flow left the column by overflow and was then directed towards the capillary rheometer.

2.1. Activated sludge rheology

To determine the rheological behaviour of the activated sludge under study, a capillary rheometer was designed and constructed (Fig. 1b) inspired by the tubular rheometer used by Ndoye et al. (2013) for the rheological study of a whey protein suspension. This type of rheometer is mechanically simple and allows the application of a wide range of shear stress (between 10^{-2} and 10^7 s^{-1}). The instrument configuration helps to avoid low MLSS concentration samples to settle during the measurements. In such systems, a rheological measurement consists in determining the longitudinal pressure loss associated to the liquid flow rate through a capillary tube of known geometry. The designed device is composed of four tubes of 4, 7, 12 and 14 mm of diameter (D=2R). The column sludge outflow was partly pumped through these tubes using a helical rotor pump characterised by a pulseless