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Power consumption, local and average volumetric mass transfer coefficient in multiple-impeller stirred bioreactors for xanthan gum solutions

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HIGHLIGHTS

- Highly viscous non-Newtonian fluids in gas liquid system were studied.
- Various impellers including small- or large-scale impellers were employed.
- The resulting heterogeneous k_La distribution were observed and investigated.
- Correlations useful for design of XG fermentation process were proposed.

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ABSTRACT

Mass transfer and mixing performances are very critical for xanthan gum fermentation process. Power consumption, local and average volumetric mass transfer coefficient (k_La) were compared for six impeller combinations in a 50 L perspex tank with xanthan gum solutions. Impellers used in various combinations can be distinguished as two categories: “small-diameter” impeller, which include Rushton turbine, hollow blade turbine and wide-blade hydrofoil impeller and “large-diameter” including ellipse gate impeller, Intermig and double helical ribbon. The results show that in order to gain the same power input, the rotating speed of “small-diameter” impeller combinations increases as the concentration of xanthan gum increases, while it decreases for “large-diameter” impeller combinations. The two categories also show distinguished mass transfer rates. For the “small-diameter” impeller combinations, the k_La values near the wall region drop faster than that in other areas as the concentration of xanthan gum increases. While for the “large-diameter” impeller combinations, the distribution of k_La is homogenous except in the bottom area but with poor gas dispersion capabilities as concentration of xanthan gum increases. The averaged k_La for each impller combination was correlated well with the specific gassed power input, superficial gas velocity and effective viscosity. The obtained correlation shows that the k_La strongly depends on specific power input and viscosity, but is less influenced by the gas flow rate.

1. Introduction

Xanthan gum (XG) is a heteropolysaccharide obtained by the *Xanthomonas* fermentation, and is widely used as thickener, suspended dispersant and oil displacement agent because of its emulsifier, thickening, dispersing and stable properties (Kennedy and Bradshaw, 1984). In 1969, the Food and Drug Authority (FDA) authorized the use of xanthan gum in food products, marking the introduction of the first industrially produced biopolymer to the food industry. Therefore, the demand for xanthan gum produced from *Xanthomonas campestris* has progressively increased at an annual growth rate of 5–10% (Ben Salah et al., 2010).

The viscosity of the broth increases gradually along the fermentation process of XG, and very high viscosity is reached at the end. The XG solution is a typical pseudoplastic fluid (Galindo et al., 1989; García-Ochoa et al., 2000). In shear thinning media, good mixing and mass transfer is maintained in the impeller swept zone due to lower local apparent liquid viscosity, but poor mixing and mass transfer in

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the zone away from the impeller zone. Viscosity gradient in the non-Newtonian broths causes poor gas redistribution in the bulk liquid. Furthermore, cavern formed in the impeller swept zone may degenerate the fermenter performance substantially (Amanullah et al., 1998; Pakzad et al., 2008). Therefore, the efficient mixing and mass transfer in highly viscous fluids remain a difficult task for the design and scale-up of the stirred tank fermentors (Aubin and Xuereb, 2006). Specific xanthan production rate is directly related to the specific oxygen uptake rate and consequently affected by the oxygen transfer rate (Schlüter and Deckwer, 1992; Suh et al., 1990). Papagianni et al. (2001) also found that increased agitation levels (100–600 rpm) resulted in higher production rates and biomass levels. Amanullah et al. (1998) presented that xanthan could continue to be produced at a level governed by a specific oxygen uptake rate, unless there are biological limitations preventing the formation of the product, and recommended that either large diameter impellers of similar design or with novel agitators could be used to obtain enhanced performance.

The gas–liquid mass transfer in stirred tank reactor has been widely studied with water–air system (Bouaifi and Roustan, 1998; Fujasová et al., 2007; Kraitschev et al., 1999; Linek et al., 1996a, b; Martin et al., 1994; Van't Riet, 1979). At the same power consumption, many researchers gained different k_La results. Martin et al. (1994) showed that the k_La values for axial flow impeller "Prochem Maxflo T" are 30% lower than that for Ruhton turbine. Kraitschev et al. (1999) reported higher k_La values for Narcissus impeller compared with Rushton turbine. Bouaifi and Roustan (1998) found the same k_La data for all configurations (A310, A315, PB impellers, Rushton turbines and their combinations). Moucha et al. (2003) considered these inconsistent results partially caused by the improper methods used for the k_La data evaluation, and employed the arithmetic mean k_La of individual stage value for multi-impeller configurations because the value is not affected by axial dispersion of both phases (Moucha et al., 1998).

There are also many correlations that have been proposed to predict the k_La in stirred reactors with non-Newtonian fluids, but the media used were usually low viscosity with the concentration of the XG or carboxymethyl cellulose lower than 1.0 wt% (Gabelle et al., 2011; García-Ochoa and Gómez, 1998; Garcia-Ochoa and Gomez, 2009; Kawase and Moo-Yong, 1988; Sideman et al., 1966). However, it is reported that at the end of industrial fermentation the xanthan concentration can reach over 4 wt% (Ben Salah et al., 2010). There have been only few studies that concern the mass transfer performance of different impellers in gas–liquid high-viscosity systems. The Rushton turbine and flat or pitched blade turbine were usually employed (Garcia-Ochoa and Gomez, 2009; Laakkonen et al., 2006). Furthermore, since k_La value is measured based on only one point for the shear-thinning fluid, it may not represent the overall mass transfer capability. This is also considered in this work.

The aim of the present work is the study of variant impeller combinations on their power consumption and mass transfer capability when they are applied to the medium and high viscosity of xanthan gum solutions. Considering both the mixing intensity and mass transfer, "small-diamter" impellers such as Rushton, and "large-diameter" impellers such as double helical ribbon, etc. are used to compare their capability in mixing and interfacial mass transfer. Results achieved in this work can facilitate impeller selection in the xanthan fermentation process.

2. Materials and methods

2.1. Experimental apparatus

Experiments are carried out in a 50 L stirred tank reactor, which is a perspex vessel with a diameter (T) of 280 mm and with working volume of 30 L. Height of ellipsoid bottom is 35 mm.

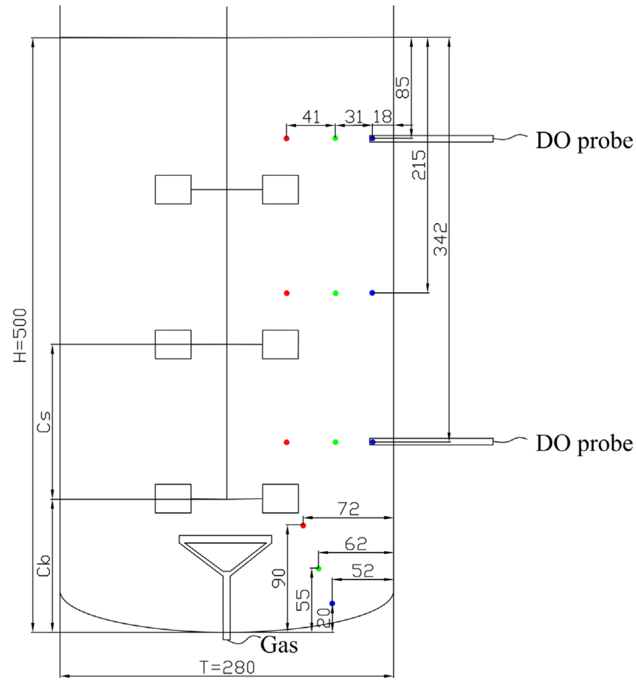

Fig. 1. Sketch of the setup.

Triple impellers are mounted on the same shaft. For the small-diameter impeller combinations, the bottom impeller clearance, C_b, is 112 mm and the inter-impeller distance, C_s, is 130 mm. Oxygen concentration response curves at twelve locations in the tank are logged for each impeller combination, and this information is then used to calculate local k_La value. The length of the oxygen probe is 120 mm and the diameter is 10 mm. A sketch of the vessel indicating locations of oxygen probes is shown in Fig. 1.

Eight kinds of impellers (Rushton turbine (RT), hollow blade turbine (HBT), wide-blade hydrofoil impeller pumping down (WHd) and pumping up (WHu), Ellipse impeller, Gate impeller, Intermig impeller (MIG) and double helical ribbon (DHR) are shown in Figs. 2 and 3) were combined to form six impeller combinations. The abbreviation used for defining the impeller combinations is straightforward: e.g., HBT+2WHd means hollow blade turbine in bottom stage with dual wide-blade hydrofoil impellers pumping down in upper stages, but the EG means Ellipse impeller in upper stage with Gate impeller in bottom stage. The tank has four vertical baffles with a width of 30 mm, which are equally mounted around the tank wall for 3RT, HBT+2WHd, HBT+2WHu and EG combinations, but no baffles are mounted for HBT+2MIG and HBT+DHR combinations. Air was introduced through a ring sparger with 40 equally spaced orifices (1 mm in diameter). The sparger is located 80 mm above the bottom of the tank, and its diameter is 90 mm.

2.2. Experimental fluid

The experimental research mainly focuses on the effect of the gradually increasing viscosity of the fermentation broth on the mass transfer. Experimental fluids are various concentrations of XG, which are typical pseudoplastic non-Newtonian fluids according to the Power Law model

$$\mu = K\dot{\gamma}^{n-1} \quad (1)$$

where μ is the apparent viscosity of the XG solution, $\dot{\gamma}$ is shear rate, K is consistency index and n is flow index. Table 1 lists the rheological properties of different XG solutions that are used in this work.