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Short Communication

Evolution of flow regimes in non-Newtonian liquids under gas sparging

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HIGHLIGHTS

- Flow visualisation was used to study the growth of active volume in a gassed viscoelastic liquid.
- Steady state active volume scales with specific power input as a power law if the flow is turbulent.
- Transition to turbulent conditions is governed by K, where $K = SPI/(G/\lambda)$.
- Turbulent conditions are obtained for $K >> 1$.

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ABSTRACT

This paper provides experimental evidence supporting the idea that the transition to turbulent flow is governed by the ratio of the specific power input (SPI) and the term G/λ, where G is the viscoelastic modulus of the liquid and λ is the relaxation time, in a vessel containing a fluid agitated by sparged gas (air) at low superficial gas velocities. This finding provides a method for judging the flow regime within a vessel a priori using a nondimensional quantity and can be used as a scale for decision-making in cases where real-time visual analysis is not possible. While the work reported below is motivated by anaerobic digestion of wastewater sludge, the results are obtained using model liquids and should, therefore, have wide application in chemical process engineering, such as CFD simulation of mixing in viscoelastic fluids and mixing in fermentation processes.

1. Introduction

Wastewater treatment plants process large quantities of sludge; a non-Newtonian viscoelastic material whose flow behaviours introduce significant technical challenges to operating efficiency. In particular, digesters relying on mixing to bring feedstock into contact with bacteria populations have traditionally been burdened with large unmixed regions due to the substrate's nonlinear stress/strain flow characteristics. The impact of this nonlinear behaviour decreases in turbulent flow regimes, but there is a notable energy penalty associated with operating under these conditions (Metzner and Reed, 1955; Dodge and Metzner, 1959). A method for determining the flow regime and extent of mixing in a digester will allow operators to take advantage of turbulent flow while minimising the associated energy cost. The focus of this work is to develop a metric to assess if flow conditions are likely to be turbulent, and predict the extent of mixing achieved with respect to the power input when gas sparging is used to agitate viscoelastic fluids.

2. Theoretical background

A recently developed flow visualisation technique (Bhattacharjee et al., 2017; Kennedy et al., 2016a; Kennedy et al., 2016b; Bhattacharjee et al., 2015) was used for the investigation, contrasting the volume of liquid in the vessel that is in motion (active region) with the volume that is stationary (inactive region). The agitation mechanism is considered only as a source of energy input, and imaging techniques indicate active region evolution over time. Active volume at steady state ($V_{a,ss}$) occurs when energy input to the system and the energy dissipation rate (ε_T), given by $\varepsilon_T = \tau\dot{\gamma}$ where τ is the shear stress (Pa) and $\dot{\gamma}$ is the shear rate (s^{-1}), balance with one another. Previous work (Kawase and Moo-Young, 1989) has shown that this analysis can be used to estimate average fluid velocity at equilibrium for an Ostwald-de Waele (power-law) liquid (Eq. (1)).

$$U_0 = 0.787 n^{-2/3} g^{1/3} D_T^{1/3} U_{sg}^{1/3} \quad (1)$$

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where U_0 is linear liquid velocity (m/s), n is the flow behaviour index, g is the gravitational constant (m/s^2), D_t is the vessel diameter (m), and U_{sg} is the superficial gas velocity (m/s). For power-law liquids, the relationship between viscosity and shear rate is described by Eq. (2).

$$\eta = k\dot{\gamma}^{-(n-1)} \tag{2}$$

where η is apparent viscosity (Pa.s), $\dot{\gamma}$ is shear rate (s^{-1}), and k is the flow consistency index ($Pa.s^n$). Power input due to gas sparging was calculated using Eq. (3).

$$E_i = \pi R^2 H \rho g U_{sg} \tag{3}$$

where E_i is power input (W), R is the vessel radius (m), H is liquid height (m) and ρ is liquid density (kg/m^3). Specific power input (*SPI*), (W/m^3) is estimated using Eq. (4).

$$SPI = \rho g U_{sg} \tag{4}$$

A relationship between specific power input (SPI) and average velocity can be established by extending this analysis (Eq. (5)).

$$U_0 = 0.787\left[SPI \times D_T/(\rho n^2)\right]^{1/3} \tag{5}$$

The assumption that underpins the above theoretical development is that the hydrodynamic condition is turbulent. It follows then, that demonstrating the relationship $V_{a,SS} \propto U_0 = 0.787\left[SPI \times D_T/(\rho n^2)\right]^{1/3}$ would indicate the assumption of underlying turbulent conditions is valid.

3. Experimental method

3.1. Rheological characterisation of model liquids and digested sludge

Aqueous xanthan gum Keltrol® (XGKT) solutions at concentrations of 0.3, 0.4 and 0.5 wt% were used to mimic the shear-thinning behaviour of wastewater sludge. Samples were characterised using an HR3 Discovery rheometer (TA Instrument, USA) at 25 °C to measure rheological and viscoelastic responses. Identical measurements were conducted on digester sludge collected from Melbourne wastewater treatment plant for comparison.

3.2. Experimental setup and procedure

Experiments were conducted in a 0.19 m diameter (D_T) cylindrical vessel set inside a square tank. The annulus between the two tanks was filled with water to reduce optical distortion. XGKT liquid height was 0.19 m. Air was introduced using a circular nozzle with diameter 3×10^{-3} m (Fig. 1(a)). An acid-base neutralization reaction was used for flow visualisation, where pH of the liquid in the tank was increased, and a fluorescent dye was added. The midplane of the vessel was illuminated with collimated beams of light and imaged using a camera (Fig. 1(b)). A 1M HCl solution was injected at the mouth of the sparger nozzle which spread with the active region causing decolouration of the dye (Fig. 1(c)). Bubbles rising from the nozzle through the central axis of the tank and recirculating streamlines were observed (Fig. 1(d)), and evolution of the active region was recorded (Fig. 1(e)). The effect of SPI on

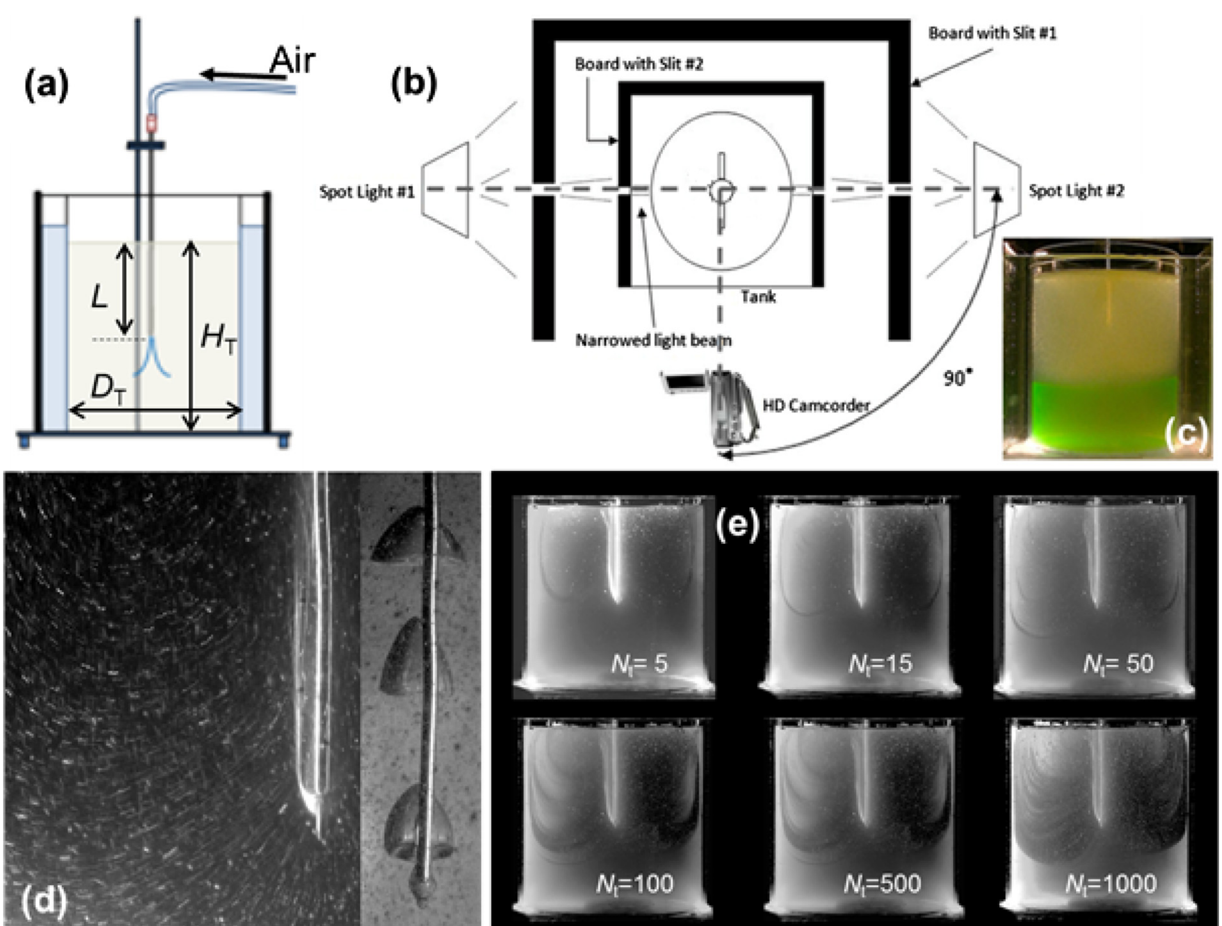

Fig. 1. (a) Schematic of experimental apparatus. (b) Top view of imaging configuration (c) Image of steady-state condition (d) Flow near the nozzle (left panel). Bubbling process driving flow (right panel). (e) Evolution of tracer front for various values of $N_t = t/t_H$, where t_H is the hydraulic retention time.