chemical engineering research and design 114 (2016) 331–340

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Accelerating the spread of the active mixing region in a sludge simulant using submerged jets

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ARTICLE INFO

Article history:
Received 10 June 2016
Received in revised form 21 August 2016
Accepted 27 August 2016
Available online 15 September 2016

Keywords:
Mixing
Flow visualisation
Non-Newtonian liquids
Sludge rheology
Inactive volume
Submerged jet

ABSTRACT

In anaerobic digesters operated in a municipal wastewater plant, submerged recirculating jet streams are often used for the purpose of agitating sludge. However, due to the complex rheology of the sludge, large portions of the digester can remain stagnant and the stagnant volume changes slowly with time. The rate of change varies with time which is determined by the rheological nature of the sludge. In our previous flow visualisation study involving a downward facing jet recirculating a transparent, non-Newtonian, sludge simulant in a model digester, we have shown that the rate of decrease of inactive volume occurs in three distinct flow regimes. In practice, some of these flow regimes can persist for an undesirably long period of time and delay the acquisition of a fully "active" state within the vessel. Our experiments in the present work carried out using the same sludge simulant reveal that the time-span of the flow regimes can be remarkably shortened by a simple change in the geometry of the recirculating jet. The findings reported here open up the possibility of improving the extent of mixing of highly viscous, non-Newtonian feeds within shorter time frame and lowering specific power input in systems operated with recirculating submerged jets.

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1. Introduction

Effective treatment of municipal wastewater is becoming increasingly important to good water governance. Population density in urban centres in both developed and developing countries is rising consistently each year. With increasing population density comes increasing pressure on water authorities to find innovative solutions in wastewater treatment. As sludge disposal currently accounts for up to 50% of the operating costs of a wastewater treatment plant (WWTP), one such solution that is widely used throughout the world is anaerobic digestion (Appels et al., 2008). Anaerobic digestion is a biological process in which microbes act in the absence of oxygen to convert wastewater sludge into methane-rich biogas and odour-free biosolids. The biogas produced via this process has a general composition of around 48–65% methane (Rasi et al., 2007) and if produced in sufficient quantities, the energy recovered from the biogas can be sold back to the grid.

As with any reactor, it is essential to operate an anaerobic digester at maximum efficiency to ensure optimal biogas generation. There are several parameters to consider in the design and operation of anaerobic digesters of which the hydrodynamic condition within the vessel is an important one. It has been argued (Tenney and Budzin, 1972) that around 50% of the geometric volume of an anaerobic digester remains stagnant and thus oversizing is a necessity. Mixing is important to the digestion process as it provides the necessary contact between the feed sludge and the active biomass, which in turn gives uniform temperature and substrate concentration throughout the digester; it can also give uniformity to a range of other biological and chemical parameters as well as prevent the formation of surface scum layers and settling of solids (Hilkiah et al., 2008). On the other hand, excessive mixing is also not good as it can be detrimental to the contact between substrate and microbe, and lead to decreased biogas production (Ward et al., 2008). Settling of solids at the tank bottom is also of particu-

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http://dx.doi.org/10.1016/j.cherd.2016.08.030
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Nomenclature

$\dot{\gamma}$	shear rate, s^{-1}
η	effective viscosity, Pa s
κ	effective diffusivity of the acid tracer, m^2/s
ρ	fluid density, kg/m^3
A_c	area of active cavern, m^2
A_n	cross-sectional area of injection nozzle, m^2
d_n	injection nozzle diameter, m
d_s	suction nozzle diameter, m
D_T	tank diameter, m
H_T	liquid height, m
N_t	normalised time scale ($\dot{Q}t/V_T$)
P	power input, W
$\dot{Q}$	liquid recirculation rate, m^3/s
t	process time, s
t_h	hydraulic residence time, s
v_n	injection velocity at the nozzle, m/s
v_r	velocity with respect to the interface, m/s
v_s	velocity of the moving interface, m/s
V_a	active mixing volume, m^3
V_i	inactive mixing volume, m^3
V_T	total liquid volume, m^3

lar concern as this can result in a thick unmixable layer that leads to a decrease in the active volume available over time, which consequently leads to expensive periodical cleaning of digesters. Furthermore, currently there is a push in the wastewater industry to process more concentrated feed stocks to conserve water. While an increase in solids concentration provides a richer feed stock for digestion, it also poses a challenge to the operation of anaerobic digesters. An increased solids concentration results in complicated rheological behaviour such as increased yield stress (Eshtiaghi et al., 2012), which necessitates a mixing system design that can handle sludge with higher apparent viscosity.

Three agitation techniques are employed in wastewater treatment plants to aid mixing within the digester. These are mechanical mixing, gas sparging, and sludge recirculation using submerged jets (Qasim, 1999). While previous studies have investigated the comparative effectiveness of the three mixing techniques (Dawson et al., 2000; Karim et al., 2005), this study is predominately related to sludge recirculation. Sludge recirculation involves pumping sludge out of the digester, passing it through a heat exchanger and returning it to the digester through a nozzle submerged in the liquid body of the digester. This configuration has found wide-spread use in the chemical industry particularly in vessels where mixing/blending with impellers is not feasible. However, much of the work that has been done in this field has limited applicability to WWTPs. For instance, the rheological behaviour of waste-water sludge can vary greatly from Newtonian fluids. In Newtonian fluids, the viscous stress varies linearly with the imposed strain rates. For sludge, however, this relationship is non-linear, and the degree of non-linearity is a function of several factors including the concentration of solids in the sludge. In addition, for promoting good microbial activity, the sludge fed into the anaerobic digester needs to be processed under laminar conditions. Under these conditions, the rheological response of the sludge can remarkably influence the hydrodynamic conditions within the digester, including determining the degree of stagnation that occurs within the vessel. These peculiarities that arise due to the unique nature of the process make it difficult to adopt approaches available in the literature to control the hydrodynamics of anaerobic digesters. Also, the use of sludge recirculation as a mode of agitation in anaerobic digesters, which is the focus of the work reported here, is of recent interest and principles for logical design of processes using this mode of agitation is not widely available in literature. Of prime interest is an understanding of how the stagnant regions that occur in rheologically complex liquids like sludge changes with time due to agitation by the recirculating stream. It is also important to know how one can influence (enhance/retard) this process by making simple adjustments to the geometry, and the operating conditions. Unfortunately, existing studies do not provide answers to this question. Detailed experimental studies, therefore, are required to generate the required information.

Studying the hydrodynamics of wastewater sludge experimentally is challenging. Sludge is an opaque material, and it is not possible to observe its mixing behaviour in the laboratory optically. Many techniques have been used in the past to study sludge mixing using chemical tracers (Monteith, 1981) computer automated radioactive particle tracking (CARPT) (Karim et al., 2007) and electrical resistance tomography (ERT) (Babaei et al., 2015). However, these techniques are costly and do not always deliver reliable data (Hui et al., 2009). This study employs a flow visualisation technique in which a transparent sludge simulant is used to determine the flow structures generated by liquid recirculation. It is an economical technique to study the hydrodynamics of non-Newtonian fluid mixing and it has been used widely to study mixing in the process industry operations (Lamberto et al., 1996; Makino et al., 2001; Yek et al., 2009). An additional advantage of using a simulant is that its rheological properties can be tuned experimentally and matched to those of municipal wastewater sludge.

The hydrodynamics in viscous non-Newtonian liquids with yield stress, similar to those in sludge with high solids concentration, occurs in two distinguishable regions. One of them the 'inactive volume' where the fluid elements remain relatively stagnant and contribute little to the chemical or biological processes that may occur within the liquid and the other, the 'active volume,' where the fluid elements are mobile and directly influence the above-said processes. In any operation involving yield stress non-Newtonian liquids, it is therefore necessary to minimise the inactive volume quickly with the minimum expenditure of energy for increasing efficiency. Conversion of inactive volume to active volume is affected by the power input due to agitation, the fluid rheology, and nozzle geometry (Low et al., 2013). Our previous study (Bhattacharjee et al., 2015) involving liquid recirculation through downward facing jet in a cylindrical tank found that the inactive volume decreases with time over three distinct regimes. Xanthan gum in Keltrol T (XGKT) solution, which possesses non-Newtonian flow characteristics, was used as the test liquid in this study. XGKT solution has been shown to simulate municipal wastewater sludge (Eshtiaghi et al., 2012) and is routinely used as sludge simulant. Among the three regimes, effectively the second regime was found to delay the transition from inactive to the fully active state. At higher liquid viscosities, the span of both the first and the second regimes was found to increase such that, over a comparable time-scale, the transition to the third regime (where the rate of decrease of the inactive volume accelerates) was not observed. An example of this phenomenon is shown in Fig. 1, where the results of two experiments conducted at identical specific power inputs ($1.4\,W/m^3$) with XGKT solutions with two different (0.3 and 0.5 wt%) concentrations are shown. It can be observed from Fig. 1 that, as the concentration of the liquid increases, the inactive volume decreases slowly. For a comparable period of time, the dynamics do not transition to the third regime in 0.5 wt% XGKT solution. Since 0.5 wt% XGKT solution represents municipal waste water sludge with higher solids concentrations than what is currently used in industry, Fig. 1 illustrates one of the challenges associated with increasing the solids concentration of the sludge fed to anaerobic digesters. The results for the 0.5 wt% XGKT solution indicate that mixing can become difficult when sludge solids loading exceeds a critical value. From an operational perspective, it would be beneficial to determine a simple process of shortening the extent of regime 2, or quicker transitioning from regime 2 to regime 3. This will also help to identify ways of controlling the span of these three flow regimes inexpensively and without increasing the specific power input to the vessel. Although it is recognised that the effects of rheology and fluid mechanics may decouple at some point, no attempt was made in this study to isolate the two phenomena, and both phenomena were studied together.

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