Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Mechanism of waste-heat recovery from slurry by scraped-surface heat exchanger

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HIGHLIGHTS

- The complete and precise rheological behaviour of slurry was proposed and validated.
- The heat transfer performance of SSHE with slurry as working fluid was simulated.
- The waste heat recovery process in full-scale biogas plant with SSHE was analyzed.

ARTICLE INFO

Article history:
Received 15 January 2017
Received in revised form 12 May 2017
Accepted 13 May 2017
Available online xxxx

Keywords:
Slurry
Biogas production
Scraped surface heat exchanger
CFD
Waste-heat recovery

ABSTRACT

Waste-heat recovery from discharged slurries can improve the net raw biogas production in the bio-methane process in order to meet the demand for a next-generation of anaerobic digestion. In this study, a numerical model of a scraped-surface heat exchanger was proposed with the consideration of the complete and precise rheological behaviour of the slurry of animal manure for the first time for achieving highly efficient waste-heat recovery. The rheological model results were verified with new experimental data measured in this work. Subsequently, the convective heat-transfer coefficient of the scraped-surface heat exchanger was calculated numerically with the proposed numerical model, and the performance was determined. Then, the contributions of waste-heat recovery from the slurry to the biogas production using a general shell-and-tube heat exchanger and the scraped-surface heat exchanger were calculated quantitatively and compared. For the case of scraped-surface heat exchanger, the increase of net raw biogas production can be up to 8.53%, which indicates that there is a great potential to increase the net raw biogas production in the bio-methane process using a scraped-surface heat exchanger with low-cost equipment and a compactible structure.

1. Introduction

With increasing demand for renewable energy and environmental protection, the anaerobic digestion of the biogas production process has attracted increasing attention. The main goal of the next-generation of anaerobic digestion is to enhance the methane production [1]. Among the various methods for improving the biogas production process, it has been reported that, with a thermophilic fermentation, the rate of biogas production can increase by 41–144% [2,3]. This requires a large amount of reaction heat, accounting for 70–80% of the total energy utilization [4]. For bio-methane processes—especially those without thermogenesis, such as the cogeneration process—it is difficult to integrate other heating systems and very common to provide the process heat from the burning of the produced biogas. Consequently, it is crucial to use the waste-heat effectively in order to decrease the amount of burnt biogas and improve the net raw biogas production (NRBP). Previous studies have shown that a considerable amount of energy can be recovered by preheating the feed using the waste-heat of effluent slurries [5,6]. However, the quantitative contribution of the waste-heat recovery from slurries to the NRBP remains unclear.

To enhance the waste-heat recovery, a heat exchanger with an external heating process is generally used for an anaerobic digestion system. The heat-transfer efficiency of such external heating is relatively high compared with that of the internal heating (heat-exchange coil). Heat exchangers and the corresponding external circulation units have been designed for full-scale biogas plants. However, the fouling, blocking, and low efficiency, as well as the high investment cost for the heat exchanger remain

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http://dx.doi.org/10.1016/j.apenergy.2017.05.111
0306-2619/

Nomenclature

T	temperature
μ	viscosity, kg/(m·s)
k	consistency coefficient, Pa·s^n
n	power law index
ρ_w	density of water, kg/m^3
ρ_s	density of a slurry, kg/m^3
t	hydraulic retention time of reactor, 20 day
t_w	operation time of waste-heat recovery, h
$c_{p,w}$	specific heat of water, kJ/(kg·K)
$c_{p,s}$	specific heat of slurry, kJ/(kg·K)
λ	thermal conductivity, W/(m·°C)
$\boldsymbol{U}$	velocity vector, m/s
U_∞	overall average velocity, m/s
d_h	hydraulic diameter, m
τ	shear stress, Pa
Ne	Newton number
To	torque, N·m
δ	clearance between blades and stator, 130 μm in this work
$\dot{\gamma}$	shear rate, s^{-1}
Ta	Taylor number, dimensionless
D_s	diameter of stator, m
A	heat exchange area, m^2
D_r	diameter of rotor, m
Re_g	Reynolds number, dimensionless
Nu	Nusselt number, dimensionless
ω	rotor speed, rad/s
V_r	volume of the anaerobic reactor, m^3
ΔT_m	logarithmic mean temperature difference, °C
$\Delta_c H_{CH4}$	combustion heat of methane, 39745.5 kJ/m^3
V_{biogas}	biogas production, m^3/day
Re_r	rotational Reynolds number, $\omega D_s^2 \rho/\mu$
To	torque, N·m
P	average mechanical power, W
q	heat flux, W
SSHE	surface scraped heat exchanger
NRBP	net raw biogas production
STHE	shell-and-tube heat exchanger
TS	total solid, wt.%
CSV	critical-shear viscosity, kg/(m·s)
ZSV	zero-shear viscosity, kg/(m·s)
WHRP	waste-heat recovery process
CFD	computational fluid dynamics

problems, and the conventional heat-transfer study cannot fulfil the requirements of anaerobic digestion slurries with special properties [7]. The viscosity—or, more accurately, the rheological properties—of slurries including those from anaerobic digestion is very different from that of normal working fluids. The viscosity of slurries depends on not only the temperature but also the shear rate and can be 30–700 times higher than the viscosity of water at temperatures ranging from 8 to 60 °C when the total solid content (TS) of slurries exceeds 7% [8]. Therefore, special considerations are needed for designing or improving the heat-transfer systems for such special complex rheological slurries with a high potential of fouling.

Scraped-surface heat exchangers (SSHEs) have been widely used to conduct the heat exchange for the fluids with a high apparent viscosity and fouling problem in the pharmaceutical, food, and chemical industries [9]. An SSHE consists of two coaxial cylinders with different diameters, between which a heat-transfer medium flows. A rotating shaft with two or more blades is set inside the external cylinder. Trommmelen et al. [10] presented the mechanisms of the flow and heat transfer in an SSHE, and it reveals that the rotation of the blades eliminates or weakens the fouling problems and enhances the mixing of the flow from the boundary layer with that in the bulk in the internal cylinder, resulting in a strong convective heat transfer.

For SSHE, numerous experimental studies were performed to determine the flow field and the correlations between the Nusselt number (Nu) and the operation variables, such as the Taylor number (Ta), Reynolds number (Re), and Prandtl number (Pr). Maingonnat et al. [11,12] established the correlation of Nu from the most common parameters (i.e. the rotational Reynolds number (Re_r) and Pr), which is valid for both Newtonian and homogenous non-Newtonian fluids. Dumont et al. [13] measured the shear rates of wall using the electrochemical method and reported the critical Taylor number defining the transition from a laminar flow to vortex flow. Naimi [14] studied the heat-transfer coefficient determined by Ta in different flow regimes in an SSHE. In all these experimental studies, only Newtonian and homogenous non-Newtonian fluids, such as carboxymethyl cellulose (CMC), alginate, and Carbopol solutions, were studied.

Numerical methods based on computational fluid dynamics (CFD) have been used to investigate the effects of the geometry and flow pattern on the heat transfer performance in an SSHE with 'model' fluids. Pawar et al. [15] reported that the k–ε model performed better than the Reynolds stress model (RSM) with regard to the convergence of the scraped-surface geometry, and they also pointed out that, for Newtonian fluids, only the blade could change the flow pattern. Yataghene and Legrand [16] simulated the performance of SSHE with non-Newtonian fluids containing 2 wt.% CMC and 0.2 wt.% Carbopol in a three-dimensional numerical SSHE model. They obtained the exponents of the axial Reynolds number (Re) and rotational Reynolds number (Re_r) with values of 0.059 and 0.28, respectively, in the case of 2 wt.% CMC. This implies that, for non-Newtonian fluids, the increase of the mas flow rate reduces the efficiency of the SSHE. Dehkordi et al. [9] further studied the heat-transfer performance according to Yataghene and Legrand's work [16], and their numerical results reveal that increasing the number of blades improves the local heat-transfer rate but also causes backflow at the same time. In addition, the vertical blades can sweep the fluid cross the surface of the stator-wall completely compared with the curved geometry. Therefore, the geometry with two vertical blades was recommended.

However, in the previous work on SSHE, the research focus is mainly on how to enhance the heat transfer by changing the rotation rate and the geometry of the blades. This is because that most of the fluids studied in the previous work are Newtonian or homogenous non-Newtonian, and thus the axial Reynolds number (Re) only shows a slightly influence on the heat transfer performance. This implies that there is no need to consider the effect of the mass flow rate of the fluid on the performance of SSHE for Newtonian or homogenous non-Newtonian fluids. To the best of our knowledge, the performance of SSHE has never been studied when the fluid is slurry with complex rheological properties.

For complex fluids (e.g. slurry that is an inhomogeneous non-Newtonian fluid), their axial flow rate (or their axial Reynolds number) will also affect the performance of heat exchangers (either shell-and-tube heat exchanger (STHE) or SSHE). The axial flow rate is strongly linked to the overall thermal cycle, and the performance of the heat exchanger needs to be considered