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Heat-transfer Enhancement with Pulsating Flow in Twisted Hexagonal Tube for Manure Slurry from Biogas Plants

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ABSTRACT
Biogas is one of the most crucial renewable energy and achieving high-efficient heat exchangers is the key to improve its production. In this study, the effect of pulsating flow on heat transfer in a twisted hexagonal tube with manure slurry was investigated for the first time by using computational fluid dynamics CFD. The performances of pulsating flows were simulated under different conditions, including the inlet velocity, frequencies, and amplitude of pulsating flow in the twisted hexagonal tube with different torques. Pressure drops at different frequency were further investigated. Moreover, the mechanism of heat-transfer enhancement was revealed with the evolution of the heat-transfer coefficient over time. It was found the pulsating flow achieves an 18.9% enhancement at low torque.
Keywords: heat-transfer enhancement, pulsating flow, twisted hexagonal tube, CFD, manure slurry.

NONMENCLATURE

Abbreviations	
CT	Circular tube
THT	Twisted hexagonal tube
TS	Total solid
CFD	Computational fluid dynamics
Symbols	
f	Pulsation frequency, Hz
c	Amplitude, m/s
S	Torque, m/360°
U	Inlet velocity, m/s
U_t	Transient inlet velocity, m/s
t	Time, s
K_i	Heat-transfer coefficient, W/(m^2·s)
ΔP	Average pressure drops, Pa
E	Enhancement of performance

1. INTRODUCTION

Biogas generated from waste with anaerobic fermentation is one of the most effective and clean processes to obtain renewable energy. Thermophilic fermentation at 50°C and sanitation at 70 °C are commonly operated in a full-scale biogas plant, and more than 70% of the total energy is used for realizing these operations [1]. Hence, high-efficient heat exchangers are needed to heat the substrate in feeding, maintain the operating temperature in a large-scale reactor, and cut down the heat utilization.

Slurry is the primary working fluid in biogas plants, which exhibits a high viscosity and strong non-Newtonian and shear-thinning behavior [2, 3]. Moreover, biomass particles and fibers suspended in slurries are easy to cause fouling and even clogging problems when transported in tubes for heat exchangers [4]. The complex rheological properties and particle-suspension characteristics of slurries make the conventional heat exchangers cannot fulfil the requirements from biogas plants. In our previous study [5], twisted hexagonal tube (THT) was screened as the optimal geometry for slurries from multiple twisted geometries, and its enhanced factor is up to 2. With the enhancement of heat-transfer using THT heat exchangers, up to 17% and 39% increases of production are achieved from waste-heat recovery [5] and energy conservation in external heating [6], respectively, for a full-scale biogas plant. Still, there is a need to greatly increase the production by using heat exchangers with higher performance.

Pulsating flow of complex and non-Newtonian fluids through different geometries is of great interest in various industries such as filtration devices, production of fiber-reinforced composites, catalytic chemical

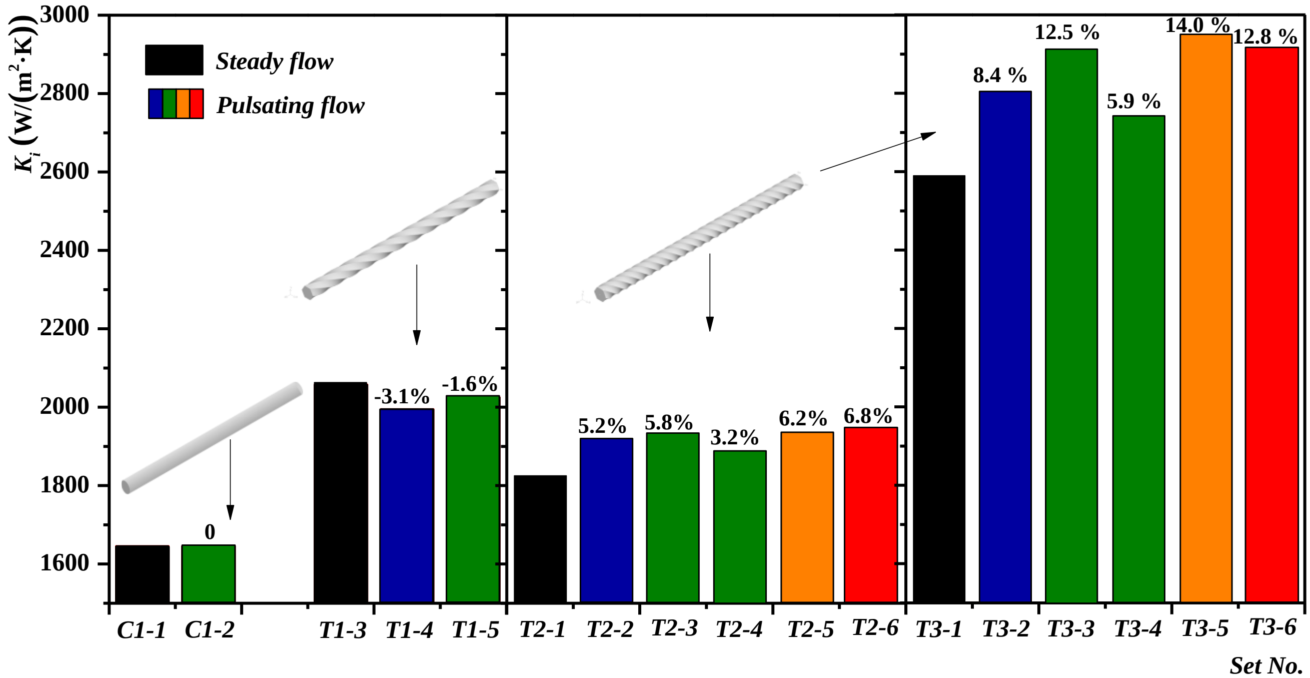

Fig 1. Performacne of pulsating flows at different tubes and operating conditions

reactors and many more [7, 8]. Tu and Deville [9] presented one of the earliest studies of blood (non-Newtonian fluid) under a pulsatile flow in arterial stenoses. Akshay et. al [10] simulated the effects of pulsating flow upon the thermal and hydrodynamic behavior of shear-thinning non-Newtonian fluid while it flows past a semi-circular cylinder channel. With the introduction of pulsation, an overall augmentation in *Nu* up to 144% was observed at the proper combination of amplitude and forcing frequency. There was also a maximum 55% decrease in the drag coefficient. Yu et. al [11] tested experimentally the fluid flow and mass transfer of sodium carboxymethyl cellulose solution in wavy-walled tubes under both steady and pulsating flows. Flow and heat-transfer behaviors with pulsating flow for non-Newtonian fluids have been extensively studied in various geometries, including the arterial stenoses [10], confining channel with a semi-circular cylinder [11], rectangular cylinder [12], microchannel heat sink [13]. However, there is no investigations of pulsating flow in twisted geometries with slurries.

In this study, manure slurry was selected as the working fluid to identify the effect of pulsating flow on flow and heat transfer in THT. CFD simulations were performed. The heat-transfer performances of THT at both steady and pulsating flows in THT, together with those of circular tubes (CTs) were simulated. The effects of inlet velocity (*U*), frequency (*f*), and amplitude (*c*) of pulsating flow in THT with different torques (*S*) on heat-transfer coefficient were investigated. Pressure drops at different *f* were calculated. Moreover, the mechanism of heat-transfer enhancement for manure slurry was revealed with the evolution of heat-transfer coefficient over time.

2. CFD MODELING

2.1 Computational domain

The parameters of THT, including their cross-sections, as well as those of CTs are the same as in our previous studies [3, 5, 6]. Considering the constraints in manufacture, the values of torque (S) in the range of 0.21–0.69 are recommended in the heat-exchanger industry [14]. Thus, THTs with *S* = 0.5 and 0.25 were studied.

2.2 Properties of manure slurry

Dynamic viscosity, density, heat capacity, and thermal conductivity are required to conduct numerical simulations. Manure slurry with TS = 9.1 was selected as the working fluids. These remaining properties of the manure slurry were determined in our previous study [3].

2.3 Boundary conditions

The sine pulsating flows with different *U*, *c*, and *f* were applied as inlet flow, as Eq. (1). For different *U*, c/U was fixed. The detailed sets of *U*, *c*, and *f* for simulation cases are listed in Table 1. For the cases of steady flow (*f* = 0), the inlet velocity is the same as *U* in pulsating flows for comparison. The other boundary conditions, including the inlet and wall temperatures, were the same for both steady and pulsating flows, and they were set as 293 and 333 K, respectively.

$U_t = U + c \cdot \sin(2\pi \cdot t \cdot f)$ (1)

Table 1. Set of the boundary conditions for the simulation

	S	*U*	*c*	*f*	*SET No.*
CT	-	2.1	0	0	*C1-1*
			1.5	8	*C1-2*
THT	0.5	2.1	0	0	*T1-3*
			1.5	4	*T1-4*
			1.5	8	*T1-5*
	0.25	0.9	0.65	0	*T2-1*
			0.65	4	*T2-2*
			0.65	8	*T2-3*
			0.45	8	*T2-4*
			0.65	16	*T2-5*
			0.65	32	*T2-6*
	0.25	2.1	1.5	0	*T3-1*
			1.5	4	*T3-2*
			1.5	8	*T3-3*
			1	8	*T3-4*
			1.5	16	*T3-5*
			1.5	32	*T3-6*

3. RESULTS AND DISCUSSIONS

Numerical methods for simulating heat-transfer performance and pressure drop of slurries in THT at steady flow have been validated in our previous studied [5, 6]. For the unsteady flow, i.e., the pulsating flow, the state at a specific time is the same as the steady flow at the same transient inlet velocity U_t. Hence, the average heat-transfer coefficient and pressure drop calculated with CFD are reliable.

3.1 Heat-transfer performance

The numerical results of average heat transfer coefficient K_i (in one pulse period) at different pulsating flows in two torque, i.e., a low twisted degree S = 0.5 and a high twisted degree S = 0.25 are illustrated in Fig 1. The conditions for the relevant numerical results are listed in Table 1.

It was found that the pulsating flow shows an evitable enhancement (3-14 %) on heat-transfer in THT with S = 0.25 (cases *T2-2* to *6* vs. *T2-1*, cases *T3-2* to *6* vs. *T3-1*), and no effect on performance in CT (case *T1-2* vs. *T1-1*), while a negative effect in THT with S = 0.5 (cases *T1-4* and *5* vs. *T1-3*). These indicate that the enhancement of performance with pulsating flow in THT can only be triggered at a high twisted degree, i.e., S = 0.25.

A higher amplitude c shows a more positive effect on the heat-transfer performance (cases *T2-3* vs. *T2-4*, cases *T3-3* vs. *T3-4*). It was also observed that the enhancement at high inlet velocity U (5.9-14.0 %) is stronger than that at low U (3.2-6.8 %). For the heat-transfer process at high U, i.e., the external heating, an optimal frequency of f = 16 was obtained for improving the performance.

3.2 Pressure drops

Pressure drop ΔP is another parameter for evaluating the heat-transfer performance. The lower the ΔP, the better the total performance for a heat-transfer process. For the THT with S = 0.25, the relation between ΔP and frequency f is displayed in Fig. 2. The pulsating flow decreases ΔP for manure slurry, which is consistent with our previous study [10].

The enhancement of performance (E) [15] was further calculated, as described in Eq. (2). Hence, E at optimal operating conditions of the pulsating flow, i.e., S = 0.25, U = 2.1 m/s, c =1.5 m/s, and f = 16 Hz can be obtained and the value is 18.9%.

$$E = \frac{(K_i)_{pulsating}/(K_i)_{steady}}{[(\Delta P)_{pulsating}/(\Delta P)_{steady}]^{1/3}} \quad (2)$$

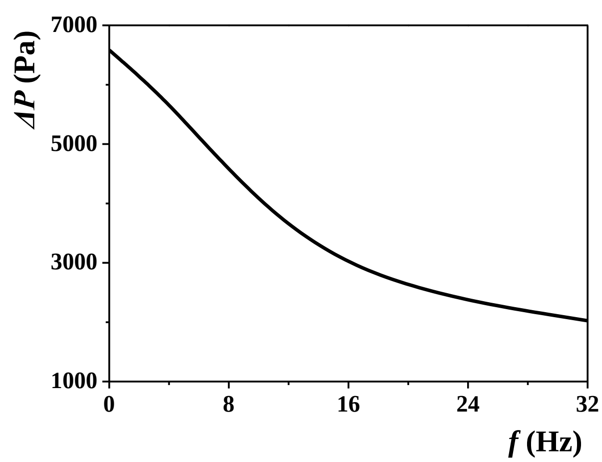

Fig 2. Average pressure drop at dfferent frenquency for THT with S = 0.25 at U = 2.1 m/s

3.3 Mechanism of heat-transfer enhancement

For the unsteady state at pulsating flow, the evolutions of heat transfer coefficient K_i at different frequencies fs are shown in Fig 3. At f = 8, the oscillation of K_i is similar to that for U_t (see Eq. (1)). This indicates the oscillation of velocity mainly determines the heat-transfer performance. It also can be observed that the duration of positive effect (higher K_i than that of steady flow) in the acceleration of pulsating flow is longer than that of negative effect (lower K_i than that of steady flow) in deceleration of pulsating flow. It can be obtained that the acceleration of pulsating flow shows a larger effect than the deceleration on heat-transfer performance. Moreover, at high frequency, i.e., f = 16 and 32, the performance is kept at a higher value compared to that of steady flow, and these trends of K_i show a higher frequency compared to the f of their inlet velocity. Hence, the total performance at an oscillation period is enhanced.

Manure slurry shows shear-thinning behavior. It is understandable that the energy of the acceleration period of pulsating flow is stored in the fluid itself. And this energy is released at the deceleration period. These explain the longer positive effect from pulsating flow on the heat-transfer performance at an oscillation period.

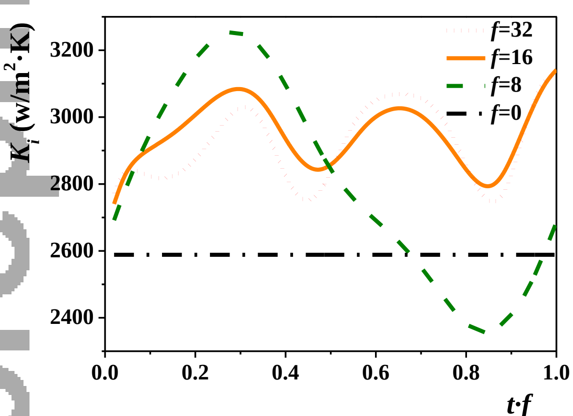

Fig 3. Heat-transfer coefficient evolution with time of pulsating flows

4. CONCLUSIONS

The effect of pulsating flow on the heat-transfer performances of manure in twisted hexagonal tubes was simulated with CFD.

The pulsating flow shows an 18.9% enhancement of performance at low torque. The mechanism of the heat-transfer enhancement was revealed as that the shear-thinning behavior of manure slurry leasing to the hysteresis of positive effect of acceleration on the performance.

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