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Flow Analysis of the Symmetric Airfoil NACA0015 Blade at Different Angles of Attack and Mixing Velocities in a Continuous Stirred Tank Reactor (CSTR)

W Manosroi[1,*], C Phapisarn[1], N Moonmuang[1] and N Yasan[1]

[1]Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, Thailand

[*]Corresponding Author: E-mail: woradej.manosroi@gmail.com

Abstract. Biogas produces from the degradation of organic compounds of garbage and water wastes from various sources such as ranch and agricultural industries, usually by the fermentation process with anaerobic microorganisms. Layers of sediment are often occurred that can block the flow and longer mixing time is required for a more homogenous mixing. The objective of this study is to solve the non-uniform and non-homogenous as well as to save the mixing time in the fermentation process of biogas production using a model-mixing reactor. Flow analysis using an image processing technique of the symmetric airfoil NACA0015 blade at different angles of attack and mixing velocities in a Continuous Stirred Tank Reactor (CSTR) was examined. The CSTR was equipped with two and three airfoil blades at the angles of attack 0, 10, 16(stall angle) and 20° operated at the mixing velocities at 80, 110, 140 and 190 rpm. The mixing efficiency was evaluated from the homogenous appearance of plastic particles (5 mm diameter) dispersed in water by an image processing technique. The results showed that the mixing efficiencies of CSTR with three blades were higher than that of the CSTR with two blades of about 1.3 folds. The mixing efficiency increased with increasing mixing velocities and angles of attack, and was almost constant when the blade angles of attack increased from 16° to 20° and the mixing velocity increased from 140 to 190 rpm. This may be due to the airfoil blade stall and the saturation of the mixing. A new blade design for the CSTR system from this study can give a more efficient stir and mixing flow which will not only be beneficial for biogas production in the laboratory scale, but also a model design for the industrial biogas production as well.

1. Introduction

Continuous Stirred Tank Reactor or CSTR is a reactor widely used for producing biogas from energy crop, manure, municipal waste, sewage, green waste or food waste due to its high mixing capability. CSTR gives higher stir and mixing efficiency than the traditional biogas digester tank. A more homogenous system will be obtain due to the higher mixing and mass transfer rate. With effective mixing, the reactive materials homogeneously distributed with negligible mass transfer resistance resulting a more biogas generation [1]. The degradation time is also shorter and higher biogas production rate achieve. A parametric study on the design variable and flow distribution of CSTR by the numerical method using the Lattice Boltzmann Technique conducted by Satjaritanun et al. [1]. CSTR for investigation of the anaerobic co-digestion of *Pennisetum purpureum* cv. Pakchong1 grass and chicken layer has been performed [2]. Watanabe et al. [3] have examined the continuous production of 6-*O*-

decanoyl, dodecanoyl, or tetradecanoyl L-ascorbate through the immobilized lipase-catalyzed condensation of L-ascorbic acid and decanoic, dodecanoic, or tetradecanoic acid in acetone using a CSTR. The dynamic behavior and thermal stability of an autothermal CSTR with two stable operation units have investigated by Furusawa et al. [4]. They found that both experimental and computational results were in good agreement. Mavros et al. [5] have used the Laser Doppler Velocimetry (LDV) to investigate the flow pattern in a stirred tank by an axial-flow impeller, while Bakker et al. [6] have investigated the flow pattern of a pitched blade turbine using Laser Doppler Velocimetry (LDV) and Digital Particle Image Velocimetry (DPIV). The flow was generated by an axial flow impeller in batch has been simulated by Khopkar et al. [7]. The effects of shaft eccentricity on the hydrodynamics of unbaffled stirred tank examined by Montante et al. [8]. There are also some studies on the flow on the hydrofoil and airfoil blade. The flow characteristics of the novel hydrofoil OK-2003 comparing with NACA0015 in the water tunnel investigated by Amromin et al. [9]. They have also investigated the lift and drag characteristics of hydrofoil shape comparing with NACA0015 in the water tunnel [10]. Weetman et al. [11] have examined the fluid forces of impeller and airfoil blade in tank.

Airfoil can generate different flows in the CSTR. However, there is no study on flow analysis of symmetric airfoil NACA0015 blades at different angles of attack and mixing velocities in the CSTR system, also, there is still no data of mixing efficiency comparison in the CSTR between the airfoil blades and other blade types. The objective of this study is to analyze and compare the flow characteristics and mixing efficiency of particles suspended in water using the two and three airfoil NACA0015 blades at different angles of attack and mixing velocities. This study can obtain a new blade design of the CSTR system for a more efficient stir and mixing flow of substances suspended in water, which will be applicable for biogas production in both the laboratory and industrial production scale.

2. Materials and Methods

2.1. Equipment and Materials

The experimental equipment was consisted of the CSTR system and a camera.

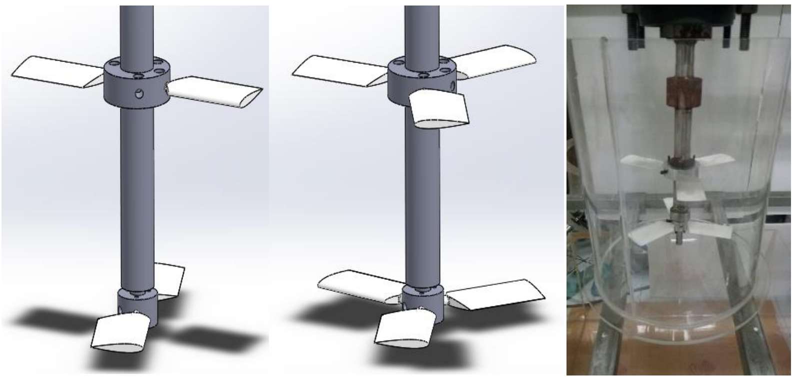
2.1.1 The CSTR system

The CSTR system consisted of an acrylic tank, a motor and the blades. The height, diameter and thickness of the tank were 0.4, 0.3 and 0.02 m respectively. **Figure 1** presented the CSTR system (b) and an acrylic tank (a). The motor was the Mitsubishi Super Line Series Induction Motor SF-JR 1/2 HP. **Figure 2** showed the plastic particles for imitating the organic substance for biogas production. The weight, density and diameter of each plastic particle were 0.11 g, 1680 kg/m^3 and 5 mm respectively. Five hundred plastic particles used in this study. The blades were the symmetric airfoil NACA0015 with two and three blades as shown in **Figure 3**.

(a) (b)

Figure 1. (a) The acrylic tank (b) The CSTR system

Figure 2. The plastic particles used in the experiment



(a) (b) (c)

Figure 3. (a) The airfoil NACA0015, (b) two blades, (c) three blades, (d) The airfoil NACA0015 with three blades in the CSTR system

2.1.2 The Camera

The Canon 600D camera used for taking pictures to investigate the mixing efficiency.

2.1.3 The Mixing Efficiency

The Mixing Efficiency analyses from the distribution of the particles using the ImageJ program and determines by the cross section area of plastic particles that detect by the camera divide by 500 plastic particles cross section. Cross-section area (A_c) of the 500 sphere plastic particles (diameter 0.5 cm each) determine by:

$$A_c = \frac{\pi(0.005)^2}{4} x500 = 9.817x10^{-3}\ m^2$$

The mixing efficiency calculates by cross section area that inject by the camera divide by cross-section area (A_c) of the 500 sphere plastic particles. For example the inject area of the plastic particles by the camera is 5.788x10^{-3} m^2:

$$Mixing\ efficiency\ = \frac{5.788x10^{-3}}{9.817x10^{-3}} = 0.59$$

2.2 *Experimental*

Figure 4 shows the experimental setup. The camera mount in front of the tank. The white paper put behind the tank for good image quality. The core in the CSTR system rotated by the motor.

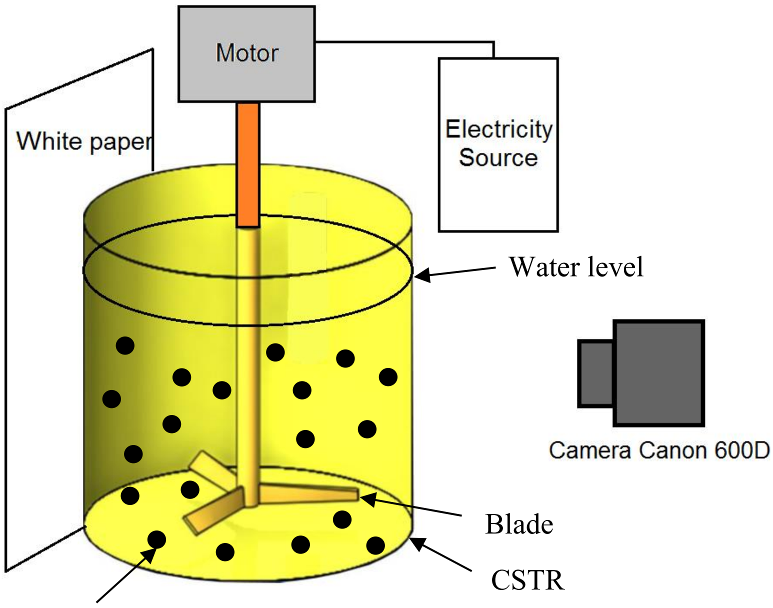


Figure 4. Experimental setup

The experiment started by five hundred plastic particles were suspended in 23 litres of water in the CSTR system as shown in with two or three blades at different angles of attacks (0, 10, 16 and 20°). Then, the motor turned on. The pictures took by the camera every second as shown in **Figure 5**. The mixing efficiency was then analysed. The mixing efficiency was increased with times and approximately constant at three second as presented in **Figure 6**. The constant mixing efficiency was determined at each combination of mixing velocities and blade angles of attack.

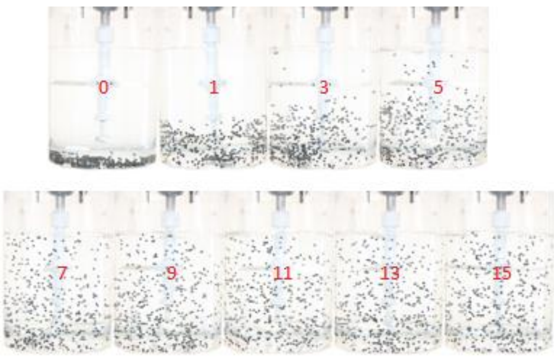


Figure 5. The CSTR pictures taken during the experiment at 0-15 s

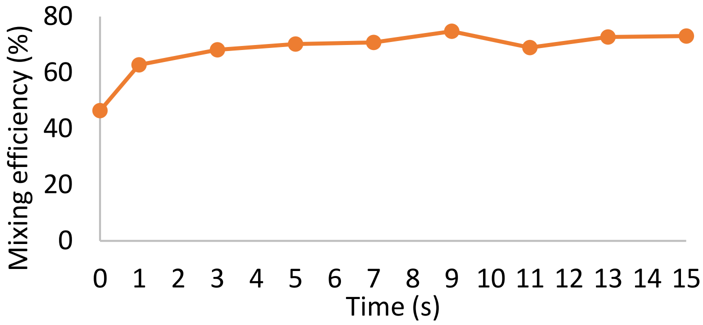


Figure 6. The mixing efficiency at each time interval (in seconds) at the angle of attack 10° and velocity at 80 rpm

3. Results and Discussion

3.1 *Effects of angles of attack on mixing efficiencies*

Figures 7, **8**, **9** and **10** displayed the effects of angles of attack at the mixing velocities of 80, 110, 140, 190 rpm respectively. The highest and lowest mixing efficiencies were 90.89 and 25.55% respectively. In almost every case, mixing efficiencies increased with increasing angles of attack. This may be due to the increase of the performing force between the particles and the blade, which increased with increasing angles of attack. The mixing efficiencies in every case of the three blades were higher than that of the two blades due to the increase of the contact area between the particles and the blades. For the two-blade system at the low mixing velocity (80 rpm) and low angles of attack (0 and 10°), mixing efficiencies were constant when the angles of attack increased from 0 to 10° owing to the not sufficient force to distribute particles in the water as shown in **Figure 7**. At high mixing velocities (140 and 190 rpm) and high angles of attack (16 and 20°), the mixing efficiencies were almost constant when the angles of attack increased from 10 to 20° because of the reaching of mixing saturation and the airfoil blade stall (16°) [12] as shown in **Figures 9** and **10**. This phenomenon agree with the work of Weetman et al. [11]. A stall is a reduction in lift coefficient generated by as Airfoil angles of attack increase. It caused by the separation of the flow behind the airfoil blade at higher angles of attack.

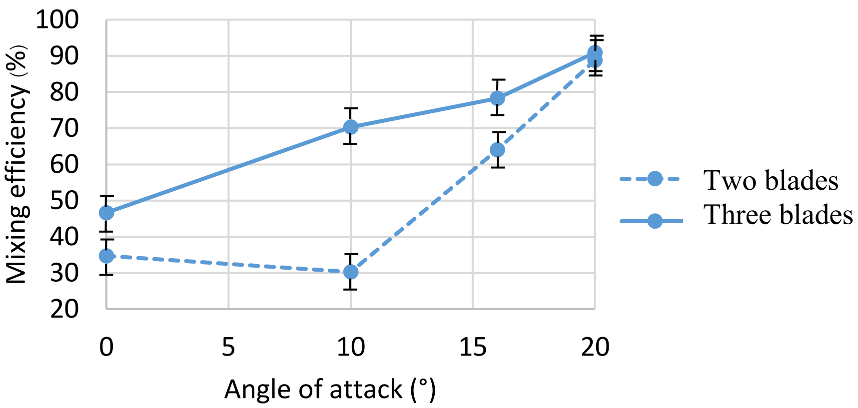


Figure 7. The mixing efficiency at each angle of attack of the mixing velocity at 80 rpm

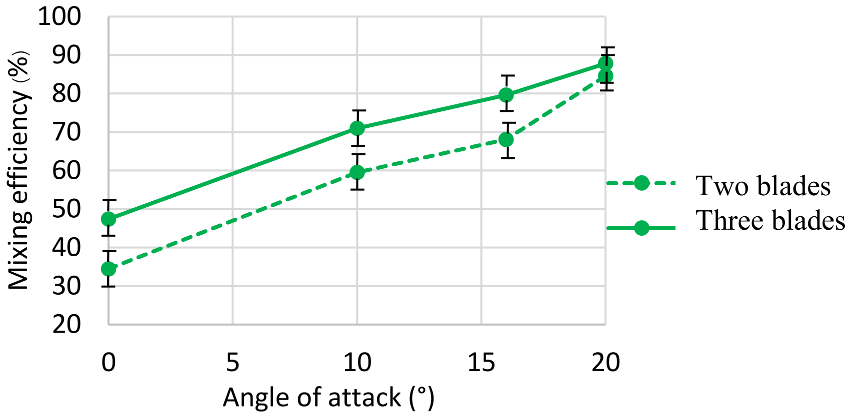


Figure 8. The mixing efficiency at each angle of attack of the mixing velocity at 110 rpm

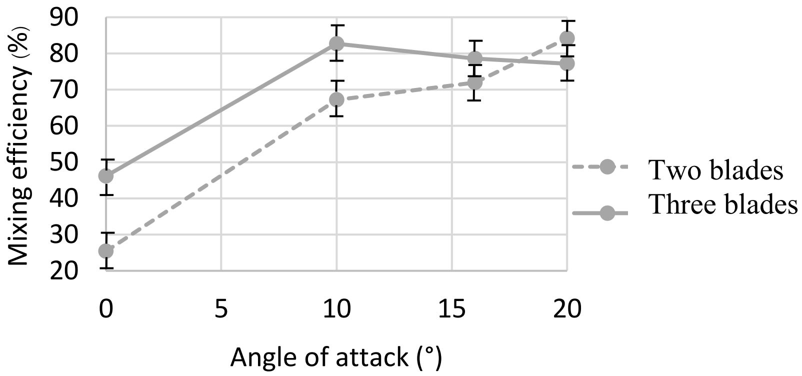


Figure 9. The mixing efficiency at each angle of attack of the mixing velocity at 140 rpm

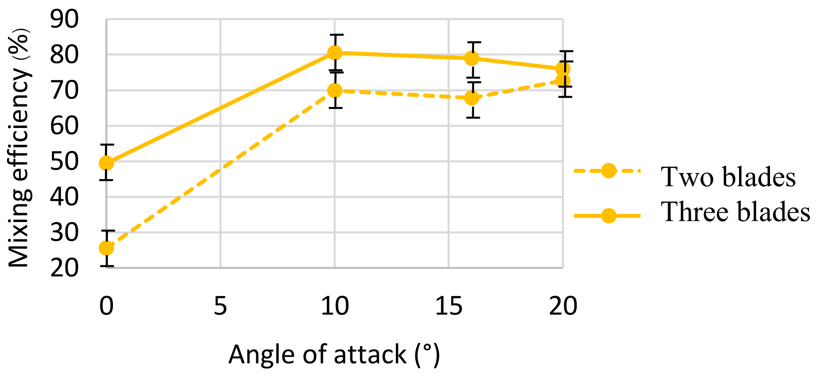


Figure 10. The mixing efficiency at each angle of attack of the mixing velocity at 190 rpm

3.2 Effects of mixing velocities on mixing efficiencies

Figures 11, **12**, **13** and **14** exhibited the effects of mixing velocities at angles of attack 0, 10, 16 and 20° on mixing efficiencies respectively. In **Figure 11** at the angle of attack at 0°, the mixing efficiency of the two blades was slightly decreased and almost constant in the case of the three blades system with increasing mixing velocity. This can be explained that at the angle of attack 0°, the force was very weak and was not enough to distribute the particles in water. In **Figure 12**, at the angle of attack 10°, the mixing efficiency increased with increasing mixing velocity due to the increasing force also the turbulent intensity of the flow that can drive the particles to distribute into the water. This result appeared to agree with the study of Khopkar et al. [7]. They reported that turbulent intensities increased with increasing mixing velocities. At high angles of attack (16° and 20°), mixing efficiencies were almost constant at the angle of attack 16° and a slight decrease at the angle of attack 20° was observed due to the airfoil blade stall (16°) as shown in **Figures 13** and **14**.

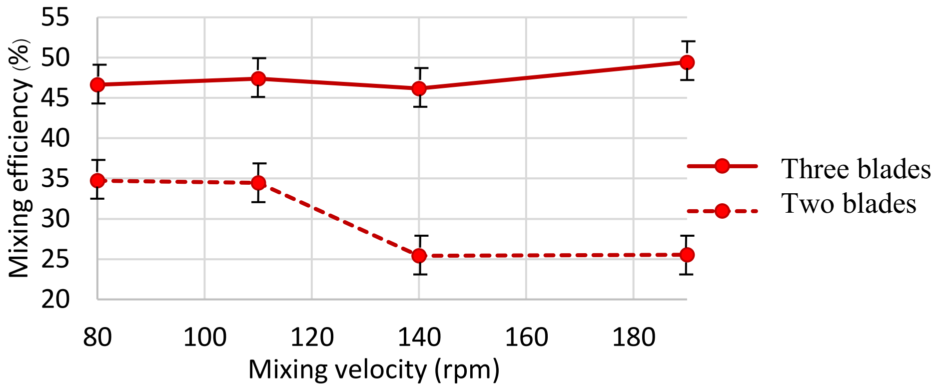


Figure 11. The mixing efficiency of each mixing velocity at the angle of attack 0°

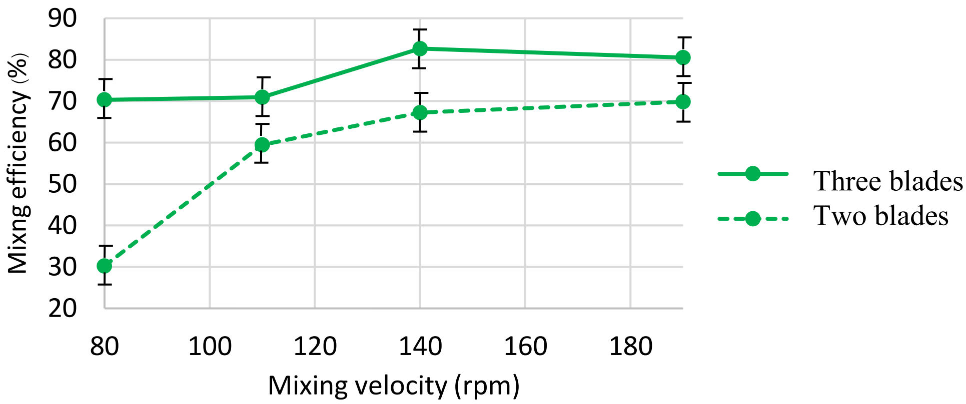


Figure 12. The mixing efficiency of each mixing velocity at the angle of attack 10°

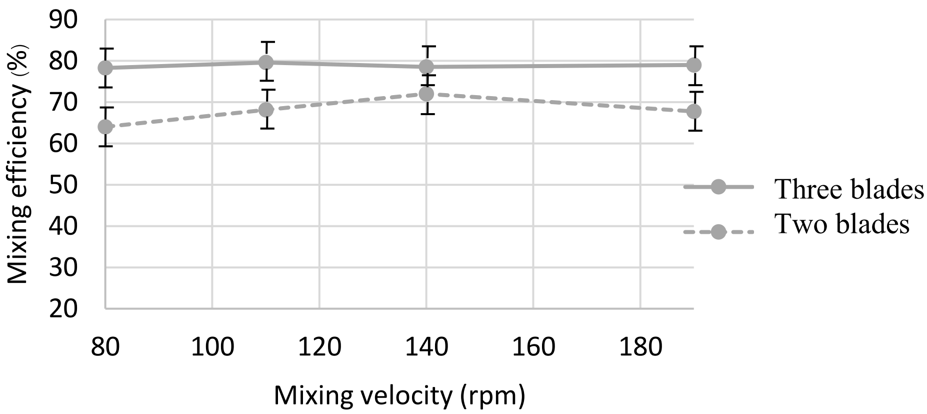


Figure 13. The mixing efficiency of each mixing velocity at the angle of attack 16°

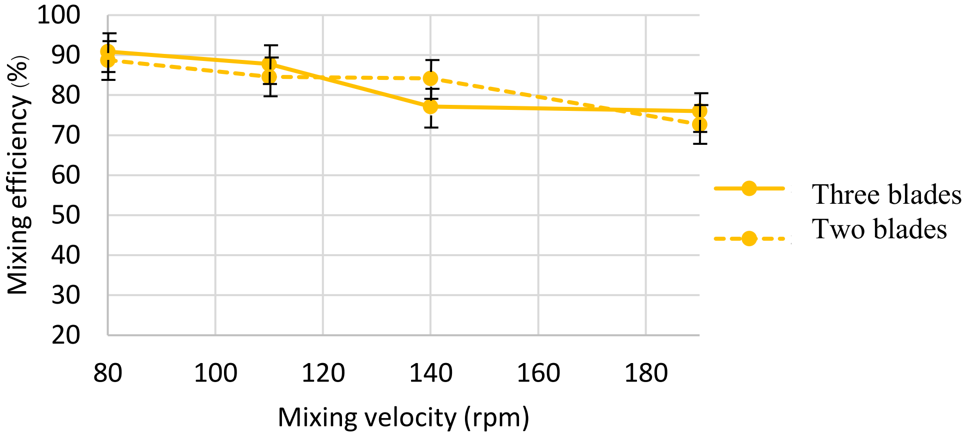


Figure 14. The mixing efficiency of each mixing velocity at the angle of attack 20°

4. Conclusion

This study has presented the flow analysis in the CSTR system using the airfoil NACA0015 of two and three blades. Effects of angles of attack and mixing velocities on mixing efficiencies were demonstrated. The mixing efficiency of the three-blade system was higher than that of the two-blade system of about 1.3 folds due to the more contact area between the particles and the blades of the three-blade system than that of the two-blade system. The mixing efficiency increased with increasing mixing velocity and angles of attack. The mixing efficiency was almost constant when the blade angles of attack increased from 16° to 20° owing to the airfoil blade stall. The mixing velocity was also almost constant when the mixing velocity increased from 140 to 190 rpm because of the reaching of mixing saturation. The information from this study can applied for a novel airfoil blade design for more mixing efficiency in the CSTR system that can be applied for not only in the biogas production, but also for other mixing operation in the CSTR system as well.

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