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Research paper

Numerical analysis of the mixing characteristic for napier grass in the continuous stirring tank reactor for biogas production

P. Satjaritanun [a], Y. Khunatorn [a], N. Vorayos [a], S. Shimpalee [b,*], E. Bringley [b]

[a] Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand
[b] Department of Chemical Engineering, University of South Carolina, Columbia, SC 29208, USA

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ABSTRACT

The objective of this work is to conduct a parametric study on the design variables and flow distribution of a Continuous Stirred Tank Reactor (CSTR). The numerical solutions were obtained by using Lattice Boltzmann Method (LBM) technique. Three different designs of CSTR with Napier grass as substance were evaluated for mixing efficiency, vorticity, and flow behavior, Model 1: one propeller no baffle tank, Model 2: one propeller with baffles tank, and Model 3: double propellers with baffles tank. The results show that the fluid velocity and the direction of fluid motion play the major role on the mixing characteristic. The propellers, baffles plates, and stirring speeds are significant factors on the fluid direction and thus the mixing performance. The solid–liquid mixing efficiency can be calculated from the numerical results of Discrete Phase Model (DPM) by image analysis technique. The mixing efficiency of Models 1, 2, and 3 are 10.08%, 23.77% and 34.66%, respectively. The power numbers which indicate the power consumption of the system of Models 1, 2, and 3 are 0.91, 1.20 and 2.00, respectively. Therefore, Model 3 gives the best mixing efficiency but requires higher energy consumption. This work also characterized the mixing quality in various depth levels. The predictions implement along with the mixing efficiency in order to evaluate mixing efficiency of the system completely.

1. Introduction

CSTR is the technology used for producing biogas from energy crop, manure, municipal waste, sewage, green waste, or food waste [1,2] due to its mixing capability. With effective mixing, the reactive materials will be homogeneously distributed with negligible mass transfer resistance resulting more biogas generation. Napier grass (Pennisetum purpureum) or elephant grass is one of the most popular energy crops for biogas production in the CSTR system. This grass is mainly composed of cellulose and hemicellulose that can be fermented to produce biogas using several microbial processes. The specific species of Napier grass that suits best as energy crop in Thailand is Pakchong 1 [3,4]. This grass has high growth and yield rates. It can be harvested 5–6 times per year with a 45–60 days harvest period producing 375–635 tonne per hectare per year (1 tonne = 1000 kg). However, the Napier grass experiences poor homogeneity in a CSTR due to its low specific gravity; thus, the current designs are inadequate for efficient biogas production [3].

Biogas can be produced by anaerobic digestion and fermentation of biodegradable materials by microorganisms inside a closed system. Other technologies for biogas production generally used are the fixed dome digester, channel digester, or up-flow anaerobic sludge blanket, for the effectiveness in the medium fermentative [5]. These systems have many advantages due to their simple construction and easy maintenance, however, they do not have the mixing capability in their system. Therefore, the advantages of the CSTR make it a preferable choice to the aforementioned technologies.

The propeller types used for agitation in the CSTR are pitched blade turbine, Rushton turbine, and Hydrofoil [6,7], all suitable for high concentrations of solid mass. The stirring system is generally installed in the vertical or oblique direction and stopped periodically. The homogeneity also depends on other design parameters such as the presence of baffles, fluid velocity, and the direction of fluid motion.

* Corresponding author.
E-mail address: shimpale@cec.sc.edu (S. Shimpalee).

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The three-dimensional (3D) Computational Fluid Dynamics (CFD) modeling with the Lattice Boltzmann Method (LBM) was used to study the characteristics of the particles movement and mixing capability in the CSTR [8]. The multiphase model used in this work was the incorporation of the solid–liquid phase in the reactor, which has the working fluid as Napier grass (solid) mixed with the water (liquid). The tank geometry has a capacity of 20 L with a flat bottom. The CSTR has a 3-blade propeller at 45° and an adjustable rotation rate. The studies in this work include the study of causes from vortex formation, flow patterns, and the power consumption [9–11]. These studies analyzed the motion of solid particles in the liquid to find the solid–liquid mixing efficiency by using the Discrete Phase Model (DPM) with the image analysis. The DPM technique put a finite number of solid particles that have a specific size and density into the reactor to investigate the solid particles movement and their distribution in the liquid. Furthermore, the factors that impact the mixing of substance inside the reactor and their influences were discussed. The relationship between rotation rate and mixing time that affects the power consumption to agitation and economic value were reported.

2. Model development

2.1. Lattice Boltzmann method (LBM)

LBM was originally developed as an improved modification of the Lattice Gas Cellular Automata (LGCA) to remove statistical noise and achieve better Galilean invariance for fast flows [12,13]. LBM is one of the most powerful techniques for computational fluid dynamics of a wide variety of complex fluid flow problems including single phase, free surface, and multiphase flow model in complex geometries. This method is the concept of streaming and collisions of particles that incorporate the essential physics of microscopic and mesoscopic processes so that the macroscopic averaged properties obey the desired macroscopic equations [14]. Boltzmann's transport equation is defined as follows:

$$f_i\left(\vec{x}+\vec{e}_i\Delta t, t+\Delta t\right) - f_i\left(\vec{x},t\right) = \Omega_i\left(f_1\left(\vec{x},t\right),\ldots,\left(f_b\left(\vec{x},t\right)\right)\right),\quad i=1,\ldots,b \tag{1}$$

where f_i is the particle distribution function in direction i, $\vec{e}_i$ is the particle discrete velocity and Ω_i is the collision operator. The LBM makes use of a statistical distribution function with real variables, preserving by construction the conservation of mass, momentum, and energy [14]. In the most common approach, the collision operator can be approximated by the Bhatnagar-Gross-Krook (BGK) single relaxation time (SRT) from:

$$\Omega_i^{BGK}\left(f_i\left(\vec{x},t\right)\right) = \frac{1}{\tau}\left[f_i^{eq}\left(\vec{x},t\right) - f_i\left(\vec{x},t\right)\right] \tag{2}$$

The Boltzmann's transport equation with a single relaxation time in the Lattice Bhatnagar-Gross-Krook (LBGK) model for collision operator can be written as:

$$f_i\left(\vec{x}+\vec{e}_i\Delta t, t+\Delta t\right) - f_i\left(\vec{x},t\right) = \frac{1}{\tau}\left[f_i^{eq}\left(\vec{x},t\right) - f_i\left(\vec{x},t\right)\right] \tag{3}$$

where f_i^{eq} is the equilibrium distribution function and τ is the relaxation time which is related to the macroscopic velocity. Usually, the equilibrium distribution function adopts the following expression:

$$f_i^{eq} = \rho w_i\left\{1 + \frac{\vec{e}_{i\alpha}\vec{u}_\alpha}{c_s^2} + \frac{\vec{u}_\alpha\vec{u}_\beta}{2c_s^2}\left(\frac{\vec{e}_{i\alpha}\vec{e}_{i\beta}}{c_s^2} - \delta_{\alpha\beta}\right)\right\} \tag{4}$$

where c_s is the sound speed ($c_s = c/\sqrt{3}$), ρ is the macroscopic density, $\vec{u}$ is the macroscopic velocity, δ is the Kronecker delta, α and β subindexes denote the different spatial components of the vectors appearing in the equation, and w_i is the weight factor. The multi scale Chapman-Enskog expansion gives us the relation between the macroscopic viscosity (ν) and the relaxation parameter:

$$\nu = c_s^2\left(\tau - \frac{1}{2}\right) \text{ and } c = \frac{\Delta x}{\Delta t} \tag{5}$$

where Δx is the lattice space and Δt is the time step. For the positive viscosity, $\tau > \Delta t/2$ is required as a stability condition in addition to the relaxation time greater than 0.5.

Macroscopic variables such as density ρ and velocity $\vec{u}$ can be calculated as the moments of the density distribution function:

$$\rho = \sum_{i=1}^{b} f_i \tag{6}$$

$$\rho\vec{u} = \sum_{i=1}^{b} c f_i \vec{e}_i \tag{7}$$

The macroscopic fluid pressures are calculated from the equation of stage:

$$P = \rho c_s^2 \tag{8}$$

LBM schemes are classified as a function of the spatial dimensions m and the number of distribution functions n, resulting in the notation DmQn. The most common schemes in two dimensions are the D2Q7 and D2Q9, while in three dimensions the most used schemes are the D3Q13, D3Q15, D3Q19 and D3Q27. In this work the commercial LBM solver, XFlow 2014 (Build 94), was chosen to perform the calculation. This solver uses the twenty seven velocity D3Q27 lattice model as shown in Fig. 1.

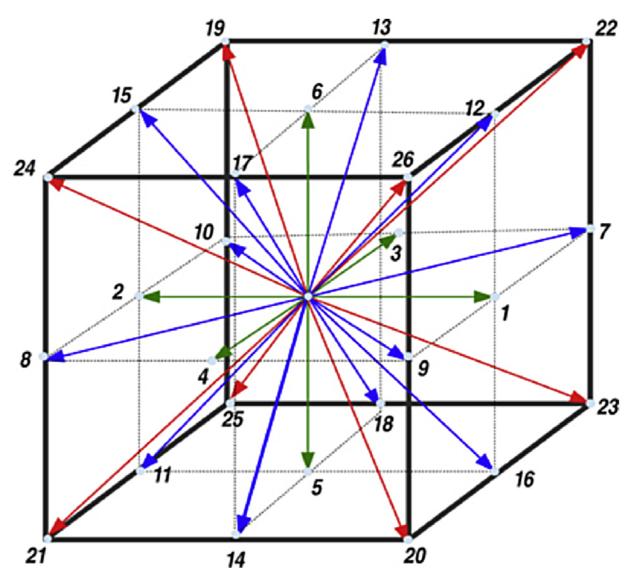

Fig. 1. The lattice structure of D3Q27 model. The weight factors (w_i) for the D3Q27 are $w_0 = 8/27$ (the cell-center), $w_i = 2/27$ (i = 1–6), $w_i = 1/54$ (i = 7–18) and $w_i = 1/126$ (i = 19–29).