The influence of bamboo-packed configuration to mixing characteristics in a fixed-bed reactor

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Abstract. Fixed-bed reactors are commonly used as bioreactors for various applications, including chemicals production and organic wastewater treatment. Bioreactors are fixed with packing materials for attaching microorganisms. Packing materials should have high surface area and enable sufficient fluid flow in the reactor. Natural materials e.g. rocks and fibres are often used as packing materials. Commercially, packing materials are also produced from polymer with the advantage of customizable shapes. The objective of this research was to study the mixing pattern in a packed-bed reactor using bamboo as packing material. Bamboo was selected for its pipe-like and porous form, as well as its abundant availability in Indonesia. The cut bamboo sticks were installed in a reactor in different configurations namely vertical, horizontal, and random. Textile dye was used as a tracer. Our results show that the vertical configuration gave the least liquid resistant flow. Yet, the random configuration was the best configuration during mixing process.

1. Introduction

Reactor type and design are determining factors in chemical and biological processes. Fixed-bed reactors are high performance reactors where the reactions occur in packing (support) material. Fixed-bed reactors are commonly used as bioreactors for various applications, including chemicals production and organic wastewater treatment [1].

Fixed-bed reactors use materials such as plastics, rocks, or ceramics as support material and locus of microbial attachment [2]. Performance of a fixed-bed reactor depends on the availability of surface area; the higher the surface area, more microorganisms can attach and form biofilm. Even though a higher surface area can be achieved by reducing the size of packing materials, smaller materials can increase the risk of pressure drop in the reactor. The ideal characteristic of packing material should have enough surface area, high porosity level, stable at various pH condition, not easily degraded or oxidized, and not toxic [3]. On the other hand, the support materials should be easy to process, low cost, and preferably available using local material.

Toda et al. [4] compared vertical and horizontal configuration of rectangular tapered packed-bed reactors. They found horizontal packed-bed reactor produced higher yield of alcohol from glucose fermentation compared with vertical packed-bed reactor. Horizontal packed-bed reactor showed high
sedimentation and accumulation of free cells, which was not occurred in the vertical packed-bed reactor.

Reactor performance is also influenced by fluid flow inside the reactor. In an up-flow fixed-bed reactor, the fluid flows from the bottom to the outlet at the upper part of the reactor. This reactor type is often used to reduce the high concentration of organic content in the agro-industrial waste [5]. This wastewater must be treated properly before being discharged into the environment.

Bamboo can grow easily and abundantly in Indonesia. The tubular form and the structural strength of bamboo can be used as an alternative for packed bed material. Bamboo has been used as packing materials for treating domestic, leather industry, milk processing, and tapioca wastewater [6–10]. Organic matter removal on bamboo media takes place through two mechanisms: absorption and decomposition by microbes [10,11]. Both of these mechanisms are supported by a specific surface area of bamboo that can reach 2100 m²/m³, which is comparable to some synthetic media of polypropylene and polyethylene [7,10].

As packing material, bamboo has the advantage of high lignocellulosic content. Experiments with various acid, alkali, and solvents showed that bamboo fibre was insoluble in 10% sulphuric acid, 15% hydrochloric acid, 17% nitric acid, 5% sodium hydroxide, ethyl acetate, carbon tetrachloride, and 13% sodium hypochlorite [12]. For application in bioreactors, such extreme condition rarely occurs. The degradation of bamboo as filter material in an anaerobic process treating wastewater from cassava starch production showed no degradation of the bamboo pieces at the end of the experiment. The lignin and cellulose remaining should not be subjected to further degradation [13].

The flow inside a fixed-bed reactor is often assumed as homogeneous. However, the structure and configuration of packing materials have significant influences on the flow [14]. For bamboo, this includes the hollow cylinder dimension and shape that influence pressure inside the reactor. The configuration of cutting bamboo as a support material must be designed to minimize disturbance of fluid flow, but still enable efficient mixing process.

In this research, the fluid flow and mixing process in a lab-scale fixed-bed reactor were investigated. Three bamboo configurations: random, vertical, and horizontal configurations were compared using water as the working fluid. Textile dye was used as the tracer.

2. Material and methods

2.1. TiO₂ photoelectrode preparation

To enable observation of fluid flow in the reactor, the experiments were performed in a transparent acrylic reactor with 18.5 cm diameter and 50 cm height (figure 1(a)). A plate was placed at 10 cm from the bottom to support the bamboo. The empty volume of the reactor (without bamboo) was 12.6 L, while the volume between bottom and top plates was 6.6 L.

![Figure 1. Reactor with different bamboo configuration: (a) Empty (control), (b) Random, (c) Vertical, (d) Horizontal.](image-url)
Bamboos with diameter of 3 - 4.5 cm were obtained from local vendor. The bamboo pieces were cut into 4.5 cm length. Bamboo pieces were placed in the reactor in random, vertical, or horizontal configuration (figures 1b - (d)). The numbers of pieces were 84 for random, 105 for vertical, and 86 for horizontal configurations. The bamboos were soaked for seven days before used for the experiment. Compared with bamboo before soaking, the soaked bamboo absorbed 0.9 L of water during the soaking process.

Water was used as the working fluid for the experiment. Red textile dye at the concentration of 0.005% (w/v) was used as the tracer.

2.2. Experimental setup
The experimental setup is presented in figure 2. The reactor was first filled with water without tracer. Colored water as the tracer was flowed into the feeding tank and let overflow to keep the water level in the feeding tank. The colored water was subsequently flowed by gravity from the feeding tank to the reactor and mixed with the water inside the reactor. The tracer needed about 60 minutes to replace the water in the reactor until they are completely mixed.

2.3. Analysis
The measured parameters during this experiment were flow rate and tracer concentration. The input flow rate was constant due to the use of pump. The output flow rate from the reactor was calculated by measuring the accumulated volume of fluid in the outlet with a measuring cylinder. Flow acceleration was analysed by comparing flow rate gradient between the three configurations during the unsteady state. To determine the flow regime inside the reactor, Reynold number (Re) was calculated as follow [15]:

\[ Re = \frac{\text{Inertial force}}{\text{Viscous force}} = \frac{\rho v L}{\mu} \]  

\( \rho \) = fluid density  
\( v \) = velocity along fluid trajectory  
\( L \) = Length of fluid trajectory  
\( \mu \) = Dynamic viscosity

Figure 2. Experimental setup.
Tracer concentration was measured with a spectrophotometer at 496 nm. The change of relative concentration between the output and input of the reactor was used as an indication of mixing process inside the reactor.

3. Results and discussion

3.1. Fluid flow profile
The flow rate from the reactor was measured and the results for the three bamboo configurations, i.e. random, vertical, and horizontal, are presented in figure 3. Experiment with a reactor with no bamboo was used as a control.

Figure 3 shows that all configurations required 15 minutes to reach a steady state. The flow rates for random, vertical, and horizontal configurations were 7.8, 8.0, and 7.3 cm³/s, respectively. Compared with the flow rate of the control experiment (8.2 cm³/s), vertical configuration had the closest and highest flow rate. As shown in figure 4, vertical configuration also showed similar trend in reaching steady state compared with control.

Due to the limitation of experimental set up, the flow rate inside the reactor could not be measured. Assuming there was no significant difference between output flow rate and flow rate inside the reactor; Reynold numbers for all experiments were in the range of 126 - 141, which means the flow inside the reactor was laminar [15]. The presence of bamboo should create local turbulences; however, the overall flow was still laminar.

In this experiment, the ratio between bamboo length and diameter was 1:1 to 1.5:1. Higher ratio (longer bamboo cut) may cause a higher flow resistance in random and horizontal configurations. On the other hand, a higher length:diameter resulted in a lower flow resistance in vertical configuration [16]. In a laboratory, lab-scale bioreactor with the same dimension using cut-bamboo with length: diameter 2:1 in vertical configuration resulted in no significant flow reduction between inlet and outlet (unpublished result).

3.2. Mixing profile
Mixing characteristic of the fluid in the reactors could be approached by comparing the color intensity of the colored water in the outlet with the inlet. Bamboo could influence mixing process in the reactors. Figure 5 shows the fluctuation of tracer concentration presented as relative concentration to inlet.
Experiment without bamboo reached a steady state after 27 minutes, after which the steady state concentration still fluctuating at 46±5%. Experiment with configuration took 33 minutes to reach the steady state concentration of 49±3%. The concentration gradient for both experiments were quite similar at 1.7 (figure 6). Random configuration showed a distinct transfer from unsteady state to steady state. The steady state concentration of 57±2% was reached after 27 minutes. Similar steady state concentration of 58±2% was occurred in horizontal configuration. However, the time to reach
steady state was 33 minutes. The results suggest that random and horizontal configuration is more optimum for mixing.

Compared to this experiment, a higher length:diameter ratio of bamboo cut may decrease the Reynolds number in random and horizontal configurations [17]. It resulted in less mixing. On the other hand, a higher length:diameter may increase Reynolds number in vertical configuration that resulted in better mixing [16].

The number of bamboo pieces in vertical configuration (105) was higher than horizontal (86) and random (84). The dye seemed to attach on the surface area of bamboo, as observed in the change of bamboo's color. Figure 5 shows that tracer concentration in vertical configuration was lower than horizontal and random. With the higher surface area in vertical configuration, more dye in the liquid could be attached compared with the other configurations. The attachment could reduce the color intensity in the reactor outlet.

Figure 6. Concentration changes during unsteady condition.

A study conducted by Swaine and Daugulis [18] confirmed the difficulties of getting a determined certainty of liquid flow characteristics in the reactor. Aspect ratio of system, packing size, reactor size, and selection of suitable tracer could influence the result of liquid flow. On the other hand, tensile stress on the position parallel to the bamboo fibre direction was about 18 times higher than to the perpendicular direction of the fibre. This characteristic can be used for the application of bamboo cutting in the bigger scale anaerobic reactor [19].

4. Conclusions
Bamboo configurations in packed/fixed bed system influence the flow rate and mixing process in the reactor. Vertical configuration in fixed bed reactors showed the least liquid resistant flow in the reactor that results in a fastest flow rate. Random configuration showed the best configuration in mixing process.

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