

HYDRAULIC BEHAVIOR IN THE DOWNFLOW HANGING SPONGE BIOREACTOR

Karakteristik Hidraulik pada Bioreaktor Downflow Hanging Sponge

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ABSTRACT

Performance efficiency in a Downflow Hanging Sponge (DHS) bioreactor is associated with the amount of time that a wastewater remains in the bioreactor. The bioreactor is considered as a plug flow reactor and its hydraulic residence time (HRT) depends on the void volume of packing material and the flow rate. In this study, hydraulic behavior of DHS bioreactor was investigated by using tracer method. Two types of sponge module covers, cylindrical plastic frame (module-1) and plastic hair roller (module-2), were investigated and compared. A concentrated NaCl solution used as an inert tracer and input as a pulse at the inlet of DHS bioreactor. Analysis of the residence time distribution (RTD) curves provided interpretation of the index distribution or holdup water (active volume), the degree of short-circuiting, number of tanks in series (the plug flow characteristic), and the dispersion number. It was found that the actual HRT was primarily shorter than theoretical HRT of each test. Holdup water of the DHS bioreactor ranged from 60% to 97% and 36% to 60% of module-1 and module-2, respectively. Eventhough module-1 has higher effective volume than module-2, result showed that the dispersion numbers of the two modules were not significant difference. Furthermore, *N-values* were found larger at a higher flow rate. It was concluded that a DHS bioreactor design should incorporated a combination of water distributor system, higher loading rate at startup process to generate a hydraulic behavior closer to an ideal plug flow.

Keywords: DHS bioreactor, tracer study, plug flow reactor, hydraulic behavior

ABSTRAK

*Efisiensi unjuk kerja bioreaktor Downflow Hanging Sponge (DHS) berkaitan dengan lamanya waktu tinggal limbah berada di dalam bioreaktor tersebut. Bioreaktor DHS dianggap sebagai suatu reaktor aliran sumbat (plug flow) dimana waktu tinggal hidraulik (HRT) tergantung pada volume pori material isian dan laju alir. Dua jenis modul digunakan dalam penelitian ini, yang diberi nama dengan module-1 dan module-2 untuk melihat pengaruh jenis modul terhadap karakteristik hidraulik. Dalam eksperimen ini, nilai HRT diteliti menggunakan metode pencacahan (tracer). Hasil dari kurva residence time distribution (RTD) dianalisis nilai volume aktif, tingkat short-circuiting, karakteristik plug flow (jumlah seri tangki berpengaduk, *N-value*), dan bilangan dispersi. Dari hasil penelitian diperoleh HRT aktual lebih singkat dari HRT teoritis. Volume aktif bioreaktor bernilai antara 60% sampai 90% dan 36% sampai 60% untuk masing-masing modul-1 dan modul-2. Walaupun volume efektif module-1 lebih besar dari modul-2, bilangan dispersi untuk kedua modul tidak berbeda secara signifikan. Nilai *N-value* diperoleh lebih besar pada laju alir lebih besar. Dari penelitian ini, maka dapat disimpulkan bahwa desain bioreaktor DHS sangat berhubungan dengan sistem distribusi limbah cair dan laju alir yang tinggi untuk mendapatkan kondisi bioreaktor mendekati sistem plug flow ideal.*

Kata kunci: Bioreaktor DHS, tracer, reaktor plug flow, karakteristik hidraulik

INTRODUCTION

Downflow Hanging Sponge (DHS) bioreactor has acknowledged significant courtesy as an appropriate municipal wastewater treatment technology which can produce highly organics, ammonium, and pathogen removal efficiency as well as a novel and low cost system (Machdar et al, 2000; Tandukar et al., 2006; Uemura and Harada, 2010).

DHS bioreactor adopts an attached growth approach by employing polyurethane sponge foam as bedding media for the growth of microbial consortium. The concept of DHS bioreactor originally proposed by Machdar et al. (1997) as a post-treatment unit of an upflow anaerobic sludge blanket (UASB) reactor for treatment of municipal wastewater.

To date, DHS bioreactors have been applied in various wastewater treatments, such as onion dehydration waste-water (El-Kamah et al., 2011) or a textile factory wastewater (Tawfik et al. 2014). The key concept of the DHS bioreactor is hanging a pore inert material in the open air. Therefore, air dissolves into the wastewater as it flows down in the DHS bioreactor and no need for external forced aeration. Moreover, the sponge material has a relatively high emptied volume which benefit for growth and attachment of active biomass (Uemura et al., 2016). Characteristics or behavior of water flowing inside the sponge material will induce biomass growth and effectiveness.

Design parameter such as types and sizes of sponge material becomes a crucial footprint during development of DHS bioreactor. Therefore, in this study, water distribution behavior in PUF sponge media was considered. Furthermore, the performance of a DHS bioreactor can be improved by modifying such parameters. Hence, the objective of this study was to investigate the influence of the sponge module type and flow rate on the plug flow characteristics of the DHS bioreactor. The study was done using tracer experiments, which produce the residence time distribution (RTD) curves.

METHODS

Experimental Set-up

The research was conducted in the Laboratory of Unit Operation of Chemical Engineering Department, Syiah Kuala University, Indonesia. The schematic set up of the experiment is presented in Fig. 1. The experiment was composed with the following units: peristaltic pump, tracer injection, DHS bioreactor, effluent bucket and magnetic stirrer, and digital conductivity meter. The DHS bioreactor consisted of two similar DHS unit set up in series. The bioreactor was made of plexiglass had height of 200 cm and internal diameter of 10 cm. A total of 254 sponge modules were loaded into the bioreactor.

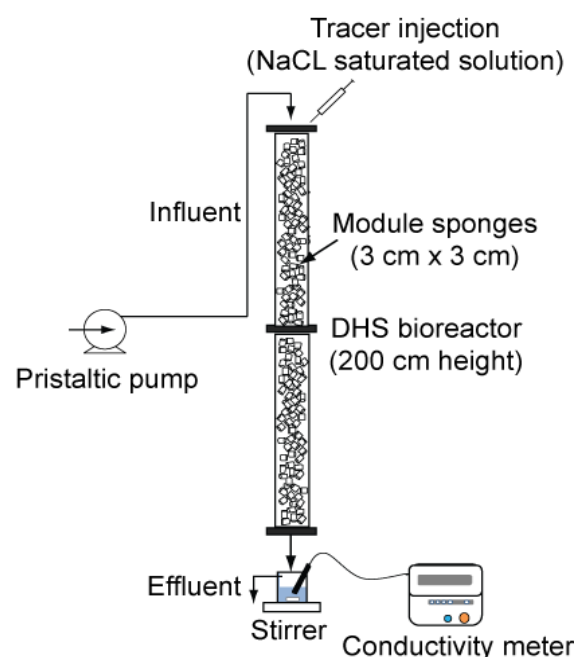


Fig. 1. Schematic diagram of experimental set-up

In this experiment, two types of sponge module were applied and evaluated at clean condition (without biomass). Sponge module-1 and module-2 were both polyurethane foam (PUF) based sponge (widely used as flexible foam seating). The sponge has a porosity lying in the range 96% to 98%. Each sponge modules is cylindrical, 35 mm in diameter and 30 mm long. Sponge module-1 and module-2 covered by a cylindrical plastic

frame to prevent compaction of the sponge. The covering of module-1 was provided by NIES-Japan and the specification available in Onodera et al., (2014). The covering of module-2 is a newly developed for scale-up purposes with budget consideration. Module-2 was covered by a plastic hair roller. The roller was easily found in market and cheaper. Fig. 2 shows photograph of the sponge modules.

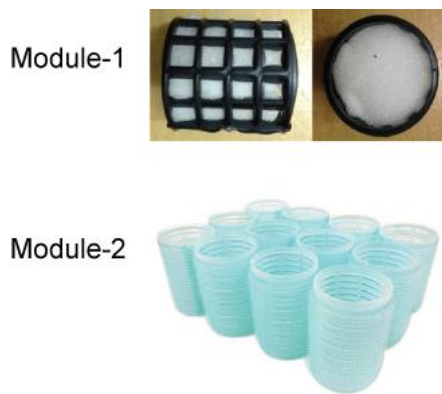


Fig. 2. Closed-up photograph of sponge module-1 and module-2

Tracer studies

A concentrated salt solution of sodium chloride (NaCl) in distilled water was used for testing of hydraulic behavior in the DHS bioreactor. This high concentration was injected in order to utilize a minimal quantity and avoid interference in the influent flow. Digital conductivity meter was continuously monitored time dependency NaCl concentration at the outlet of the DHS bioreactor to obtain residence time distribution (RTD) curves. A series of experiments were conducted at variation of flow rates and sponge module types.

Tracer data analysis

The RTD in the bioreactor can be described by the $E(t)$ curve that gives the variation of tracer concentration at the effluent and is given by the following equation (Levenspiel, 1999).

$$E(t) = \frac{C(t)}{\int_0^{\infty} C(t) dt} \quad (1)$$

It described in a quantitative appearance of a fluid distribution (hydraulic behavior) in the bioreactor. The average residence time is calculated from Eq. (2). The average residence time (t_{ave}) or actual hydraulic retention time (HRT) is a function of C_i , the measured tracer concentration at time t_i , and Δt_i which is the interval between two measurements.

$$t_{ave} = \frac{\sum_i t_i C_i \Delta t_i}{\sum_i C_i \Delta t_i} \quad (2)$$

The variance of the RTD, σ^2 , and the normalized variance, σ_{θ}^2 , can be evaluated as Eq. (3) and (4), respectively.

$$\sigma^2 = \frac{\int_0^{\infty} t^2 C dt}{\int_0^{\infty} C dt} - t_{ave}^2 \quad (3)$$

$$\sigma_{\theta}^2 = \frac{\sigma^2}{t_{ave}^2} \quad (4)$$

A dispersion number (D/uL) has been formulated by Levenspiel (1999) for significant deviations from plug flow reactor. In this context, the DHS bioreactor is assumed to be plug flow reactor. The solution is given in Eq. (5).

$$\sigma_{\theta}^2 = 2 \left(\frac{D}{uL} \right) - 2 \left(\frac{D}{uL} \right)^2 (1 - e^{-\frac{uL}{D}}) \quad (5)$$

The DHS bioreactor can be considered as a plug flow reactor. The number of tanks-in-series in the DHS bioreactor can be estimated as (Levenspiel, 1999):

$$N = \frac{1}{\sigma_{\theta}^2} \quad (6)$$

Index distribution or holdup water (active volume) is assumed by ratio of actual retention time to theoretical one.

RESULTS AND DISCUSSION

In this experiment, two replicate tests were each conducted for the 30, 60, and 90 min HRT in sponge module-1 and module-2. The representative RTD curves for the replicate tests are presented in Fig. 3. Summary calculation of tracer data analysis can be found in Table 1.

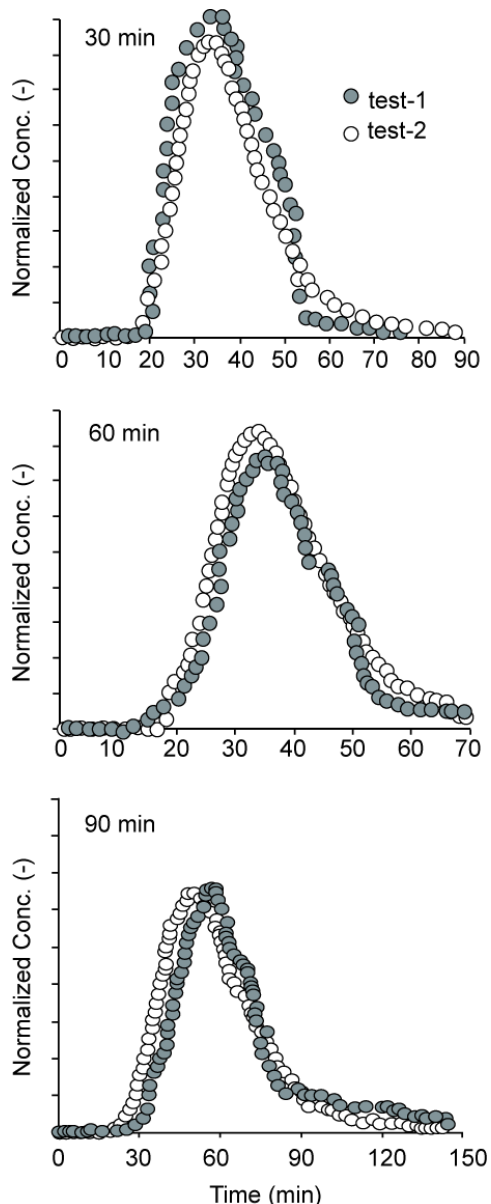


Fig. 3. Representatif RTD curve at 30 min, 60 min, and 90 min of theoretical HRT

Through Fig. 3, it is possible to examine the behavior of fluid influence to the flow pattern inside the DHS bioreactor. The RTD curve performs the probability that a fluid constituent will movement

inside the pore of sponge modules in an amount of time identical to the actual HRT. It was found that, the actual HRT was primarily shorter than theoretical HRT of each test. This was likely due to the incorporation of valuable flow pattern resulting in short-circuiting and areas of dead volume in the DHS bioreactor. Fig. 3 illustrates the presence of short-circuiting (stagnant region) in the DHS bioreactor, with inert tracer concentration increasing promptly to a maximum peak and decreasing constantly to the initial concentration. The phenomena of short-circuiting in the plug flow reactor were also reported by other researchers as a well (Yuan et al., 2004; Alcocer et al., 2012).

In this experiment, there was no significant long tailing found in the RTD curves. Tailing and attenuated peak are indicative the existence of dead zones (Levenspiel, 1999), and may also result from inflow and outflow or internal dispersion of inert tracer in a pore material. Thus, it was not observed tailing phenomena in these experiments.

From the tracer data analysis, it can be explained that the actual HRT was around 36% to 69% of the theoretical HRT, except for module-1 at an actual HRT of 30 min. This percentage values was comparable to water hold up inside the DHS sponge pore module. Lower flow rate (higher HRT) decreased the water hold up. This effect was likely due to the smaller water shear stress to penetrate at a deeper inside the sponge pore, leading to a lower a sponge pore to hold up the water. These drawbacks were generally improved through a water distributor modification and growth of the entrapped sludge inside the sponge pore (Onodera et al., 2014).

The DHS bioreactor is a plug flow system and it was equal to a number series of a continuous flow stirred tank reactor (CSTR). Therefore, if N (Eq. 6) is equal to 1, the DHS bioreactor represent one CSTR or similar to CSTR. Therefore, N number of the DHS bioreactor should be greater than one. It was found that, in module-1, lower flow rate (higher HRT) decreased N number, while in module-2, the flow rate did not affect N number significantly.

Table 1. Summary calculation of tracer data analysis

| | Module-1 | | | Module-2 | | |
|---------------------------------------|-----------------------|------|------|-----------------------|------|------|
| | Theoretical HRT (min) | | | Theoretical HRT (min) | | |
| | 30 | 60 | 90 | 30 | 60 | 90 |
| Actual HRT (min) | 29 | 36 | 62 | 18 | 30 | 31 |
| Standard Deviation (min) | 3 | 1 | 3 | 1 | 2 | 1 |
| Number of tanks in series (N) (-) | 12 | 13 | 9 | 4 | 6 | 6 |
| Dispersion coefficient (D/uL) (-) | 0.04 | 0.04 | 0.06 | 0.10 | 0.08 | 0.09 |
| Water holdup (%) | 97 | 60 | 69 | 60 | 42 | 36 |

Dispersion coefficient ranged from 0.04 to 0.06 and 0.08 to 0.10 for module-1 and module-2, respectively. Slightly higher dispersion numbers were obtained with the module-2. As the water moves along the porous sponge media, and both of the modules used similar sponge media, thus sponge media cover type would be expected to effect water dispersion.

This investigation have several constraints included the size of the bioreactor and water distributor. However, the results were found to be representative of DHS bioreactor to describe as a plug flow reactor. The effects of stagnant volume and short-circuiting of clean module and dispersion fluid were extending due to an inappropriate of the water distributor. However, these drawbacks could be anticipated in actual condition by installation an acceptable distributor system. Nevertheless, information of the hydraulic behavior of the DHS bioreactor that is necessary to improve treatment efficiency.

CONCLUSIONS

The conductivity tracer method was useful for obtaining the RTD in the DHS bioreactor. The short-circuiting and dead volume, plug flow, number of CSTR, dispersion coefficient, and water hold-up were investigated using empirical model. Results indicated that flow rate was significant parameter to be considered in the actual design of a DHS bioreactor. At a clean condition (sponge module without biomass), higher loading of water flow rate gave actual HRT closer to the theoretical HRT for the both modules. The use of module-2 (plastic hair roller) would aim to increase dispersion number and that would

increase contact time and growth of biomass.

Overall, this study presented a useful understanding into the operating condition of the DHS bioreactor which accomplishes flow profiles of plug flow characteristics. The information will help in choice of module types for scale up purpose in order to improve the DHS bioreactor removal performance.

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