Biochemical Engineering Journal 128 (2017) 186–194

Contents lists available at ScienceDirect

Biochemical Engineering Journal

journal homepage: www.elsevier.com/locate/bej

Full length article

Performance evaluation and hydraulic characteristics of an innovative controlled double circle anaerobic reactor for treating traditional Chinese medicine wastewater

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ARTICLE INFO

Article history:
Received 1 July 2017
Received in revised form
21 September 2017
Accepted 2 October 2017
Available online 4 October 2017

Keywords:
Controlled double circle anaerobic reactor
Start-up
Traditional Chinese medicine wastewater
Upflow velocity
Residence time distribution

ABSTRACT

An innovative controlled double circle (CDC) anaerobic reactor modified from the IC reactor was proposed, and the start-up process and performance of treating the traditional Chinese medicine (TCM) wastewater using both "IC reactor" and "CDC reactor" were compared. Through the controlled internal & external circulation system, sludge granulation was performed by inoculating flocculent sludge and a better performance was obtained in "CDC reactor". COD removal efficiency, methane production and volatile fatty acids (VFAs) in the stable stage of "CDC reactor" were approximately 95%, 0.33 L (g COD)$^{-1}$ and 90 mg L^{-1} respectively, with an organic loading rate (OLR) of 14.67 kg COD m^{-3} d^{-1}. Hydraulic characteristics of the CDC reactor with different upflow velocities were analysed using the residence time distribution (RTD) method. The results showed that a higher upflow velocity could lead to a smaller dead space in the CDC reactor, and thus a higher processing efficiency could be achieved. The tanks-in-series (TIS) model was proved to be more adaptive to simulate the flow characteristics of the CDC reactor than the axial dispersion (AD) model under the present experimental conditions. The hydraulic characteristics demonstrated that the good performance of the CDC reactor was ascribed to the improved reactor configuration.

1. Introduction

In recent years, the traditional Chinese medicine (TCM) industry has been rapidly developed due to the unique effectiveness of TCM, which results in a corresponding increase in TCM wastewater production [1]. The composition of TCM wastewater is determined by raw materials and production processes, mainly coming from the washing water of raw materials, the residual liquid of original medicine and floor washing water [2–4]. In general, TCM wastewater contains a large number of organic pollutants, such as lignin, pigments, carbohydrates, proteins, amino acid, alkaloids, phenols, alcohols and their hydrolysates [5,6]. Therefore, TCM wastewater is a kind of high concentration organic wastewater with poor biodegradation, which will cause the serious pollution to the environment if it is not handled.

At present, the anaerobic treatment, as a sustainable technology, is widely used in the field of industrial wastewater treatment. As a representative of the third-generation of anaerobic reactor, the internal circulation (IC) reactor has attracted more and more attention, which has many special advantages such as high organic loading rate (OLR), land-saving, resistance to shock loading, and high processing efficiency [7]. However, IC reactor has two main technical bottlenecks, which greatly limit the application of IC reactor. Firstly, IC reactor could quickly start only by the inoculation of granular sludge cultivated by the same or similar wastewater, and the seed granular sludge is very expensive. Secondly, IC reactor could only be used for high organic concentration and well biodegradable wastewater such as brewery wastewater, sugar refinery wastewater and citric acid wastewater [8,9]. However, like TCM wastewater, there are a number of industrial wastewater types with poor biodegradation and even containing toxic materials in real life, such as pharmaceutical wastewater and dyeing wastew-

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https://doi.org/10.1016/j.bej.2017.10.005
1369-703X/

ater. IC reactor is often very helpless for these types of industrial wastewater. This is because that by feeding these types of wastewater IC reactor cannot produce enough biogas to drive inner liquid circulation, so the mass transfer in IC reactor is too low to ensure a good removal efficiency [10].

For TCM wastewater, attempts have already been made by some researchers to work with anaerobic processes [2,5,11]. It has been noted that one-phase anaerobic reactors show poor removal efficiency because of the difference in the rates of acidogenesis and methanogenesis, and two-phase anaerobic reactors are difficult to control and more complex due to the increase of processing units. Therefore, in order to get a simple and efficient anaerobic reactor for treating TCM wastewater, an innovative controlled double circle (CDC) anaerobic reactor was designed by the authors on the basis of IC reactor. The CDC reactor was divided into two reaction zones by the internal & external circulation system, so the phase separation was realized in one reactor. The utilization of forced internal & external circulation devices could make up for the IC shortage of processing refractory wastewater, and could make it possible to start the CDC reactor by inoculating flocculent sludge.

The conversion of organic and inorganic matter in an anaerobic digestion process is primarily governed by two interrelated factors: the performance of the microbiological processes and the reactor's hydrodynamics which are predominantly impacted by its construction [12]. The strong interdependence of hydraulics and kinetics means that the hydraulic performance directly affects the pollutant removal performance [13,14]. Because of simple operation and high efficiency, residence time distribution (RTD) has been a popular hydraulic analysis approach in evaluating the mixing pattern and the dead space distribution in a reactor [15].

In a word, the research on the performance and hydraulic characteristics of the innovative CDC anaerobic reactor has not been reported. In this study, the start-up strategy and treatment efficiency of the CDC reactor for treating the TCM wastewater were studied. A series of RTD studies of the CDC reactor was performed to illustrate that the variance of upflow velocity (V_{up}) affected the mixing pattern and dead space. So the first objective of this research was to verify the feasibility of the CDC reactor for the treatment of TCM wastewater, and the second objective was to analyze the hydraulic characteristics of the CDC reactor to explain a more successful biological process.

2. Materials and methods

2.1. Experimental equipment

The CDC reactor has been approved as a Chinese patent (Publication Number: CN105753147A). The schematic diagram of the CDC anaerobic reactor modified from the traditional IC reactor is shown in Fig. 1. The ordinal numbers in the diagram indicate the following: I – 1st reaction area. II – 2nd reaction area. III – Precipitation area. IV – Gas-liquid separation area. 1– Influent tank. 2–Thermostatic water bath. 3– Effluent tank. 4 – Influent peristaltic pump. 5 – Hot water circulation peristaltic pump. 6 – Forced internal circulation peristaltic pump. 7 – Forced external circulation peristaltic pump. 8 – Internal circulation conversion device. 9 – External circulation conversion device. 10 – Internal circulation downcomer. 11– External circulation downcomer. 12 – CDC/IC conversion valve. 13 – Absorption bottle. 14 – Wet gas meter. 15 – Control cabinet. 16 – Heat preservation jacket. 17 – Temperature probe.

The CDC reactor was made of a polymethyl methacrylate column with a height of 1750 mm and an effective volume of 7.5 L. Similar to IC reactor, the CDC reactor was also divided into four parts from bottom to top: 1st reaction area, 2nd reaction area, precipitation area and gas-liquid separation area, whose effective volume were 2.4 L, 4.0 L, 1.1 L and 1.6 L respectively. The major differences between the CDC reactor and IC reactor were the added external circulation device and internal & external circulation conversion devices. By converting the CDC/IC conversion valve, the conversion between the CDC run mode and the IC run mode could be achieved. The CDC run mode: the internal recycle mixed liquor could come back to the first reaction area through the internal circulation downcomer, and the external recycle mixed liquor could come back to the second reaction area through the external circulation downcomer. The internal & external circulation conversion devices were composed of the switching valve set for the conversion between the automatic operation mode and forced operation mode of internal & external circulation system. In the forced operation mode, the 1st and 2nd reaction areas were forced fluidization to ensure the best mixing intensity of the biomass with wastewater regardless of whether adequate biogas was generated during operation or the initial stage of start-up. By turning off the CDC/IC conversion valve, the CDC reactor could be instantaneously converted into the IC run mode in the automatic operation mode. The IC run mode: the mixing liquid in the first reaction zone could also flow back to the first reaction zone through the internal circulation downcomer, while the mixing liquid in the second reaction zone could overflow along the inner edge of the gas-liquid separator to the first reaction zone. The CDC reactor was operated at 35 ± 1 °C, which was controlled by a thermostat. The generated biogas was passed through an absorbent bottle containing 0.5 mol L^{-1} sodium hydroxide solution to absorb carbon dioxide gas. The volume of remaining gas could be roughly defined as methane production (Methane ratio >95%) and recorded by a wet gas meter (Senlod*-LML-1, Nanjing, China).

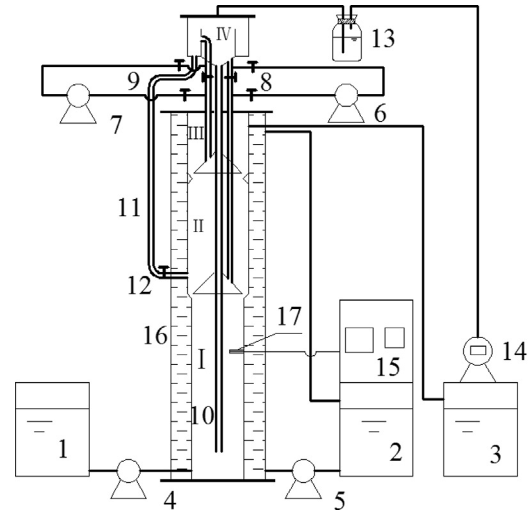

Fig. 1. Schematic diagram of the CDC anaerobic reactor.

2.2. Sludge inoculation and experimental wastewater

Flocculent sludge for inoculation was obtained from the sludge thickener of a TCM wastewater treatment plant (Hubei, China). A two-phase anaerobic-anoxic-aerobic process was adopted in this wastewater treatment plant. The seed sludge was inoculated to 30% of the reactor volume, and the suspended solids (SS) and volatile suspended solids (VSS) concentrations were 14.8 and 7.3 g L^{-1} respectively. Actual TCM wastewater that collected from the effluent of the same TCM factory was used in the start-up and stable operation of the CDC reactor. 35 wastewater samples were detected within three months in order to obtain characteristics of the raw TCM wastewater (Table 1). Tap water was used to dilute