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Study on the flow characteristics and the wastewater treatment performance in modified internal circulation reactor

Jiade Wang *, Weijun Xu, Jingjia Yan, Jianming Yu

College of Biological and Environmental Engineering, Zhejiang University of Technology, No. 18 Chao Wang Road, Hangzhou, PR China

HIGHLIGHTS

- A modified internal circulation reactor with external circulation system was made.
- The MIC reactor enhances mass transfer effect relative to the IC reactor.
- The performance of MIC reactor was better than IC reactor in different stages.
- The hydrodynamics of the MIC reactor was analyzed using CFD method.
- The optimal flow rate of external circulation in MIC reactor was 12 L min^{-1}.

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ABSTRACT

A modified internal circulation (MIC) reactor with an external circulation system was proposed and the performance of treating dyeing wastewater using both MIC and typical IC reactor were compared. Utilization of the external circulation system in the MIC reactor could dramatically improve the mixing intensity of the biomass with the wastewater and resulted in better performance. The COD removal efficiency, biogas production, volatile fatty acids and effluent color were approximately 87%, 98 L d^{-1}, 180 mg L^{-1} and 100 times, respectively, in the MIC reactor with a hydraulic retention time of 5 h and organic loading rate of 15 kg COD m^{-3} d^{-1}. The hydrodynamics of the MIC reactor under different flows rate of external circulation were also analyzed using computational fluid dynamics (CFD) method. The optimal flow rate of external circulation was 12 L min^{-1}, which resulted in a corresponding up-flow velocity of 40 m h^{-1}. The consistency of the result between experiment and simulation validated the scientificity of CFD technique applied to numerical simulation of the MIC reactor.

1. Introduction

Internal circulation (IC) anaerobic reactors can effectively solve the problem of the contradiction between long sludge retention time and short hydraulic retention time (HRT) that occurs in a traditional reactor by integrating two up-flow anaerobic sludge blanket reactors in a vertical series and a gas-driven IC system; therefore, they have become an outstanding representative in the third generation of anaerobic reactors (Lettinga et al., 1991; Pereboom and Vereijken, 1994; Habets et al., 1997; Ji et al., 2012). Owing to its many merits, which include a high organic loading rate (OLR) (20–50 kg COD m^{-3} d^{-1}), large height-diameter ratio (4–8), land saving, good granular sludge activity, steady operation, resistance to shock loading, and high processing efficiency, IC anaerobic reactors are currently being used for the treatment of limited high concentration organic wastewater and well biodegradable wastewater such as brewery wastewater and citric acid wastewater (Deng et al., 2006; Cui et al., 2011). These types of wastewater have pollutants that can be easily biodegraded by anaerobic microbial communities because of the high BOD/COD ratio of this type of wastewater; therefore, the reactor can produce higher volumes of biogas. Large biogas production at high OLRs results in a good mixing effect in the lower portion of the reactor and the high circulation ensures good mass transfer effect between granular sludge and wastewater (van der Last and Lettinga, 1992). However, the use of this system for anaerobic treatment of poorly biodegradable wastewater, such as dyeing, pharmaceutical, chemical and tannery wastewater, is still under investigation. The textile industry is one of the largest water consumers in the world (Wouter et al., 1998). Wastewater generated by different production steps of a textile mill have high pH, temperature, detergents,

* Corresponding author. Tel.: +86 571 88320915.
E-mail addresses: jdwang@zjut.edu.cn, xwj.24@163.com (J. Wang).

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oil, suspended and dissolved solids, toxic and non-biodegradable matter, color and alkalinity (Pala and Tokat, 2002). The reason for "the poor removal efficiency" when the reactors are applied to treat these types of wastewater is that there is less biogas production during the start-up period, which results in low up-flow velocity that cannot drive liquid circulation, so the mass transfer in the reactor is too low to enable a better removal efficiency.

During wastewater treatment, the substrate is first transferred from the bulk liquid via diffusion to the surface of the granule, after which successive intra-granule mass transfer and biochemical reaction within the granule occurs (Chou et al., 2008). Accordingly, hydraulic circulation enhances the mass transfer between the substrate and sludge, thereby improving performance of the treatment, including microbial growth and biodegradation, and accelerating the start-up procedure. The modified IC (MIC) reactor with external circulation could clearly demonstrate the effect of the hydraulic circulation on the reactor performance (Ding et al., 2004). Based on the IC reactor, the utilization of an added external circulation device can make up for the IC shortage due to the reduced biogas production when it is used to treat poorly biodegradable wastewater or during the start-up period. Accordingly, the anaerobic reactor has an obvious effect on removal of pollutants, which shows great potential for its application. Therefore, recent studies have focused on improving the IC reactor structure (Zhang et al., 2009). The external circulating-added IC reactor has been applied to treat brewery wastewater, and the influence of external circulation on up-flow velocity has been thoroughly investigated (Ding et al., 2004). The reactor has been shown to have good treatment efficiency, enabling great contact between wastewater and sludge. However, few studies have been conducted to explore the suitability of the MIC anaerobic reactor for poorly biodegradable wastewater treatment. Therefore, our first objective is to investigate the performance of the MIC reactor for the treatment of actual dyeing wastewater at medium temperature range. Specifically, this study was conducted to explore a feasible anaerobic reactor to treat poorly biodegradable wastewater.

Computational fluid dynamics (CFD) has been an effective approach in simulating the flow field because of its advantages, such as the reduction of time and costs (Manninen et al., 2013). In order to forecast the treatment performance, the hydrodynamics of the MIC reactor under different flows rate of external circulation was evaluated by using CFD tools (Deshmukh et al., 2009). The CFD tools make it possible to visualize the detailed velocity distribution of the fluid in the reactor under different operating conditions (Kumar and Bansal, 2012). Our second objective is to analyze velocity fields, turbulence intensity and volume fraction of sludge by CFD to explicate the reason of different treatment performance.

2. Materials and methods

2.1. Experimental equipment

A schematic diagram of the MIC anaerobic reactor modified from the traditional IC anaerobic reactor is shown in Fig. 1. The reactor was composed of a polymethyl methacrylate column with a diameter of 150 mm, height of 2500 mm, and effective volume of 20 L. The reactor could be divided into five areas from bottom to top: a mixed area, 1st anaerobic area, 2nd anaerobic area, precipitation area and gas–liquid separation area, similar to the IC reactor (Cui et al., 2011). This device also consisted of two three-phase separators, a biogas rising pipe and a sludge descending pipe (Irvine and Busch, 1979). In addition, the reactor was equipped with a heat preservation jacket, and a thermostatic water bath to control the reactor temperature by circulation of water. All technological parameters were adjusted by a computer controller. The major difference between the MIC reactor and the IC reactor was the external circulation device, which was added to the 1st anaerobic area to create fluidization of the 1st anaerobic area to ensure the best mixing intensity of the biomass with wastewater regardless of whether less biogas was generated during operation or the initial stage of startup. The flow rate of the external circulation was controlled by a recirculation pump. As a result of the improved structure, the mass transfer effect and the treatment efficiency were strengthened, which could save time at start-up and be applied to treat poorly biodegradable wastewater.

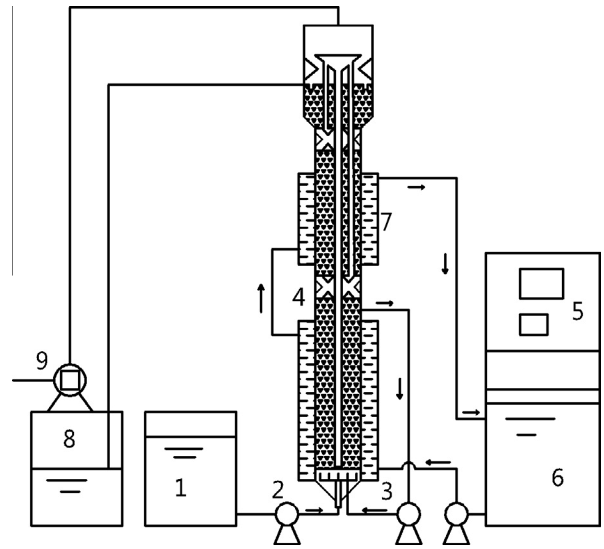

Fig. 1. Schematic diagram of the MIC anaerobic reactor. 1 – Influent tank. 2 – Influent peristaltic pump. 3 – External circulation device. 4 – Key reactor. 5 – Control cabinet. 6 – Thermostatic water bath. 7 – Heat preservation jacket. 8 – Effluent tank. 9 – Wet gas meter.

2.2. Experimental wastewater

Dyeing wastewater used in this study was obtained from a printing and dyeing mill located in Shaoxing City, Zhejiang Province. The pH of the original sample was approximately 8–10, while the COD and BOD were about 3000 ± 200 and 600 ± 100 mg L^{-1}, respectively. H_2SO_4 was used to adjust the feed water to pH 6.5–7.5 to ensure the optimal pH range of microorganisms. Urea and KH_2PO_4 were added to regulate the value of COD/N/P to be about 200/5/1 throughout the experimental process. The wastewater also contained some trace elements, including Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+}, Co^{2+}, Mn^{2+} and Ni^{2+}.

2.3. Sludge inoculation

Flocculent sludge for inoculation was obtained from the printing and dyeing mill as described above. The average diameter of the seeds was 45.6 μm, and the initial SS concentration of the reactor was 10.4 g L^{-1} and VSS/SS was 0.5.

2.4. Experimental methods

The flocculent sludge was activated and inoculated in the anaerobic reactor. The experiments were carried out under the same conditions to assess the performance of the IC reactor and the MIC reactor. The COD removal rate was investigated under different external circulation flow rate (3, 6, 9, 12, 15 L min^{-1}) before this experiment. And the optimal flow rate of external circulation was 12 L min^{-1}, which resulted in a corresponding up-flow