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Techno-economic analysis of dark fermentative hydrogen production from molasses in a continuous mixed immobilized sludge reactor

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ABSTRACT

The techno-economic analysis of dark fermentative hydrogen production from molasses in a novel continuous mixed immobilized sludge reactor was performed. The hydrogen-producing plant was assumed to be built in Hangzhou with lifetime of 10 years. The effect of the working volume (10–50 m^3) on the economic performance of hydrogen-producing plant was also investigated. The mass and energy balance of the bioprocess was simulated using Super-Pro Designer. The return on investments increased from −37.2% to 47.3% with scales increasing from 10 m^3 to 50 m^3. Only the scales of 40 m^3 and 50 m^3 could get positive benefits with payback periods of 9.7 years and 6.9 years, respectively. The internal rate of return of scales of 40 m^3 and 50 m^3 were 0.63% and 9.25%, respectively, which meant the hydrogen-producing plant with higher scale (50 m^3) would be more economically feasible.

1. Introduction

Fossil fuels have played an important role in the development of society and industry (Jung et al., 2011). Now, they are facing two major problems: gradual depletion and environmental pollution (Wang et al., 2011). So, it is necessary to find alternative energy sources which are sustainable and environmentally friendly (Van-Ginkel et al., 2005). Hydrogen is considered to be a promising alternative energy since it is renewable and clean. Moreover, the energy density of hydrogen is 122 kJ/g which is three times of fossil fuel (Abbasi and Abbasi, 2011; Han et al., 2016). However, hydrogen is not available in nature and produced by costly chemical process, such as steam reforming of natural gas (Kim et al., 2011). Biological hydrogen production has attracted great attention because it can be performed at ambient temperature and pressure (Hallenbeck et al., 2012; Das and Veziroglu, 2008). Generally, biological hydrogen production could be divided into two categories: photo fermentation and dark fermentation (Panagiotopoulos et al., 2010). Compared to photo fermentation, dark fermentative hydrogen production could be realized with advantages of higher hydrogen production rate and absence of light (Sagnak et al., 2011). Moreover, dark fermentation could utilize a wide range of organic substrates (such as hexoses and pentoses) for hydrogen production (Urbaniec and Grabarczyk, 2009; Panagiotopoulos et al., 2015). At present, the major challenges to the development of dark fermentative hydrogen production are the low hydrogen yield and high cost (Xu et al., 2011; Kengen et al., 2009). Utilization of raw material (such as molasses) as substrate for dark fermentative hydrogen production, which could effectively reduce the cost, is regarded as a promising solution (Özgür et al., 2010; Urbaniec and Grabarczyk, 2009).

Suspended cell cultures have been frequently used for dark fermentative hydrogen production, such as continuous stirred tank reactor (CSTR) (Tang et al., 2014) and continuously stirred anaerobic bioreactor (Li et al., 2012). However, the suspended cell system often encounters the problem of biomass washout at high dilution rates and needs to recycle biomass from the effluent to maintain sufficient cell density (Ren et al., 2010). Immobilized cell system has been successfully applied to wastewater treatment in various bioreactors, including fluidized bed reactors (Barros and Silva, 2012), carrier induced granular sludge beds (Lee et al., 2008) and up-flow anaerobic sludge beds (Cheng et al., 2012). However, researches on using immobilized sludge for dark fermentative hydrogen production are limited.

In our previous study, we have successfully demonstrated the feasibility of dark fermentative hydrogen production from molasses

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in a novel continuous mixed immobilized sludge reactor (CMISR) (Han et al., 2012, 2015a). The CMISR, which has been proved to be operated with low pH, high organic loading rate (OLR) and low hydraulic retention time (HRT), could be a promising immobilized sludge system for dark fermentative hydrogen production. In the light of the technical feasibility, this study aims to evaluate the economic feasibility of dark fermentative hydrogen production from molasses in the CMISR. It is hoped that data obtained from this study will provide basic information for dark fermentative hydrogen production in the industrial scale.

2. Materials and methods

2.1. Process description

The process for dark fermentative hydrogen production from molasses in the CMISR was based on our previous study (Han et al., 2012) and the process scheme was depicted in Fig. 1.

Molasses was used as raw material for dark fermentative hydrogen production in this study. It was collected from a local sugar refining industry and its characteristics were shown in Table 1. The sucrose concentration was determined using the high performance liquid chromatography (HPLC) system, which was equipped with a BIO-RAD column, a refractive index detector and a photodiode array analyzer. The detailed procedure of sucrose measurement was described in our previous study (Han et al., 2015b, c). The seed sludge used in this study was the anaerobic sludge obtained from a local municipal wastewater treatment plant. Before used as inoculum for dark fermentative hydrogen production, the seed sludge was heat pretreated at temperature of 100 °C for 6 h to inhibit methanogenic activity and then added into the CMISR.

The CMISR was initially packed with activated carbon as support carrier for cell immobilization and retention at a volume (L) to mass (g) ratio of 1:200. The heat pretreated sludge was first seeded in the CMISR for 24 h at a hydraulic retention time (HRT) of 6 h for immobilization of cells. It was observed that the heat pretreated sludge immobilization on activated carbon and granular sludge were formed after 24 h of cultivation in the CMISR. The physical characteristics of granular activated carbon were described in our previous studies (Han et al., 2012, 2015a). Then, the CMISR was operated for dark fermentative hydrogen production from molasses. The optimal conditions were obtained with an organic loading rate (OLR) of 32 kg/(m^3 d), temperature of 35 °C and HRT of 6 h. As the result, the maximum hydrogen production rate of 12.51 mmol/(hL) or 6.73 L H_2/(dL) was obtained (Han et al., 2012). According to the achieved hydrogen production rate, the annual hydrogen yield of the hydrogen-producing plant with different working volumes (10–50 m^3) could be calculated.

The produced biogas (mainly hydrogen and carbon dioxide) was separated by a purification system which included a low-pressure gas tank, a carbon dioxide compressor, an activated carbon filter, an absorbing type desiccator, a compression refrigerator and a storage tank. It was assumed that 8% of the produced hydrogen was lost in the purification system and the purity of the purified hydrogen was 99% (Chang et al., 2011; Li et al., 2012).

2.2. Economic analysis

With the mass and energy balance from the simulation of SuperPro Designer, various economic parameters (such as equipment purchase cost and additional direct/indirect cost) and variables (such as the quantity of molasses treated, hydrogen and carbon dioxide prices) were assessed to conclude the economic feasibility of dark fermentative hydrogen production from molasses in the CMISR.

2.2.1. Total capital investment

Total capital investment (TCI) could be divided into two categories: equipment purchase cost and additional direct/indirect cost for building the plant (Eq. (1)) (Kalinci et al., 2015). The equipment quotations were provided by Shuangzi Machinery Factory in Zhejiang province, China. In addition to the purchase of bare equipment, additional direct/indirect costs (such as installation, piping and construction) were also considered (Urbaniec and Grabarczyk, 2014).

$$\begin{aligned}\text{TCI} = {} & \text{Equipment purchase cost} \\ & + \text{Additional direct/indirect costs}\end{aligned} \tag{1}$$

2.2.2. Total annual cost

The total annual cost of the hydrogen-producing plant included annual depreciation cost, annual working cost and annual production cost. As the lifetime of the hydrogen-producing plant was 10 years, the annual depreciation cost could be calculated according to Eq. (2).

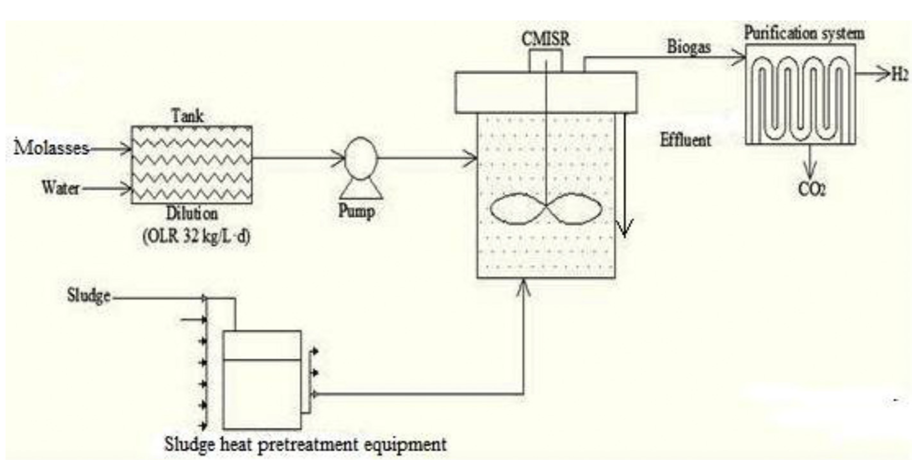

Fig. 1. Process scheme of dark fermentative hydrogen production from molasses in the CMISR.