Bioresource Technology 156 (2014) 357–363

Contents lists available at ScienceDirect

Bioresource Technology

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

Review

Fermentative hydrogen production in anaerobic membrane bioreactors: A review

P. Bakonyi, N. Nemestóthy, V. Simon, K. Bélafi-Bakó *

Research Institute on Bioengineering, Membrane Technology and Energetics, University of Pannonia, Egyetem ut 10, 8200 Veszprém, Hungary

HIGHLIGHTS

- Anaerobic, integrated membrane bioreactors (AnMBRs) are reviewed.
- Specific AnMBR applications for biohydrogen production are discussed.
- Hydrogen generation possibilities and potentials in AnMBRs are critically evaluated.

ARTICLE INFO

Article history:
Received 6 December 2013
Received in revised form 16 January 2014
Accepted 20 January 2014
Available online 28 January 2014

Keywords:
Biohydrogen
Bioreactor
Design
Membrane
Integrated system

ABSTRACT

Reactor design considerations are crucial aspects of dark fermentative hydrogen production. During the last decades, many types of reactors have been developed and used in order to drive biohydrogen technology towards practicality and economical-feasibility. In general, the ultimate aim is to improve the key features of the process, namely the H_2 yields and generation rates. Among the various configurations, the traditional, completely stirred tank reactors (CSTRs) are still the most routinely employed ones. However, due to their limitations, there is a progress to develop more reliable alternatives. One of the research directions points to systems combining membranes, which are called as anaerobic membrane bioreactors (AnMBR). The aim of this paper is to summarize and highlight the recent biohydrogen related work done on AnMBRs and moreover to evaluate their performances and potentials in comparison with their conventional CSTR counterparts.

1. Introduction

Hydrogen represents one of the highly attractive directions in alternative energy research (Winter, 2009). It is an environmentally gentle compound which can be formed by several biological ways including both the light-dependent and dark fermentative processes (Show et al., 2012). Nowadays, considering practicality aspects, the latter class seems more feasible and therefore not only receives high scientific attention in laboratories but also there is a remarkable, ongoing progress towards scaling-up. As a result, a couple of pilot plants have recently been established (La Licata et al., 2011; Lin et al., 2011) and demonstration as well as full-scale facilities may be expected (Guo et al., 2010). Although fermentative hydrogen production is undoubtedly promising and it is developing step by step to a level of real field applications, scientists need to spend additional efforts to enhance the overall process efficiency, preferentially by using waste materials (Sinha and Pandey, 2011). In particular, from the upstream point of view, further advancements are essential to attain better generation rates and yields so that hydrogen can be made more competitive with other energy carriers e.g. in economical terms (Hallenbeck and Ghosh, 2009). Nevertheless, it has been shown that the fate of biohydrogen is also dependent on the successfulness of the downstream technology which may contribute to the intensification of the production side (Bakonyi et al., 2013).

Hence, various biological and engineering approaches have been suggested with the aims mentioned, such as the construction of more sufficient and robust hydrogen producer microorganisms (metabolic- and genetic engineering), fermentation optimization and bioreactor design (Guo et al., 2010). All of these approaches possess high importance because strains require proper surroundings (e.g. pH, temperature, H_2 partial pressure, mass transfer, etc.) to express their advantageous properties (Wang and Wan, 2009). Moreover, since bioreactors are the places of the microbiological hydrogen conversion, their quality features such as type and configuration significantly affect the applications reliability. In the last decade, as a response to the demand for biosystems with upgraded hydrogen generation performance, several researchers have started to deal with the novel and innovative way of combining traditional hydrogen fermenters with membrane technology. Recently, our group comprehensively assessed the integration

---

* Corresponding author. Tel.: +36 88 624726; fax: +36 88 624292.
E-mail address: bako@almos.uni-pannon.hu (K. Bélafi-Bakó).

0960-8524/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2014.01.079

possibilities of membranes and bioreactors for biohydrogen recovery and enrichment in *gas separation membrane bioreactors* (Bakonyi et al., 2013) or in other words, in *hydrogen extractive membrane bioreactors* (Ramírez-Morales et al., 2013). This is one particular way to establish membrane-based systems for fermentative hydrogen technology. Another one is the design of anaerobic bioreactors employing membranes in the liquid phase, which are in the scope of the present paper. Although a couple of review papers have recently been published on anaerobic membranes bioreactors (AnMBR) (Lin et al.,2013; Ozgun et al., 2013; Singhania et al., 2012; Smith et al., 2012) and their potential for hydrogen production was enlightened (Gallucci et al., 2013; Jung et al., 2011), H_2 production in systems combining liquid filtration membranes has not specifically been addressed and evaluated so far.

Therefore, this work attempts to overview the progress on the anaerobic membrane bioreactors used in the fermentative hydrogen technology. Firstly, the main features of conventional, anaerobic membrane bioreactors are presented. Thereafter, several main process considerations (retention time, nutrient loading, membrane related issues) affecting the performance of *anaerobic hydrogen producing membrane bioreactors* (AnHPMBR) are discussed. Finally, the feasibility of AnMBRs for biological hydrogen generation in comparison to the traditional CSTRs will be evaluated.

2. General features of AnMBR systems

AnMBRs have been used for a long time in different fields, mostly in waste water treatment for process intensification purposes even at full-scale plants (Judd, 2008).

Integrated systems assisted by membranes – being either aerobic or anaerobic and regardless the purpose of use – can be distinguished as external loop (Fig. 1A) and submerged (Fig. 1B) bioreactors (Yang et al., 2006). In the former case, as indicated in Fig. 1A, the liquid filtration membrane module is linked to the reactor from outside and handles the circulating fermentation broth. In the latter solution, as demonstrated in Fig. 1B, the membrane module is sunk in the liquid phase of the reactor vessel or sometimes immersed in a separate tank.

Both types of bioreactors have their own advantages and disadvantages. Basically, the external loop arrangement is recognized with a higher operation energy demand but cleaning and replacement of the membrane is easier to perform. On the other hand, submerged membrane bioreactors are less energy intense but require larger membrane surface area to ensure sufficiently high permeate fluxes in comparison to their external loop counterparts (Lin et al., 2013). As foreshadowed in Figs. 1B and 2, AnMBRs can be operated in bubble coarse mode when headspace gases are recycled to the bottom of the reactor through diffusers or spargers. On one hand, it can help mixing and gas bubbles contacting the membrane surface may contribute to reduce the developing cake layer. On the other hand, continuous gas flushing can improve the liquid to gaseous phase mass transfer rate so that dissolved gases are more efficiently removed. Theoretically, it is desirable in the case of dark fermentative hydrogen production since the catalytic activity of hydrogenase enzymes can be sensitive to increasing H_2 concentrations in the aqueous phase (Bakonyi et al., 2013; Hallenbeck, 2009; Nath and Das, 2004; Ramírez-Morales et al., 2013).

Taking into account the possible reactor configurations, membranes are most commonly joined to completely stirred tanks. However, there are some alternative solutions such as certain kinds of upflow- and granular sludge bioreactors (Ozgun et al., 2013). From the viewpoint of the membrane, it can be noticed that membranes made of several commercial polymers e.g. PE, PP, PVDF, etc. are preferentially applied due to process economical reasons. These materials are often built into flat sheet and tubular modules. Furthermore, the hollow fiber configuration is also favorable because of its high packing density (Santos and Judd, 2010).

In general, based on the experiences with anaerobic membrane bioreactors their implementation could appear to be prosperous but it is important to note their limits and drawbacks. It is a common observation that in integrated systems – combining

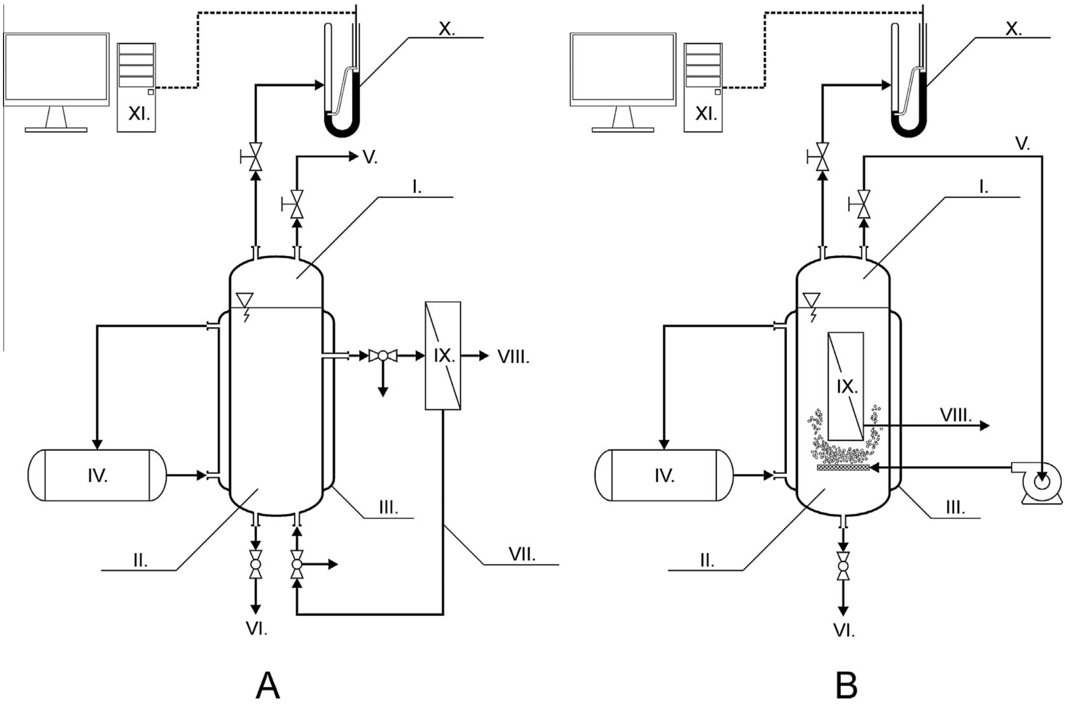

Fig. 1. External loop (A) and submerged (B) anaerobic membrane bioreactors I – Headspace, II – Fermentation media, III – Double-wall water jacket, IV – Temperature control, V – Gas sampling/recycling, VI – Spent media, VII – Retentate stream, VIII – Permeate stream, IX – Membrane module, X – Gas meter, XI – Data acquisition (PC).