Optimization of a Two-stage Bio-hydrogen Fermentation Process

W. Wukovits, D. Foglia, A. Friedl, M. Ljunggren

This document appeared in

Detlef Stolten, Thomas Grube (Eds.):
18th World Hydrogen Energy Conference 2010 - WHEC 2010
Parallel Sessions Book 2: Hydrogen Production Technologies – Part 1
Proceedings of the WHEC, May 16.-21. 2010, Essen
Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-2
Institute of Energy Research - Fuel Cells (IEF-3)
Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010
ISBN: 978-3-89336-652-1

Optimization of a Two-stage Bio-hydrogen Fermentation Process

Walter Wukovits, **Domenico Foglia**, **Anton Friedl**, Vienna University of Technology, Austria
Mattias Ljunggren, Lund University, Sweden

1 Introduction

The transport sector accounts for 60% of the world's oil consumption. Substituting oil with a CO_2 free emission energy carrier would significantly slow down the increase in CO_2 concentration in the atmosphere and therefore solve most of the problems related to greenhouse gases [1].

Different processes are under investigation for the production of cheap sustainable hydrogen, including thermochemical conversion of biomass and waste, biological water splitting with algae and fermentative processes. Other processes under discussion involve electricity obtained from renewable resources to obtain hydrogen through electrolysis of water.

Compared to thermochemical conversion, advantages of fermentative hydrogen production are mainly connected to the possible integration of production facilities in the local agricultural context, due to the possible use of different types of wet feedstock and residues, the opportunity to produce hydrogen in small scale facilities, and the possible use of fermentation effluents as a fertilizer.

2 Process Description and Simulation Models

A 2-stage bioprocess investigated in the EU-project HYVOLUTION is a promising method for biological production of hydrogen from biomass [2]. The proposed process consists of a pretreatment step to make sugars contained in the feedstock available for the thermophilic bacteria, a thermophilic fermentation step (THF) to produce hydrogen, CO_2 and intermediates followed by a photo-heterotrophic fermentation step (PHF), in which these intermediates are converted to more hydrogen and CO_2. Produced raw gas from both fermentation steps is purified up to 97 % (v/v) hydrogen in a gas-upgrading step.

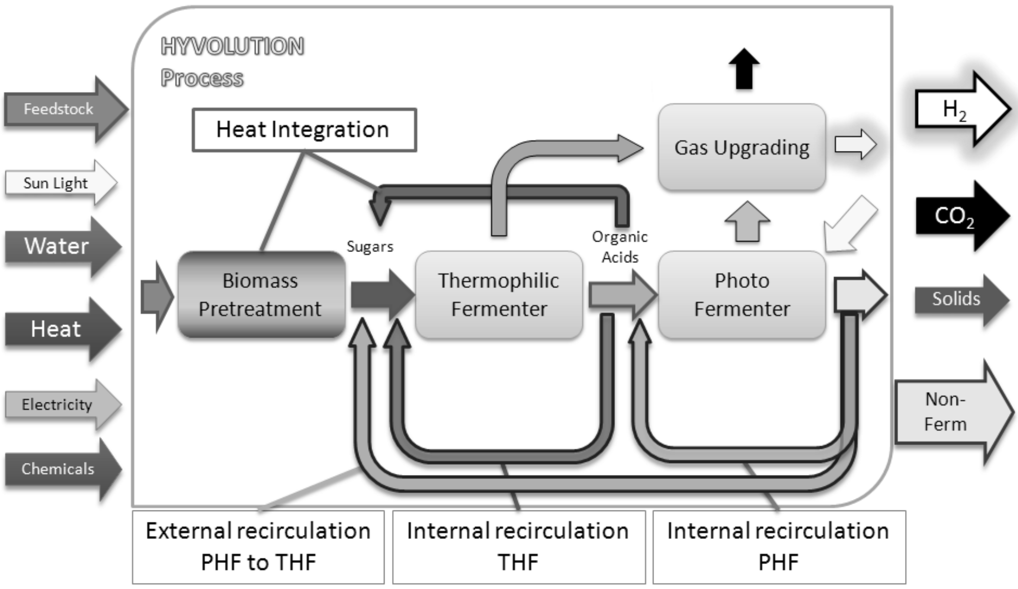

Figure 1: Scheme of HYVOLUTION process.

The different process steps has been implemented in the flow sheeting program Aspen Plus® (V7.1, Aspen Technology, Inc., Burlington, USA, 2008) which is used to solve mass and energy balances. The process has been scaled to obtain 60 kg/h of pure hydrogen 97 % (v/v), equivalent to 2 MW of thermal power, considering 10 % hydrogen losses during gas-upgrading.

Work presented here is based on feedstock molasses, a residue from processing of sugar beet. The investigated feedstock option does not require any pretreatment, since the sugars present in molasses can be directly fermented in the THF.

Table 1: Basic settings for HYVOLUTION process.

Plant capacity	60 kg/h Hydrogen (97 % v/v)
Feedstock	Molasses
Sugar conversion to H_2 in THF	80 % (wt)
Sugar conversion to cell mass in THF	15 % (wt)
Acetic acid conversion to H_2 in PHF	60 % (wt)
Acetic acid conversion to cell mass in PHF	15 % (wt)
Temperature THF	70 °C
pH THF	6.5
Substrate concentration THF	10 g/l Sugar
Temperature PHF	30 °C
pH PHF	7.3
Substrate concentration PHF	40 mM Acetic Acid
Hydrogen losses in Gas-Upgrading	10%

Feedstock has to be diluted before being introduced to the thermophilic fermentation to obtain a concentration of 10 g/l of sugars. The motivation of such a low concentration is that the selected bacteria are negatively affected by high osmotic pressure, which would reach harmful levels already at concentrations of 13 g/l sugars [3, 4].

The diluted liquid stream is heated to 70 °C and fed to the thermophilic or dark fermentor (THF). During THF, thermophilic bacteria convert the sugars into hydrogen and organic acids, preferably acetic acid. Part of the sugars is also used for cell growth. Process parameters and substrate conversion for the investigated case are presented in Table 1 and are based on feasible assumptions discussed with partners within the EU-project Hyvolution.

The liquid effluent from the THF is further diluted and fed to the photo-heterotrophic fermentation, where the organic acids are converted to more hydrogen and carbon dioxide. Photo-fermentation is a light driven process which requires sunlight and operates at a temperature of about 30°C.

3 Results and Discussion

To reduce heat and water demand, a previous study on wheat suggested the use of a combination of recirculation of process effluents of PHF to THF (external recirculation) and to PHF (internal recirculation PHF), together with heat integration by introducing a heat exchanger to the thermophilic fermentation step [3].

Recirculation has been defined as the percentage of reduction of dilution water, by substitution of fresh water with the PHF effluent. Four levels of recirculation have been selected for calculation: no reduction, 30%, 60% and 90% reduction of dilution water in the corresponding fermentation steps.

The influence of effluent recirculation on the mass and heat balance of the process based on feedstock molasses is presented below.

Figure 2 reports the simplified mass and energy balances of the heat integrated process option without effluent recirculation. At these conditions, Hyvolution process would require an high water demand of 198 t/h as well as thermal input of 2.6 MW, which is higher than the plant capacity corresponding to 2 MW thermal power.

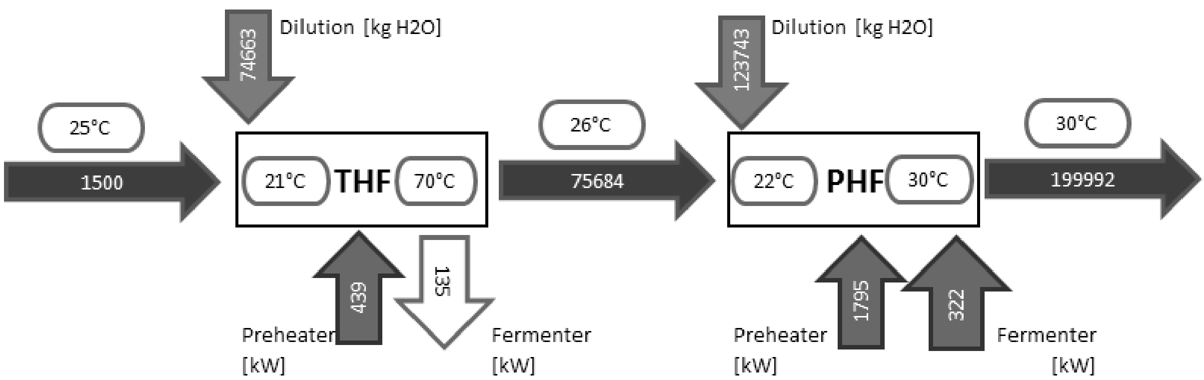

Figure 2: Basic mass and heat balance of heat integrated Hyvolution process based on Molasses (mass flow in kg/h).

Introduction of effluent recirculation in the process reduces heat and water demand of the process. Figure 3 illustrates the total heat and water demand for Hyvolution process based on molasses with increasing recirculation rate. The total heat demand is defined as the sum of all required heat inputs in the process steps. Replacing 90% of fresh water by effluent of PHF reduces the water and heat demand from 198 t/h to 21 t/h and 2570 kW to 760 kW, respectively.

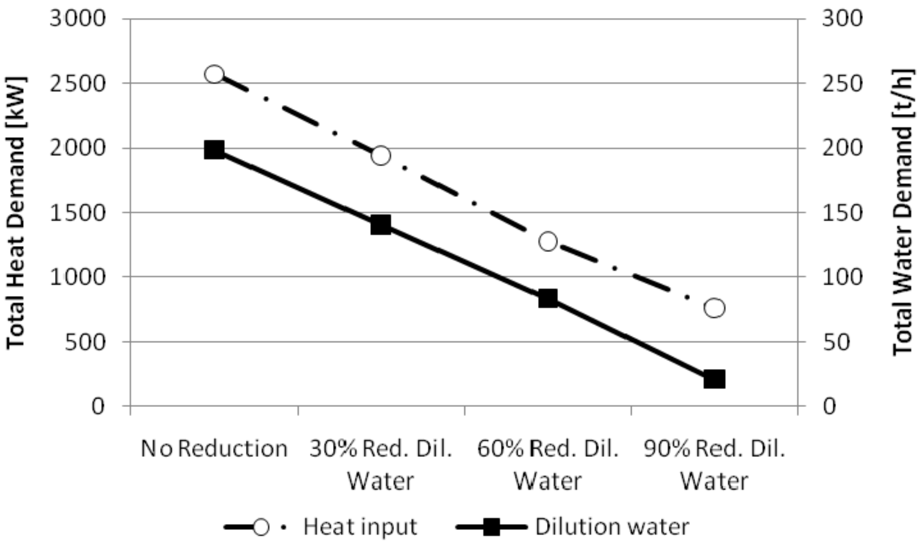

Figure 3: Comparison of overall heat (dashed/dotted line) and water (solid line) demand for different recirculation options.

An important point to take in consideration is the heat duty of PHF and the connected temperature levels (Figure 2). The photo-fermentor could be seen as a sun heater and would need rather cooling than heating. However, the simulation program calculates the heat or the cooling demand necessary to reach 30°C necessary for fermentation, by considering only the temperature of the photo fermentor inlet streams. Without recirculation the heat demand account for 80% of the heat demand of the entire process, but depending on outdoor conditions and season the heat demand of photo-fermentor might be covered completely by solar irradiation. As an alternative, low temperature heat could be applied by integration of hydrogen production with a sugar plant, as proposed by Markowski et al. (2009) [5], using the available off-heat from the sugar refining process at 60°C. In this way, the heat demand of the process (with/without recirculation) could be reduced to less than 500 kW.

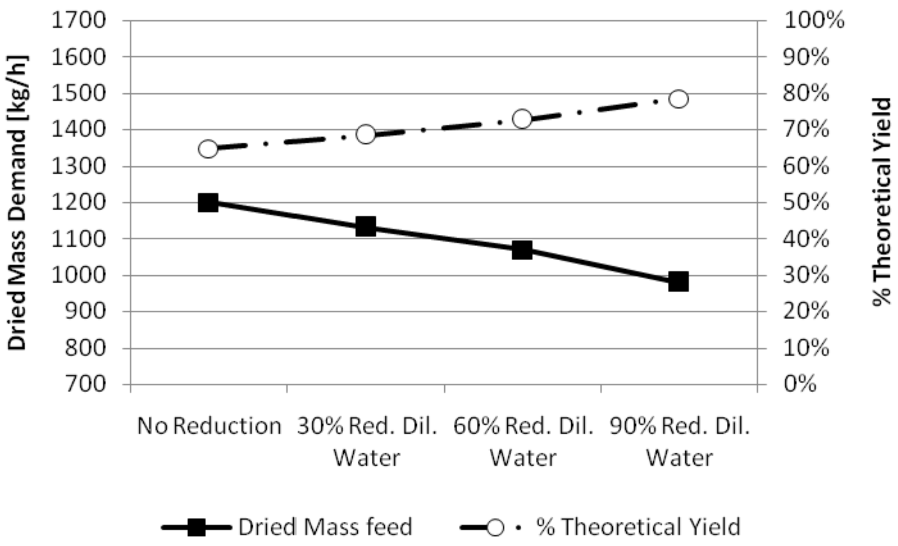

Figure 4: **Comparison of dried mass feed (solid line) and overall conversion of sugars to hydrogen (dashed/dotted line) for different recirculation options.**

Further analysis of the effects of recirculation, shows that with increasing recirculation rate, less feedstock is required to produce the same amount of hydrogen (Figure 4). This behaviour is caused by the not complete conversion of substrate in the PHF step: the recirculation of the not reacted organic acids allows a further reaction in PHF and thus the reduction of feedstock demand by 18%. The overall conversion of sugars to hydrogen in the process increases from 65% to 79% of the maximum theoretical value.

4 Conclusions

The work presents results of an integration study to reduce heat and water demand of the fermentative production of hydrogen from molasses. Recirculation of effluents from the photo-heterotrophic fermentor to the thermophilic and the photo-heterotrophic fermentor - referring to internal and external recirculation - together with a proper heat recovery seems to be practicable to obtain a reduction of heat and water demand up to 70% and 90%, respectively. Moreover the overall conversion of fermentable sugars into hydrogen would increase from 65% to 79% of the maximum theoretical value.

Implementation of improved process parameters extrapolated from experimental results will allow further insight to the feasibility of process and heat integration options and play an important role in the final selection of a promising process route for HYVOLUTION process.

Acknowledgments

The authors gratefully acknowledge the support of the project by the European Union’s 6th Framework Program on Sustainable Energy Systems (Hyvolution, Contract-No 019825).

References

[1] L. Fulton. Reducing Oil Consumption in Transport: Combining Three Approaches, IEA/EET working paper, April 2004.

[2] P.A.M. Claassen; T. de Vrije. Non-thermal production of pure hydrogen from biomass: Hyvolution, Int. J. Hydrogen Energy, 31 (2006) 1416-1423.

[3] D. Foglia, W. Wukovits, A. Friedl, M. Ljunggren, G. Zacchi, K. Urbaniec, M. Markowski, M. Modigell. Integration study on a two-stage fermentation process for the production of biohydrogen, 2009, Chemical Engineering Transactions 18, pp. 345-350

[4] K. Willquist, P.A.M. Claassen, E.W.J. van Niel. Evaluation of the influence of CO_2 on hydrogen production by Caldicellulosiruptor saccharolyticus, Int. J. Hydrogen Energy, 34 (2009) 4718-4726.

[5] M. Markowski, K. Urbaniec ,A. Budek, M. Trafczynski , W. Wukovits ,A. Friedl, M. Ljunggren , G. Zacchi. Heat integration of a fermentation-based hydrogen plant connected with sugar factory, 2009, Chemical Engineering Transactions 18, pp. 351-356.