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Heat integration of a fermentation-based hydrogen plant connected with sugar factory

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The paper is concerned with heat integration of a conceptual hydrogen plant connected with a sugar factory. The sugar factory serves as a source of sucrose-containing thick juice for the hydrogen plant, where this feedstock is processed to hydrogen. Moreover, this connection gives an opportunity to utilize waste heat from the sugar factory. Hydrogen is produced by two-stage fermentation, that is, thermophilic fermentation followed by photofermentation. The gas mixture obtained in the two process stages is supplied to the gas separation system, composed of absorbing and stripping columns for circulating amine solution, to separate hydrogen from carbon dioxide. Using Pinch Technology and considering sugar factory with its CHP plant as an energy source, the hydrogen plant is heat-integrated to minimise the energy consumption.

1. Introduction

The Hydrogen Plant producing hydrogen from syrup obtained in a Sugar Factory is considered. The production process starts with the conversion of syrup by thermophilic bacteria. Thermophilic bacteria produce hydrogen together with carbon dioxide and acetic acid. The co-product acetic acid, is a prime substrate for H_2 production in a subsequent photofermentation by phototrophic bacteria. Finally, hydrogen is separated from carbon dioxide in a gas upgrading unit (Claassen et al., 2005; Claassen et al., 2006).

This paper presents the first results of heat integration of the Hydrogen Plant connected with Sugar Factory and explains the influence of process parameters on energy consumption in the Plant. Of the different biomass types suitable for hydrogen fermentation, only sugar beet material is considered.

Because of lack of reliable experimental data the values of mass streams in the process are calculated starting from a simplified process model:

thermophilic fermentation

$$C_{12}H_{22}O_{11} + 5H_2O \rightarrow 8H_2 + 4CH_3COOH + 4CO_2$$

photofermentation

$$CH_3COOH + 2H_2O \rightarrow 4H_2 + 2CO_2$$

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The assumed conversion factors are: sugar to hydrogen 66%; acetic acid to hydrogen 67%. As photofermentation is dependent on sunlight and therefore can only be operated intermittently, it is assumed that this process stage runs 12 hours per day.
On the basis of this simplified process model, heat integration between equipment units in the Hydrogen Plant is considered.

2. Energy and mass balance of the Hydrogen Plant

In the literature, the fermentative hydrogen production process is considered as a sequence of three main stages (Claassen et al., 2006):

- Biomass pretreatment,
- Thermophilic fermentation and photofermentation,
- Gas upgrading.

In the case considered here, biomass pretreatment takes place in the existing Sugar Factory and therefore this process stage is omitted when calculating the energy balance of the Hydrogen Plant.
The flow-sheets of process stages are shown in two figures:

- Fig. 1 presenting thermophilic fermentation and photofermentation,
- Fig. 2 presenting gas upgrading based on amine absorption method.

2.1 Thermophilic fermentation and photofermentation

Syrup obtained in the Sugar Factory is diluted and supplied to the thermophilic bioreactor (Fig. 1). The assumed content of sugar in the feed is 50 g/l. At a temperature level of about 70°C the thermophilic bacteria convert sugar mainly into hydrogen, carbon dioxide and acetic acid (van Niel et al., 2002). To promote a high hydrogen yield, the pressure in the bioreactor has to be maintained at a level of 50 kPa.
The outflowing liquid from the first fermentation step contains organic acids and mainly acetic acid. The liquid is cooled down to 35°C, diluted by water to the concentration of 100 mmol/l and supplied to the next bioreactor where photofermentation takes place at room temperature under influence of sunlight, yielding hydrogen and carbon dioxide (Eroglu et al., 2008). To compensate for reduced throughput of the photofermentation step at nighttime or on cloudy days, a storage tank is provided before the photofermentor.
The by-product of photofermentation is water mixed with non-fermentables; it might be re-used for the dilution of syrup supplied as feedstock to the thermophilic bioreactor. However, there is the risk of accumulation of undesirable compounds that are poisonous to the thermophilic bacteria. Water re-use is therefore controlled depending on the composition of water available for recycling. If the concentration of poisonous compounds exceeds the safety limit, then water is discharged to the wastewater treatment system and make up water is supplied to the thermophilic bioreactor. Make up water is also supplied during nighttime and cloudy days when the photofermentor cannot be operated normally.

2.2 Gas upgrading

The gas upgrading process employs a concept proposed for CO_2 sequestration (Herzog 1999), modified by taking special requirements of two-stage fermentative hydrogen production into account. In the initial process step (Fig. 2), steam-containing gas

mixture is cooled down causing the steam to condense. The resulting two-phase mixture is supplied to the separation unit where water is separated from H_2 and CO_2. The stream of separated gases flows to a two-stage vacuum pump where the pressure is increased and after that, it is mixed with the gas stream generated in the photofermentor. The dry gas is compressed by a blower to 120 kPa and subsequently fed to the absorber where absorption of CO_2 by active solvent (monoethanolamine) takes place. Finally, pure hydrogen is evacuated from the absorber.
The rich active solvent flows to the desorber (stripper) which is heated with waste steam at 60°C supplied from the Sugar Factory. The outflowing mixture of carbon dioxide and residual steam is cooled down causing steam to condense, and the two-phase mixture is subsequently directed to a separation unit where water is separated. The dry gas is compressed in the two-stage vacuum pump and discharged from the gas upgrading unit.
The lean active solvent obtained in the stripper is cooled down and recycled to the absorber.

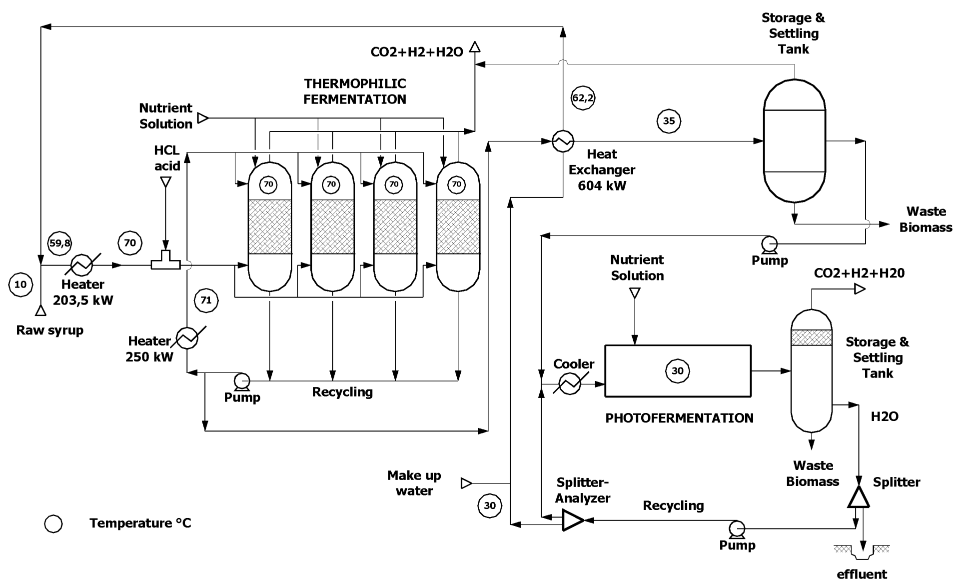

Fig. 1. Thermophilic fermentation and photofermentation

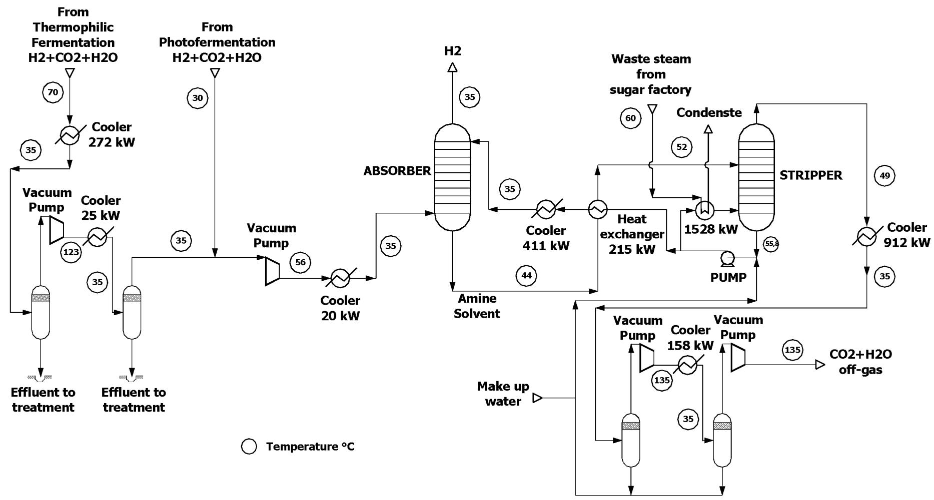

Fig. 2. Gas upgrading with amine absorption method

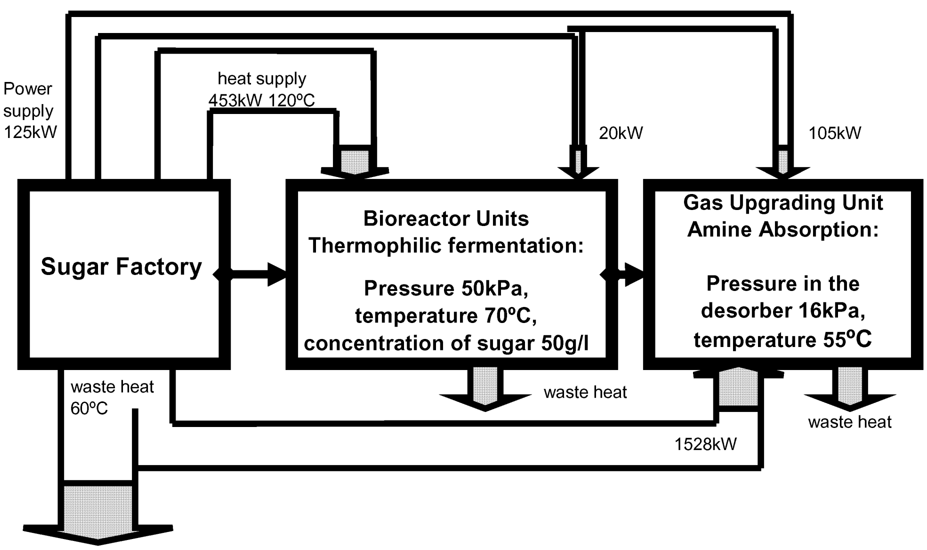

Fig. 3. Energy flows in Hydrogen Plant connected with Sugar Factory

3. Energy integration of the Hydrogen Plant

It is assumed that the gross output of the Hydrogen Plant, that is, the mass flow of hydrogen obtained from gas upgrading is 60 kg/h (equivalent to an energy flow of 2000 kW). To account for intermittent operation (12 hours per day) of the photofermentation stage, water supplied to the thermophilic fermentation is assumed to come either from photofermentation outlet, or from the source of make-up water. As a result of heat integration using Pinch Technology, for the assumed minimum temperature difference at pinch point of 5 K, the energy flows to/from the plant are determined as shown in Fig. 3.

As already stated in section 1 above, the calculations are based on the simplified process model and thus the energy consumption indicated in Fig. 3 should be understood as a preliminary estimate of energy expenditure.

4. Concluding remarks

As can be seen in Fig. 3, the main part of the necessary energy input to the Hydrogen Plant is consumed in the Gas Upgrading Unit. However, most of it (1528 kW of low-temperature heat) can be covered by waste heat discharged from the Sugar Factory.

It is interesting to compare the results indicated in Fig. 3 with those of earlier work on heat integration of a stand-alone Hydrogen Plant (Markowski et al., 2008). Contrary to the present paper where realistic values, that is, 66% respectively 67%, of conversion factors for both fermentation stages are adopted, 100% conversion was previously assumed. Furthermore, as no cost-free supply of waste heat is available for a stand-alone plant, the application of vacuum swing adsorption was foreseen in the Gas Upgrading Unit.

As can be seen in Tab. 1, despite optimistic assumptions with regard to feedstock conversion, the stand-alone plant is characterized by the energy consumption comparable to that of the other plant option. Furthermore, gas upgrading by vacuum swing adsorption is associated with a significant loss of hydrogen in CO_2 stream discharged from this process stage. When applying CO_2 absorption/desorption based on amine solvent in the Hydrogen Plant connected with Sugar Factory, the loss of hydrogen is negligibly small.

Table 1. Heat and power supply to the Hydrogen Plant

	Stand-alone Hydrogen Plant	Hydrogen Plant connected to Sugar Factory
Gas upgrading method	Vacuum swing adsorption	CO_2 absorption/desorption
Heat supply [kW]	440	453
Power supply [kW]	108	125
Loss of hydrogen [kW]	200	-

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