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Feasibility and energetic evaluation of air stripping for bioethanol production

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HIGHLIGHTS

- Suitability of air stripping in Blenke cascade as mash separation method was tested.
- Theoretical VLE calculations were carried out to confirm experimental data.
- Energy input was simulated in ChemCAD and compared to conventional distillation.

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ABSTRACT

Stripping of mashes with air as stripping gas and low ethanol contents between 3 and 5 wt% was investigated in terms of its suitability for continuous bioethanol production. Experiments in a Blenke cascade system were carried out and the results were compared with values obtained from theoretical vapour-liquid-equilibrium calculations. The whole stripping process was energetically evaluated by a simulation in ChemCAD and compared to conventional distillation. Therefore several parameters such as temperature, air volume flow and initial ethanol load of the mash were varied. Air stripping was found to be a suitable separation method for bioethanol from mashes with low concentrations. However, energetic aspects have to be considered, when developing a new process.

1. Introduction

The world's growing demand for transportation fuels, the depletion of crude oil sources and environmental issues represent a growing challenge towards cost-efficient production of sustainable gasoline substitutes. In this regard, bioethanol, especially from lignocellulosic substrates constitutes one major alternative to first generation biofuels, since the highly discussed competition with food crops won't apply. In particular, energy crops, agricultural wastes and -residues can be used, such as miscanthus, corn husks, straw or wood chips (Bai et al., 2008; Mussatto et al., 2010; European Biofuels Technology Platform, 17 June 2016) Although there are a couple of companies e.g. Iogen (Canada), Clariant (Germany) or POET-DSM (USA), who claim to have developed processes and built plants for continuous production of cellulosic ethanol, neither of them seems to work entirely economically feasibly especially with the currently low oil price. Therefore, lignocellulosic bioethanol production has to become more cost-efficient. However one major challenge is the purification of the ethanol that has been produced during fermentation of the cellulosic feedstock. Most commercial processes for production of bioethanol use distillation, although it is very energy-intensive. In particular when it comes to low ethanol contents, which are usually present, when dealing with lignocellulosic mashes, distillation is not the optimum method (Taylor et al., 2000; Gerbrandt et al., 2016). In order to reduce the amount of energy and thereby the costs required for ethanol recovery, several methods were suggested such as membrane technology (e.g. reverse osmosis) (Groot et al., 1992), solvent extraction (e.g. with dodecanol) (Minier and Coma, 1981), gas stripping directly from the fermenter (Liu and Hsien-Wen, 1990) or gas stripping in a separate column (Taylor et al., 1996). The positive effect of ethanol removal from the fermentation broth by gas stripping was widely investigated by several research groups (Taylor et al., 1997; Zhang et al., 2005; Ntihuga et al., 2012). Taylor et al. even stated that they had developed a new ethanol production process including stripping, which could save about 0.03 $ per gallon (Taylor et al., 2000). However, they mainly traced it back to the fact that they applied a 50% higher solid concentration, as the utility costs compared to conventional distillation processes

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were almost the same. This might be due to the fact that supply and/or recovery of pressurized carbon dioxide or nitrogen gas is relatively expensive. Therefore, in this work a model for the use of air as stripping gas at different temperatures was developed, supported by calculations of vapour-liquid equilibria and experimental data. Similar calculations were already carried out, though CO_2 gas was used for the model (Silva et al., 2015). Furthermore the focus was not on lignocellulosic ethanol, therefore the ethanol contents of the mash were overstated and the investigated air flows were not high enough in order to produce ethanol in sufficient amounts. Additionally, in order to evaluate the energy efficiency of the stripping process for application in bioethanol plants, in this work the most relevant energy flows were simulated for both stripping and conventional distillation. Apart from the energetic aspects, one big advantage of the utilization of stripping is the continuity of the process, even on small scale. And, as in this work, air was used as stripping gas, still further advantages were revealed. Under the condition of recirculation of a part stream of the stripped mash, enough oxygen is provided to the yeast in the fermenter. Therefore, no additional aeration is needed, provided that the air used is sterile, which offers new possibilities to the bioethanol production process.

2. Materials and methods

2.1. Concept

The aim of the project, in whose course this research was carried out, is to develop a continuously working bioethanol reactor for lignocellulosic substrates. More precisely, the plant is supposed to process 60 kg of dry matter (DM) per day, suspended to a DM content of 15%, which will result in 20 L of pure ethanol. In order to work at equilibrium the same amount (400 kg in total) needs to be removed from the system. A scheme of the process (without pretreatment of the substrate) is given in Fig. 1.

In ideal case, the mash leaving the process is completely free of ethanol. Therefore, all parameters such as temperature, volumetric flows of mash or stripping gas and working volume of the Blenke cascade have to be adjusted to this aim. In order to find out, how important the influence of the parameters are, a statistical process plan was developed by use of the statistics package Minitab (Minitab Inc., Pennsylvania, USA) and its "design of experiments (DOE)" tool. The investigated factors were temperature t (30, 50 and 70 °C), mash flow $\dot{V}_{Mash}$ (0.054, 0.084 and 0.102 m^3/h) and air flow $\dot{V}_A$ (0.6, 1.2 and 1.8 m^3/h). A fractional factorial design was used, in order to reduce the number of experiments that were necessary. With three factors and three levels each, the minimum required number of experiments was nine or eighteen, with double determination respectively.

2.2. Blenke cascade

In principle the Blenke cascade is a special type of bubble column, which contains two different kinds of inserts, so called discs and donuts (see Fig. 2). In contrast to a common gas lift reactor it thus does not behave like a single continuously stirred tank reactor (CSTR), but like several CSTR in a row. While the discs, which are shaped slightly convex, deflect the flow towards the wall of the column, the donuts, which are ring-like, deflect the mash to the centre of the cascade. Perfect mixing in each compartment can therefore be assumed and with the superimposed axial dispersion it shows plug flow characteristics (Blenke, 1989; Chisti, 1989; Ntihuga et al., 2012).

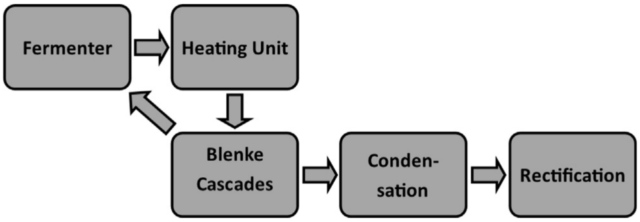

Fig. 1. Process scheme for continuous production of lignocellulosic ethanol.

2.3. Experimental plant setup

The experimental plant consisted of four main parts, the mash container, which at the same time served as heating unit, two Blenke cascades with a working volume of 15 L each, the air supply and the condensation unit. As storage unit for the mash served a simple electric heating pot with a volume of 29 L (J. Weck GmbH u. Co. KG, Wehr, Germany). From there fresh solid-free mash was pumped through both cascades with a progressive cavity pump (Allweiler GmbH, Radolfzell, Germany) until both cascades were filled up and a total mash volume of 50 L was inside the system. The mash went from the bottom of the first cascade to its top, from where it flowed to the top of the second cascade, to its bottom and back to the storage container. Stripping had to be started before the cascades were full, in order to prevent overflowing due to gas hold-up in the cascades. Pressurized air was supplied from a storage tank (500 L, 7.5 ± 0.5 bar), which was fed by a compressor (KAESER KOMPRESSOREN SE, Coburg, Germany) containing a dehumidification unit. Pressure was reduced to 2 bar before entering the cascades. The air was induced into the columns from the bottom, therefore in co-current with the mash in the first and in counter current in the second cascade. In the cascades' upper lids small outlets were inserted, through which the air was forced out from the cascades and guided to the condenser unit. This unit consisted of two respectively eight glass coolers. The Thermal G cooling agent (JULABO GmbH, Seelbach, Germany) was tempered to −30 °C. The glass coolers were connected in series, therefore both exhaust air lines were brought together before entering the first cooler. After having passed the last cooler, the air was released to the environment. The condensates from all coolers were collected separately, weighed and the ethanol concentration was determined with a density meter (Anton Paar GmbH, Graz, Austria).

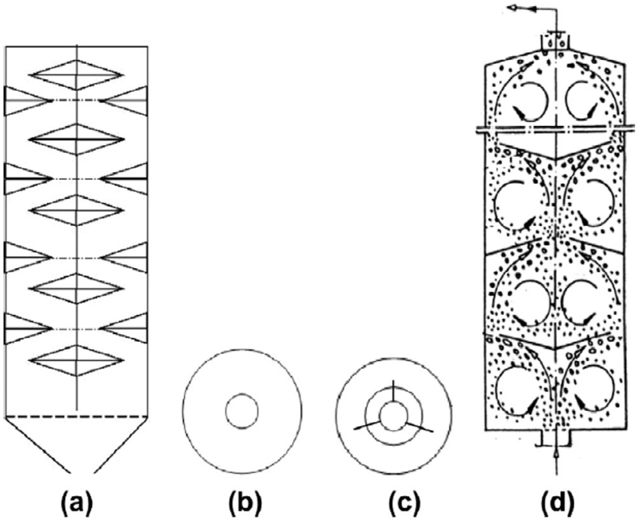

Fig. 2. Schematic drawing of the Blenke cascade with inserts (a), donuts (b), discs (c) and mixing behaviour (d). Source: Ntihuga et al., 2013.