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Ethanol concentration of fermented broth by ohmic-assisted hydrodistillation

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ABSTRACT

Ohmic-assisted hydrodistillation (OAHD) as an innovative extraction method was employed to concentrate ethanol from corn beer. OAHD reduces the time and energy required for distillation of bioethanol production compared to traditional method. OAHD process was compared to traditional hydrodistillation (HD) for 3 l of 13% (*v*/*v*) beer at a constant wattage of 168 W. Test results indicate that the required energy for separation of ethanol in OAHD is 77% less than HD. Moreover, OAHD completed the distillation process in 70.6 ± 1.8 min while HD required 116.1 ± 7.8 min. The concentrations of ethanol in the final distilled product from both methods were similar (56.5% ± 1.3 for OAHD vs. 52.3% ± 4.0 for HD). Interestingly, the process control in OAHD is faster and distillation can be stopped quickly, and consequently, it will contain less unwanted distillate in comparison with HD. The findings of this study introduce OAHD as a potentially economical and environmentally friendly method for bioethanol distillation process.

Industrial relevance: In this research, ohmic-assisted hydrodistillation (OAHD) was used as an advanced hydrodistillation (HD) technique and compared with traditional HD in concentration of ethanol from industrial fermented corn beer. OAHD method was quicker, more economical, more sustainable and with a better ability of process control than HD method. Such advantages can make OAHD as an alternative technique for the production of larger quantities and higher concentrations of ethanol by scaling up the equipments and process in biofuel factories, instead of the conventional HD process.

1. Introduction

Search for substitutes for fossil fuels has gained increasing interest in recent years as a result of higher demand for energy and forecasted depletion of fossil resources (Quintero, Montoya, Sánchez, Giraldo, & Cardona, 2008). Global warming and the need to diminish greenhouse gas emissions have encouraged the use of fuels produced from biomass (Gupta, Sharma, & Kuhad, 2009; Paris Climate Conference, 2015), which is the only renewable carbon source that can be efficiently converted into solid, liquid or gaseous fuels. Bioethanol is an attractive alternative for gasoline, and not only has a higher octane number, flame speeds and heats of vaporization, but also has less contribution to greenhouse gases and environmental contamination (Balat, Balat, & Öz, 2008).

Bioethanol can be produced by fermentation of various available feedstocks in different geographic locations, e.g. corn and beet molasses are most utilized sucrose-containing feedstocks in the United States and Europe, respectively (Balat et al., 2008). The concentration of ethanol in the fermented broth can vary by the type of feedstock and fermentation conditions but it is usually relatively low and water content of virgin bioethanol is generally higher than 80% (Quintero et al., 2008; Gupta et al., 2009). To obtain a fuel-grade product, levels of ethanol should be increased to more than 99% (ASTM Standard D4806, 2010). Separation of bioethanol from the fermentation broth starts by distillation of the dilute aqueous alcohol ethanol and concentrating in a rectifying column to reach a concentration of about 96% and followed by using a hydrophilic molecular-sieve-based drying system. The energy used for distillation may reach up to 40% of the total energy demand in bioethanol production (Huang, Baker, & Vane, 2008; Karuppiah et al., 2008). Using the traditional distillation method, hydrodistillation, (HD), to concentrate ethanol solutions is energy and time intensive. Therefore, development of new technologies that can produce ethanol with less energy consumption and processing time is of great value.

Ohmic heating is defined as a process wherein an alternating electrical current is passed through a material to generate heat within the medium (Knirsch, Alves dos Santos, Martins de Oliveira Soares Vicente, & Vessoni Penna, 2010). The heating occurs in the form of internal energy transformation (from electric to thermal which is due to Joule effect)

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(Sastry & Barach, 2000). In ohmic heating process, feedstocks are a part of an electric circuit through which alternating current flows, causing heat to be generated within the feedstock due to its electrical resistance (Ruan, Ye, Chen, & Doona, 2001). Ohmic processing enables materials to be heated at extremely rapid rates from few seconds to few minutes (Sastry, 2005). The traditional heating methods rely on heat transfer from a hot surface mainly via conduction and convection, in which a temperature gradient is needed to transfer heat to the materials. This may result in different problems including long come up time and possibility of non-uniform heating as well as overheating of the material which is in contact with the heating surface. Ohmic heating addresses these shortcomings by removing hot surfaces involved in heating of the medium (Sakr & Liu, 2014). Electrical conductivity is the main parameter in heating rate in ohmic heating treatments. However, usually low electrical conductivity does not preclude rapid ohmic heating because designing of an ohmic heater with a low electrode gap, higher voltage and electrode area will result in high field strength and rapid heating in such media. The electrical conductivity of materials changes with temperature and the current density would vary accordingly if a constant voltage is applied. Ohmic heating can be considered as an energy saving process compared to conventional heating (Gavahian, Farahnaky, Javidnia, & Majzoobi, 2012; Goullieux & Pain, 2005). Environmental impact can be reduced by reducing the use of electrical energy derived from fossil fuels combustion. To obtain one Wh electricity from coal or fuel, about 0.8 g of CO_2 will be emitted to the atmosphere during combustion of fossil fuels (Ferhat, Meklati, Smadja, & Chemat, 2006). Ohmic heating system in combination with a Clevenger type apparatus was recently utilized for the extraction of essential oils from thyme and myrtle and named "ohmic-assisted hydrodistillation" (OAHD) (Gavahian et al., 2011; Gavahian, Farahnaky, Javidnia, & Majzoobi, 2013). Previous studies have shown that this emerging technology consumes less energy and has shorter extraction times than traditional HD systems (Gavahian et al., 2011, 2012, 2013). These studies showed that OAHD can successfully perform distillation process of essential oils from different aromatic plants using a conductive salted water media. Therefore, ohmic heating (OAHD) is believed to have advantages in the bioethanol distillation process over HD technique. In a previous report of this research team, OAHD system separated ethanol from ethanol-salted water mixture faster and more economical than traditional distillation system (Gavahian, Farahnaky, & Sastry, 2016). Unlike previous reports on this emerging technique, performing OAHD for beer, as a new feed to this distillatory device which has electro conductive components naturally, may eliminate the needs for electro conductivity adjustment.

The main objectives of this study are evaluation of the efficacy of using OAHD as an alternative method for bioethanol concentration from beer, and quantitative comparison of OAHD and HD methods in terms of the time and energy consumption.

2. Materials and methods

2.1. Feedstock preparation

In all experiments, the same fermented broth (beer) was used as distillation process feed. This beer was fermented in commercial scale from corn in the Bioproducts and Bioenergy Research Laboratory, at The Ohio State University. The fermentation time and temperature were 55 h and 30.5 °C, respectively. The beer color was yellow and had a pH of 4.6, Brix of 11.2 and contained 13% ethanol (% v/v). The electrical conductance of the beer was measured by a digital conductivity meter (19101-10, Cole-Parmer Instrument Company, USA) and was 0.4 S/m. The fermented sample was kept in air-tight vessels at 4 °C in the dark before experiments. Three liters of the beer were placed in the heating vessel for the distillation process for both traditional HD and OAHD methods. Prior to the distillation process, the temperatures of all samples were adjusted to 31 ± 1 °C by preheating in the heating chamber of the distillation device.

2.2. OAHD

An ohmic distillation device, designed and developed in the Department of Food, Agricultural and Biological Engineering, The Ohio State University, was used to perform the OAHD process (Fig. 1). The device was equipped with two titanium-coated stainless rectangular electrodes (37×55 mm^2). The treatment vessel was a 5 liters round-bottom laboratory glass flask which was connected to a condenser with a length of 920 mm. Processing parameters (i.e. processing time, temperature, applied voltage, current density and power consumption), were precisely monitored using a software developed and connected to the computer via a data logger similar to that described by Ramaswamy, Marcotte, Sastry, and Abdelrahim (2014). The temperature variations can cause variations of electric conductivity of materials (Goullieux & Pain, 2005) and as a result, the current density would vary accordingly. Therefore, in this study voltage was adjusted to keep the OAHD device running in a constant wattage of 168 ± 5 W. Input voltages were controlled from the power supply of the ohmic device using a variable autotransformer (The Superior Electric Company, Bristol, CT, USA).

In the OAHD procedure, 3 l of beer (containing 13% v/v ethanol) were heated in the apparatus flask from an initial temperature of 31 ± 1 °C (same initial temperature was used in HD method). The heating process continued until the time that the boiling point of beer increased and reached 98 °C. Therefore, according to the ethanol–water diagram, all the distillation experiments were continued to the same point in which the ethanol concentration of feed was reduced to a constant amount (Rieder & Thompson, 1950). As the distillation started, the amount of collected ethanol was recorded every 10 s using a digital scale (1000C-3000D Precisa, Switzerland). The distilled product was then equilibrated to 15 °C in a preset water bath (Fisher Scientific, Isotemp 1016S, USA), and the concentration of ethanol in that product was measured by an alcoholmeter (BSG HandCraft, USA).

2.3. HD

HD, the conventional method of ethanol distillation (Huang et al., 2008), was carried out using the same system as OAHD but using a

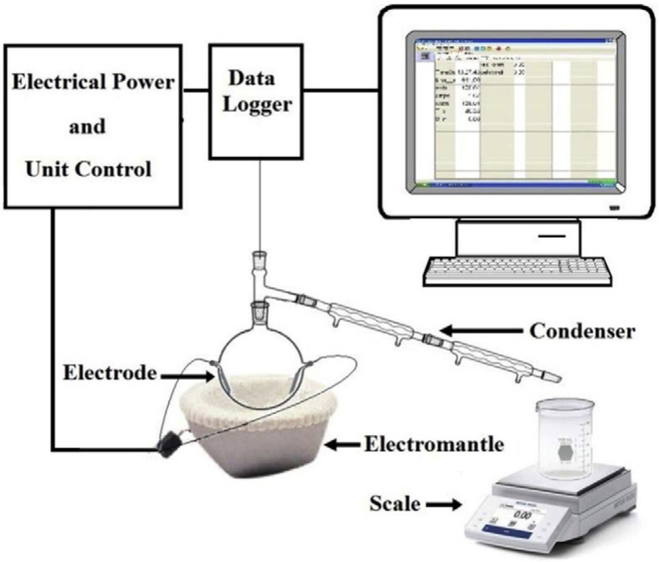

Fig. 1. Schematic representation of distillation equipment.