Contents lists available at ScienceDirect

Food and Bioproducts Processing

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

Multiple effect concentration of ethanol by ohmic-assisted hydrodistillation

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ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form 29 May 2016
Accepted 14 June 2016
Available online 20 June 2016

Keywords:
Ethanol
Energy saving
Distillation
Ohmic-assisted hydrodistillation

ABSTRACT

Our previous work on ethanol distillation by ohmic-assisted hydrodistillation (OAHD) successfully concentrated ethanol from 10 to 50% (v/v). In this work, two additional concentration steps were conducted using the 50% (v/v) product obtained from the first concentration stage at a constant wattage of 168 W using the same OAHD device. The second distillation step resulted in a product with ethanol concentration of 76% (v/v) and the third step yielded ethanol concentration of 84% (v/v). Results were compared to conventional hydrodistillation (HD), and were indicative that OAHD reduces one third of energy cost in ethanol distillation process. Not only was OAHD superior to HD in terms of time and energy consumption, but also resulted in higher ethanol concentrations than HD after the third step of distillation: $84.3 \pm 0.3\%$ vs. $82.5 \pm 0.5\%$, respectively. OAHD also showed better process control and was able to stop the distillation process faster than HD. In both second and third distillation steps, the time required to stop the process with OAHD (1 min) was shorter than for HD process (10 min). The findings of this study further confirm our previous work, and reveal that this emerging distillation technique has the potential of yielding high concentrations of ethanol from dilute alcoholic solutions in a more economical and environmental friendly way.

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1. Introduction

The increase in energy demand and possibility of energy shortage are global concerns. It is predicted that the growth in the production of convenient oil and gas will not match the projected rate of demand in next decades (Bradshaw, 2010). In addition, concerns about greenhouse gas emissions and climate changes have encouraged research and resulted in production of renewable energy resources (Sanchez and Cardona, 2008; Baeyens et al., 2015).

Bioethanol, as an alternative renewable energy source, has the largest potential to replace fossil fuels and to reduce greenhouse gas emissions significantly (Dias et al., 2013). World production of bioethanol was around 50 million m^3 in 2007 and has increased to 93 million m^3 in 2014 (Renewable Fuels Association, 2016). Annual U.S. fuel-ethanol production was around 55.6 million m^3 in 2015 which represents around 60% of the world supply (Renewable Fuels Association, 2016).

Bioethanol can be obtained by distillation of fermented broth of various raw materials including sugar-based feedstock, lignocellulosic materials and algae (Baeyens et al., 2015). Distillation is repeated several times to obtain higher percentages of ethanol (EtOH) and then, followed by a complementary drying method, usually adsorption on molecular sieves, to enhance azeotropic EtOH which contains more than 99% pure EtOH (ASTM Standard D4806, 2010).

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http://dx.doi.org/10.1016/j.fbp.2016.06.002
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Traditional distillation method, hydrodistillation (HD), is believed to be energy- and time- intensive and may consume up to forty percent of the total energy demand in Bioethanol production (Pimentel and Patzek, 2005; Huang et al., 2008). Ohmic-assisted hydrodistillation (OAHD) is an emerging distillation technique which takes advantages of ohmic heating instead of traditional heating systems. In the case of essential oil separation, this method was superior to HD system in terms of time and energy consumption (Gavahian et al., 2011, 2012, 2013). This innovative distillation method successfully enhanced EtOH concentration of EtOH-salted water mixture from 10 to around 50% (v/v) (Gavahian et al., 2016a) and also EtOH concentration of corn beer from 13 to around 56% (v/v) (Gavahian et al., 2016b). However, higher concentrations of EtOH are required in bioethanol production and some other industries. Although pure EtOH boils at about 78 °C, the EtOH is not extracted from the EtOH–water mixture in a single step distillation process. Instead, about 3 distillation steps are required to obtain a 95% pure EtOH (Pimentel, 2001; Pimentel and Patzek, 2005).

In continuation of our previous report on application of OAHD for EtOH distillation (Gavahian et al., 2016a), in the present study, distillation was continued for two more times (i.e. second and third distillation steps) using both OAHD and HD to enhance higher EtOH concentrations. The main objectives of this study were to evaluate the efficacy of using OAHD as an alternative method to traditional HD for higher concentrations of EtOH, and to perform a quantitative comparison of these methods in terms of the distilled product concentration, time and energy consumption.

2. Materials and methods

2.1. *Solutions preparation and distillation steps*

The first distillation step in our previous report (Gavahian et al., 2016a) resulted in a distilled product with EtOH concentration of 50% (v/v). Therefore, we used EtOH concentration of 50% as the feed for a second distillation step. EtOH concentration of distilled product from the second step (75%, v/v) was used as the feed of the third distillation step. In other words, For the second distillation step, 3 L of 50% (v/v) of EtOH (1500 mL EtOH 200 proof DeconLabs, USA and 1500 mL distilled water) containing 0.5% (15 g) NaCl, as the electrolyte, were prepared. Similarly, for the third distillation step, 75% (v/v) of EtOH (2250 mL EtOH 200 proof DeconLabs, USA and 750 mL distilled water) containing 0.5% (15 g) sodium chloride was used as the feed. In this paper, the distillation process of feed with EtOH concentration of 50% (v/v) and distillation process of feed with EtOH concentration of 75% (v/v) were referred as second and third distillation steps, respectively (see Fig. 1). First distillation step refers to distillation of 10% EtOH, as described by Gavahian et al. (2016a).

Prior to the distillation process, the temperatures of all samples were adjusted to 31 ± 1 °C by preheating in the flask of HD and OAHD device. Initial temperature of samples, electrolyte concentration, feed volume and input energy were the same in all the OAHD and HD treatments and similar to that of reported in the first step of EtOH distillation (Gavahian et al., 2016a).

2.1.1. *OAHD process*

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, as described by Gavahian et al. (2016a). The OAHD device was equipped with two titanium-coated stainless rectangular electrodes (37 mm × 55 mm). The treatment vessel was a 5-liter round-bottom laboratory glass flask which was connected to a condenser with a length of 920 mm. Processing parameters were precisely monitored using a software developed and connected to the computer via a data logger similar to that described by Ramaswamy et al. (2014). The temperature variations can cause variations of electrical conductivity of materials (Goullieux and 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 at 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). The amount of emitted carbon dioxide was calculated based on literature: to obtain 1 Wh electricity from fossil fuels, about 0.8 g of CO_2 will be emitted to the atmosphere (Ferhat et al., 2006). In the OAHD procedure, 3 L of EtOH–water mixture (containing 50 and 75%, v/v EtOH in the second and third distillation steps, respectively) 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 feeds increased and reached 83 and 80 °C for second and third distillation steps, respectively. Therefore, according to the EtOH–water diagram, all the distillation experiments in each step were continued to the same point in which the EtOH concentration of feed was reduced to a constant amount (Rieder and Thompson, 1950). As the distillation started, the amount of collected EtOH 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 EtOH in that product was measured by an alcoholmeter (BSG HandCraft, USA).

2.1.2. *HD process*

HD, the conventional method of EtOH distillation (Huang et al., 2008), was carried out using the same system as OAHD except using a 5-liter electromantle heater (12035-25 Hemisphere Mantle Glas-Col, USA) as the heating source instead of ohmic heating system. The device was run at a constant wattage of 168 ± 5 W, voltage of 100 ± 5 V and current density of 1.6 ± 0.1. Environmental impact of HD was calculated in the same way as in OAHD. The flask and condenser used in HD method were the same ones used in the OAHD process. Three liters of EtOH with concentrations of 50% (v/v) (in the second distillation

Fig. 1 – Steps in distillation process for both OAHD and HD: second and third steps were performed in current study, first step is described by Gavahian et al. (2016a).

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