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 three liters 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 ($56.5\% \pm 1.3$ for OAHD vs. $52.3\% \pm 4.0$ 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.

Keywords: Ethanol, Energy saving, Distillation, Ohmic-assisted hydrodistillation.

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 et al., 2008). Global warming and the need to diminish greenhouse gas emissions have encouraged the use of fuels produced from biomass (Gupta et al., 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 et al., 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 et al., 2008; Karuppiyah 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 et al., 2010). The heating occurs in the form of internal energy transformation (from electric to thermal which is due to Joule effect) (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 et al., 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 and 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 (Goullieux & Pain, 2005, Gavahian et al., 2012). 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 CO₂ will be emitted to the atmosphere

during combustion of fossil fuels (Ferhat et al., 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 et al., 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, Gavahian et al., 2012, Gavahian et al., 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 et al., 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 (Figure 1). The device was equipped with two titanium-coated stainless rectangular electrodes (37×55 mm²). 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 *et al.* (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).

Figure 1. Schematic representation of distillation equipment.

In the OAHD procedure, three liters of beer (containing 13% v/v ethanol) were heated in the apparatus flask from an initial temperature of $31 \pm 1^\circ\text{C}$ (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 and 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 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 . The flask and condenser used in HD method were the same ones used in the OAHD process. Three liters of 13% v/v beer was heated in the apparatus flask from an initial temperature of $31 \pm 1^\circ\text{C}$ and process parameters were monitored using the designed software and a data logger (Ramaswamy *et al.*, 2014). Similar to OAHD, the distillation process continued until reaching the temperature of 98°C . From the start of distillation process, the weight of collected ethanol was recorded every 10 s using a digital scale (1000C-3000D Precisa, Switzerland). The concentration of ethanol in distilled product was measured by an alcoholmeter (BSG HandCraft, USA) after equilibrating to 15°C in a water bath (Fisher Scientific, Isotemp 1016S, USA).

2.4 Evaluation of process control

Process control is one of the important aspects which should be considered before industrialization of an emerging technology. For this purpose, after disconnecting the electrical current (disconnecting the input energy to the system), for both OAHD and HD, we measured the length of the time that distillation process continued and also the volume of distilled product which was collected during this period.

2.5 Solid sedimentation

The thicknesses of sediment were measured after distillation process. Measurement was done by gently removing the remained liquid portion of the feedstock after distillation process, and the thickness of the sediment in the bottom of flask was measured in the HD and OAHD processes.

2.6 Statistical analysis

All experiments in this work were performed in triplicate. Analysis of variance (ANOVA) was performed to determine significant differences between the means. Duncan multiple range test (probability of 95%) was used to compare the mean values using SPSS (version 19.0.0; IBM Institute Inc., USA).

3 Results and discussion

3.1 Distillation kinetics

The distillation kinetics parameters including the rate of temperature increase, the come up time (i.e. starting time of distillation), the distillation duration, the total process time and the rate of ethanol distillation are presented in Table 1. To reach the boiling point (about 93 °C) and collect the first droplets of ethanol, it was necessary to heat the feed mixture for 24.9 ± 1.6 min in OAHD while this was about 45 min for HD (44.4 ± 0.6 min). The rate of temperature rise (°C/min) was obtained by dividing temperature changes from 35 to 90 °C over corresponding times (min). Table 1 shows that this parameter in OAHD was almost 1.8 times greater than that of HD. This finding is in line with previous reports on OAHD (Gavahian et al., 2011; Gavahian et al., 2012). It was previously reported that the rate of temperature increase in OAHD of the 1%

v/w salted water containing 30 g dried Shirazi thyme was six times greater than the traditional system at a constant voltage of 100 V (Gavahian et al., 2011). A similar result was reported on OAHD of *Thymus vulgaris* at the same condition (constant voltage of 100 V, electrolyte concentration 1% v/w and 30 g dried plant material) in comparison to the traditional HD (Gavahian et al., 2012). Similarly, the rate of temperature increase in this study was higher than traditional HD. Electrical conductivity, which will vary with electrolyte concentration, can influence the rate of ohmic heating (Ramaswamy *et al.*, 2014). Although the rate of temperature raise in OAHD of ethanol-salted water was higher than that of HD system, the value of temperature increase for OAHD in this study (2.7 °C/min) was higher than that reported for OAHD of ethanol-salted water mixture, 1.9 °C/min indeed (Gavahian et al., 2016). This difference is mainly because of different composition and different electro-thermal properties of beer and ethanol-salted water mixture. Moreover, the input energy determines the heating rate of ohmic process (Goullieux & Pain, 2005). The difference between OAHD and HD in terms of the rate of temperature increase in this study was less than previous reports on OAHD (1.8 times vs. 6 times, respectively) due to lower electrical conductivity and less electrical energy input. Therefore, greater rates of temperature increase could be achieved by design optimization.

The most commonly used heating techniques in the distillation industry rely on heat transfer from a hot surface. The heat can be generated directly via an electrical heating element (such as the heating system in an electromantle heater used in this study) or indirectly from a hot medium such as steam via a heat exchanger. As a traditional heating method, HD requires a temperature gradient to transfer heat to process the beer. Fouling due to high temperature of the heating surface and low heat transfer rate, which are common shortcomings of traditional heating systems, can possibly cause problems in distillation of fermented liquids. As an example, Figure

2 shows the deposited and partly burned layer of sediment at the bottom of the flask after distillation of beer in HD system. On contrary, almost no sedimentation was observed in the bottom of the flask after OAHD of beer. This issue needs attention in industrial application of distillatory systems. In a previous research on OAHD, which distilled ethanol from ethanol-salted water mixture, no sediment was observed (Gavahian et al., 2016). Formation of sediment layers can affect thermal and energy efficiency of the HD system.

Figure 2. (a) Image of sediment deposited on the inner wall of flask after HD of beer. (b) A 3D model showing the thickness of deposited layer obtained using the actual data. The model is projected on a flat surface and meshed for a better visualization. The maximum thickness of the sediment layer was 15 mm near center of the geometry.

The deposition of a sediment layer on the flask wall in HD process eventually reduces the total heat transfer rate of the system by increasing the thermal resistance of the wall in the sediment deposited area. Figure 3 illustrates the effect of a residue layer on the flask wall. In general, the heat generated in electromantle heater may be divided into two main sections: heat transferred to the flask and the heat dissipated to the ambient. Considering the heat generated by the electromantle heater is constant, as the thermal resistance of the flask increases, more energy

is wasted by dissipation to ambient air. The energy transferred to the flask is also divided into two parts: the energy used to evaporate ethanol and the heat dissipated to the air trapped in the flask via convection through the surface of the solution, which in turn will be transferred to ambient via the top section of the flask. Since the solution temperature is assumed to be fixed during the process (i.e. after reaching boiling point), then the heat dissipation remains constant as the heat transfer to the flask decreases, therefore, reduction in heat transfer to the system directly affects the evaporation of the ethanol in HD system.

Figure 3. (a) Influence of sediment layer on heat transfer rate in HD process. Red arrows represent the conductive heat transfer from heater to the ethanol solution. (b) A close up of the flask wall with deposited sediment. **The sediment area and its thickness, t_s , both increase with process time.**

For quantitative comparison of the heat transfer to the flask with and without precipitate layer, we model the system as a half sphere and ignore the heat dissipation to air due to convection through liquid surface, because it is the same in both cases. For a flask without sediment layer, the heat transferred to the solution is obtained from:

$$q = \frac{(T_o - T_i)}{R_F} \quad \text{(Equation 1)}$$

where T_i and T_o represent the inside and outside temperature of the wall, respectively, and R_F is the thermal resistance of the flask wall:

$$R_F = \frac{r_o - r_i}{2\pi r_i r_o K_g} \quad \text{(Equation 2)}$$

r_i and r_o are the inner and outer diameters of the flask wall, and K_g represents the thermal conductivity of the flask wall. For a thin flask wall:

$$R_F = \frac{t_g}{2\pi K_g r^2} \quad \text{(Equation 3)}$$

where t_g and r are the thickness and the radius of flask, respectively, and $2\pi r^2$ is the heat transfer area. For a flask with sediment deposited residues (Figure 3b), the heat transfer area should be divided in to two sections: the glass area (q_g) and the sediment deposited area (q_s).

$$q = q_g + q_s = \frac{(T_o - T_i)}{R_g} + \frac{(T_o - T_i)}{R_s} \quad \text{(Equation 4)}$$

and R_g and R_s are obtained from:

$$R_g = \frac{t_g}{A_g K_g}, \quad R_s = \frac{t_g}{A_s(t) K_g} + \frac{1}{K_s \int_{A_s(t)} \frac{dA}{t_s(t)}} \quad \text{(Equation 5)}$$

where t_g and $t_s(t)$ are the thicknesses of glass and sediment layers, respectively, shown in Figure 3b, A_g and $A_s(t)$ are the surface areas of the flask without and with sediment, respectively, and K_s is the thermal conductivity of the sediment layer. **Argument (t) represents the dependence of t_s and A_s to time.** Since the thickness of sediment layer, t_s , varies with position and also with time,

the thermal resistance in this region should be obtained by integration and increases as the thickness of deposited sediment increases with time. It should be noted that the sediment layer consists of a solid porous medium and the distillation solution that fills the pores of this layer and therefore, its to the conductivity of the sediment layer should be experimentally determined. The calculations presented here are general and if the geometry of the sediment deposited layer is known can be used to determine the change in the rate heat transfer over time as the residue layer is formed on the container surface. As shown in this section, the heat transfer rate will decrease by development of sediment layer in HD over time while in OAHD, heat generates directly inside the beer (Equation 6) and no sediment layer developed at the bottom of the flask.

$$Q = \sigma(E)^2 \quad (\text{Equation 6})$$

where Q is generated heat per unit volume in OAHD process, E is the electrical field and σ is the electrical conductivity of the medium which varies with distillation time since the solution concentration is not constant during the process. Also in OAHD, the temporary solid participates did not affect heating of the sample. Moreover, sever burning of sediment layer may result in production of odorous compounds and consequently, possible changes in the sensory quality of distilled product which can be a concern in some distillation industries. In addition, by ethanol evaporation during distillation process, the boiling point of feed will increase and cause reduction in the temperature difference between boiling beer and electromantle surface. This temperature difference reduction can reduce the heat transfer rate in HD system based on Equation 1. In this study, temperature of beer increased during the come up time step from 31 to 93 °C and also in the boiling (distillation) step from 93 to 98 due to the increase in beer boiling point by evaporation of ethanol (Rieder and Thompson, 1950). In contrast, increasing beer

temperature can enhance heating rate in OAHD due to increase of electrical conductivity of beer.

In ohmic heating, the rate of heating is directly proportional to the square of the electric field strength, and the electrical conductivity. The electrical conductivity increases with rising temperature, suggesting that ohmic heating becomes more effective as temperature increases (Ruan et al., 2001).

Our observation can confirm the advantage of a direct ohmic heating system which generates heat inside the materials over a traditional indirect heating system which needs heating surfaces and heat penetration. Ohmic heaters (i.e. OAHD) address these problems by eliminating the hot surfaces from the heating process of fluids and generating heat internally. As a result, higher heating rate can be achieved which is considered a major advantage of ohmic heating systems (Goullieux & Pain, 2005; Sakr and Liu, 2014).

The variation of distilled ethanol as a function of the distillation time is illustrated in Figure 4. Distillation with OAHD started much earlier than HD methods: about 25 min for OAHD and 45 min for HD. This is due to the more efficient heating mechanism in the ohmic system. Unlike the classical conductive heating methods, ohmic heating can heat the entire sample almost simultaneously and at a higher rate and therefore, it can rapidly increase the temperature of the solution (Goullieux & Pain, 2005; Sastry, 2005). As displayed in Figure 4, by the time the ethanol distillation started in HD (about 45 min after process starts), almost half of the distilled product had been collected using OAHD technique. For the same amount of distilled product recovery (around 80%), OAHD needed about 70 minutes while HD required nearly two hours.

Figure 4. Kinetics of ethanol distillation for three liters of corn beer in OAHD and HD.

The rates of ethanol distillation in OAHD and HD are shown in Table 1. This parameter was obtained from the slope of each graph in Figure 4 by dividing the amount of distilled ethanol (g) to its corresponding time (min), which is equal to the mean rate of ethanol distillation (g/min). The results show that the rate of distillation in OAHD was greater and OAHD isolates ethanol almost 50% faster than the conventional HD method. In addition, distillation duration time (the difference between total process time and starting time of distillation) in OAHD was shorter than HD due to higher distillation rate in OAHD. As presented in Figure 4, the yield graph of OAHD is steeper than HD. In OAHD process, the beer will be heated rapidly due to the Joule effect while electromantle heater system relies on time consuming conductive heat transfer (Goullieux & Pain, 2005).

Table 1. Comparison of the rate of temperature increase, come up time, distillation duration, total process time and the rate of ethanol distillation in OAHD and HD processes.

	OAHD	HD
Rate of temperature increase (°C/min)	2.7 ^a ± 0.2	1.5 ^b ± 0.0
Come up time (beginning of distillation) (min)	24.9 ^b ± 1.6	44.4 ^a ± 0.6
Distillation duration (min)	45.7 ^b ± 3.3	71.6 ^a ± 7.2
Total process time (min)	70.6 ^b ± 1.8	116.1 ^a ± 7.8
Rate of ethanol distillation (g/min)	11.6 ^a ± 0.6	7.9 ^b ± 0.3

^{a,b} The same letters in each row indicates that the means are not significantly different ($p < 0.05$).

3.2 Distilled product quantity and quality

Table 2 compares the properties of ethanol obtained by the HD and OAHD techniques. As presented in Table 2, the concentration and visual color of distilled ethanol by OAHD and HD were similar. After recovering the same amount of the feed ethanol (about 80% of available ethanol of the feedstock), OAHD yielded a distilled ethanol with almost the same concentration obtained by HD. In addition, the concentrations of distilled ethanol by OAHD and by HD show no significant difference (56.5%±1.3 and 52.3%±4.0, respectively). The visual colors of these distilled products were also similar.

Table 2. The properties of distilled ethanol obtained by OAHD and HD.

	OAHD	HD
Ethanol recovery (%w/w)	81.6 ^a ± 4.8	80.7 ^a ± 7.2
Distilled ethanol concentration	56.5 ^a ± 1.3	52.3 ^a ± 4.0
Distilled ethanol appearance	Clear	Clear

^{a,b} The same letters in each row indicate that the means are not significantly different ($p < 0.05$).

3.3 Evaluation of process control

The process control parameters for OAHD and HD were compared and reported in Table 3. The data presented in Table 3 indicates that OAHD provides a better process control which is one of the significant advantages of this distillation technique. After disconnecting the electrical current, in OAHD the distillation process continued only for a short period of time (i.e. 1 min) while for HD it was much longer (about 6 min). In other words, after stopping the electrical current in the distillation systems, HD will continue for 5.2%±1.7 of its total process time while in OAHD it will continue only for 1.8%±1.1 of its total process time. Stoppage time can be also prolonged by increasing the sediment thickness in the flask as this layer will act as a thermal insulator and keep the beer in distillation temperature after reaching desire point of process. Regarding the amount of distilled product after stoppage of electrical current, OAHD produced only 2.7 g of distilled product while HD yielded 14.8 g of distilled product. These findings were in line with that of reported by Gavahian et al., 2016 for distillation of ethanol from salted water-ethanol mixture. Stopping the process at the right time can play a crucial role in producing a product with a predefined concentration and quality.

Table 3. Waiting time and the amount of extra distilled ethanol after disconnecting the electrical current in OAHD and HD.

	OAHD	HD
Required time to stopping the process (min)	$1.2^a \pm 0.7$	$5.9^a \pm 1.7$
Amount of extra distilled ethanol in Stoppage period (g)	$2.7^a \pm 0.5$	$14.8^a \pm 0.2$

^{a,b} The same letters in each row indicate that the means are not significantly different ($p < 0.05$).

3.5 Cost, cleanliness and scale-up

In terms of time and energy consumption, the reduced cost of distillation is clearly an advantage for the proposed OAHD method (see Table 4). As shown in Figure 4, the traditional method (HD) requires an initial time of 44.4 min for heating three liters of beer before the distillation process begins and also 71.6 min for the distillation process, while OAHD required only a total of 70.6 min to complete the heating and distillation process, resulting in a significant reduction in the distillation time. The energy required to complete the distillation process, based on the electrical power consumptions for 1 g of distilled ethanol, was 0.61 Wh for HD and 0.14 Wh for OAHD. This indicates a substantial saving in the distillation cost by OAHD compared to the conventional HD technique in the case of using electricity as the source of energy. **However, capital costs also should be considered in economical comparison of this emerging technique to traditional system which can be varied by a number of factors including the electrodes material.**

Regarding environmental impacts, the calculated quantity of carbon dioxide (the primary greenhouse gas) emitted to the atmosphere is higher in the case of HD (0.5 g CO₂/g of ethanol) than for OAHD (0.1 g CO₂/g of ethanol). It means using OAHD will reduce the amount of emitted carbon dioxide by about 77 percent compared to HD for distillation of an equal amount of ethanol, which is very important in terms of sustainability and future plans of governments to prevent global warming (Paris Climate Conference, 2015).

Table 4. Effect of distillation method on energy consumption and emitted carbon dioxide.

	OAHD	HD
Consumed energy (Wh/g ethanol)	0.14 ^{b*} ± 0.01	0.61 ^{a*} ± 0.01
CO₂ rejected (g/g of ethanol)	0.11 ^b ± 0.01	0.49 ^a ± 0.01

^{a,b} The same letters in each row indicate that the means are not significantly different ($p < 0.05$).

In some countries the main energy source is electricity generated from nuclear sources (e.g. 75% in France, 50% in Russia, and 30% in Japan) and this trend is expected to grow in the future (World Nuclear Association, 2015). Nuclear power may be touted as an environmentally friendly source of energy. However, this source of energy has potentially negative environmental effects including the risk of radiation exposure for nearby communities. Nuclear plants also release radiological material and waste into the surrounding area that may threaten the ecology (Foss, 2011).

Based on the findings of this research and the previously reported data on ohmic heating, OAHD therefore can be suggested as an environmentally friendly distillation method in ethanol

production from beer (from the energy consumption viewpoint). OAHD can also be proposed 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.

4 Conclusion

An ohmic-assisted hydrodistillation (OAHD) process was quantitatively studied for extraction of ethanol from corn beer. Our results show that OAHD could be considered as a promising procedure to perform an accelerated beer distillation with no significant difference in quality and quantity of distilled product compared to the conventional HD technique. Moreover, this innovative distillation method consumes less energy and therefore is more sustainable than the conventional HD from environmental point of view. After 71 min of OAHD process, it was possible to collect almost 80% of feed ethanol, whereas HD needed 44 min to get the first drops of distilled ethanol and collected 80% of feed ethanol after 116 min. Not only OAHD was a time- and energy- saving method, but also showed a better process control than HD. Such advantages could make OAHD an alternative distillation method for alcohol distillation. The findings of this research were in agreement with the previous reports on OAHD. Further investigation is required on large scale distillation of ethanol and commercialization of OAHD for bioethanol concentration process.

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