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Improvement of solar ethanol distillation using ultrasonic waves

Jaruwat Jareanjit* and Thanwit Naemsai

Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Srivijaya, Songkhla 90000, Thailand

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Abstract

This report presents a study on the use of ultrasonic waves in solar ethanol distillation to investigate their performance at a frequency of 30 kHz and a power of 100 Watts in the inlet of a 10-litre distillation tank. Based on a non-continuous distillation process (batch distillation), the experiment demonstrated that using ultrasonic waves in solar ethanol distillation increased the average concentration of distilled ethanol compared to a system without this technology. Ultrasonic waves were able to enhance the separation of ethanol from the solution (water-ethanol mixture) during solar distillation. The amount of pure ethanol produced from each distillation batch using this technology was greater when the initial concentration of ethanol was lower than 50%v/v (% by volume). An average of approximately 40% and 20% were obtained for initial ethanol concentrations of 10%v/v and 30%v/v, respectively. Furthermore, the distillation rate varied with the amount of solar irradiation.

Keywords: Ethanol distillation, Ultrasonic waves, Solar distillation, Ethanol concentration

1. Introduction

Based on the current environmental and power shortage issues, a long-term solution at an international level has focused on advocating various forms of renewable energy use. The Ministry of Energy of Thailand has been planning to develop and enhance the use of renewable energy and alternative energy to 25% over 10 years (2013-2023). One of the targeted strategies was that the consumption of ethanol, which are sources of agricultural raw materials in the country, would be limited to 9 million litres per day [1]. Hence, any improvement in the ethanol production process must correspond to the Ministry of Energy's policy. Specifically, the transportation industry has been encouraged to use ethanol as a form of alternative energy [2-5]. Nonetheless, one important process in producing fuel from ethanol is fractional distillation. To increase the concentration of ethanol from 9-10% v/v to 93-95% v/v, a large amount of heat is required. In process industries, distillation remains one of the preferred processes despite its difficulties in separating mixtures with similar boiling points and those that form azeotrope. To overcome this limitation, a variety of new technologies have been explored [6-8]. Furthermore, it is possible to implement this separation technique with azeotropic distillation [9] or extractive distillation [10]. However, this process is marred by a high pressure drop and a temperature difference caused by an increase in the boiling point [11]. An analysis of energy consumption in the production of ethanol [12-13] indicated the use of fossil fuels as a source of heat energy in the production and distillation of ethanol. To produce ethanol economically [14-15], the energy ratio for the entire cycle must be greater than 1.0 and varies with the material used in production. Solar radiation, which can be used as a source of heat [16-20], can be used instead of fossil fuels in the ethanol distillation process. The previous study investigated renewable and clean solar radiation applications in non-continuous distillation processes (batch distillation) of ethanol distillation [21-23], with the goal of reducing the net energy consumed in the ethanol batch distillation systems. Using solar energy is one way to increase the energy ratio, reduce fossil fuel consumption, and reduce the cost of producing ethanol. However, solar ethanol distillation systems, which have lower thermal heat resources compared to those from the industrial combustion of fossil fuel, require repeated refining processes to increase concentration.

Therefore, the production of ethanol concentration using solar ethanol distillation in batch operation is significantly higher than that of a normal system. Researchers discovered that the ultrasonic wave energy is applicable. Previous research uncovered that ultrasonic waves are able to be applied to reduce energy consumption and improve efficiency in various industries. A frequency range of 20 to 40 kHz activates the liquid's bonding breakage, and bubbles are formed from the cavitation phenomena, which affect the mechanical properties and chemical substances [24-25]. This form of energy is widely used in optimizing the efficiency of the extraction of various substances [26-27] and can be applied to emulsification processes [28]. Particularly, alternative fuel production [29-32] can reduce the duration of the biodiesel production process through a transesterification reactor by accelerating the speed of the

*Corresponding author. Tel.: +6686 685 6747
Email address: j.jaruwat@gmail.com
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solvent; hence, the exchange area between the solvent and the solute increases [33-35]. Additionally, Yasuda et al. [36] applied this process in separating ethanol from the water solution at low concentrations using a micro-droplet, which was caused by the high frequency of an ultrasonic atomizer. This process resulted in a significant increase in the ethanol concentrations, which corresponds to the research performed by Kirpalani and Suzuki [37], who used ultrasonic waves to enhance the concentration of ethanol solutions through the condensation of aerosol mist in the ethanol-water solution using a high frequency ultrasonic wave at 2.4 MHz in a continuous extraction process of ethanol-water at low temperatures of 10°C and 24°C due to the cavitation phenomenon. Additionally, to develop the ultrasonic distillation process, studies on the vapour–liquid equilibrium (VLE) under ultrasonically intensified environments have been conducted. These include experimental studies on the VLE of methanol–water [38], MTBE methanol [39] and cyclohexane-benzene [40]. In all of the cases, positive changes in the VLE characteristics were observed, and sonication effects were proven to alter the relative volatility of azeotropic mixtures, thus enabling a higher purity separation in a single distillation column.

This study was aimed at improving solar ethanol distillation using an ultrasonic wave in a distillation tank. Therefore, this research led to the concept of applying 30 kHz ultrasonic waves as a case study in forming cavitation phenomenon for a solution in the inlet area of the distillation tank combined with a high temperature from a solar collector, thus enhancing the performance of the batch ethanol distillation process.

2. Methodology

This research presents a study on a solar ethanol distillation experiment using ultrasonic waves and compares it to a normal system (solar ethanol distillation without ultrasonic waves). The experiments were conducted at the department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Srivijaya.

2.1 Working principle of the trial set

A 30 kHz 100 Watt ultrasonic transducer (ModelAK-5030-2Q, 3 sets) and an ultrasonic generator (ModelAK-200HT) were installed in the inlet area of the distillation tank, as illustrated in Figure 1. In a batch operation, various initial concentrations of the ethanol solution were used as a raw material to absorb thermal heat from the flat plate solar collector, which had a 2 m^2 surface area exposed to direct rays. The performance of the solar collector based on the ASHRE standard is defined by $F_R(\tau\alpha) = 0.795$ and $F_RU_L = 9.85$ W/m^2K. The solar collector was installed facing south with a tilt angle of 7 degrees to the horizontal (based on the installed position latitude) so that the solar collector was perpendicular to the sun's rays and exposed throughout the trial. The centrifugal pump (1/4 hp) was used to circulate the solution (water-ethanol) directly through the solar collector at a flow rate of 0.02kg/s-m^2 to a refined cylindrical distilled tank with a 35-cm diameter, 42cm height, and 10 L capacity. The evaporation and condensation sections are placed in the same unit, as depicted in Figure 2. Using this working principle, the solution in the system reached a high temperature when exposed to the thermal energy from the solar collector. Based on the different properties of ethanol and the water's boiling point at atmospheric pressure, when the temperature increases, the lower boiling point or higher vapour pressure substance (ethanol) will evaporate at a higher rate compared to those with a higher boiling point or a lower vapour pressure (water), which varies with the quantity of initial solution in the mixture (ethanol-water). Due to the natural heat and mass transfer process in an enclosed space, the vapour will condense at the top of the distillation tank. Furthermore, ethanol and water vapour will condense at the condensation surface area that has a lower temperature than that of the evaporated surface. The temperature can be cooled by cooling water on top of the distillation tank. Then, the condensed substances at the condensation surfaces combine and drop into an accommodation tray in the middle of the distillation tank and flow out of the distillation tank.

2.2 Experimental procedure

The study was designed to apply an ultrasonic wave to solar ethanol distillation for comparison with a normal system (solar ethanol distillation without ultrasonic waves). To evaluate the performance of the distillation process with an ultrasonic wave on the distillation rate, distillation quantity and separation performance of ethanol, ethanol solutions with an initial concentration of ethanol 10, 30, 50 and 70%v/v (by volume) in a reactant of 10 L were used. The experiment was performed between 9:00-15:00(6 hours per day), and the solar radiation was measured using a pyranometre (Kipp & Zonen) Model CM11B with a resolution of +/-2 W/m^2. The temperatures were measured at various locations, including the outlet temperature of the solar collector (To), inlet temperature of the solar collector (Ti), vapour temperature in distillation (Tg), solution temperature (Ts), and temperature of the surface condensation in the tank (Tc), which were measured using a thermocouple type K with a resolution of +/-0.5°C.The radiation data and temperatures were recorded every 1 min using a data logger (Yokogawa) Model MV 2000, and the flow rate at the outlet of the solar collector was controlled at 0.02kg/s-m^2or 2.4 l/min by a rotameter. Furthermore, the distillation volume and concentration were measured at various time intervals with a cylinder and hydrometer every hour, and total/batch was used to benchmark the distillation performance in each case, as depicted in Figure 2.

The separation performance of the ethanol ($\eta_{separation}$) is examined based on the quantity of the distillation product ($m_{al_{product}}$) and the initial solution ($m_{al_{initial}}$) in terms of the ethanol distillation quantity ($m_{al_{product}}$) relative to the initial quantity of ethanol ($m_{al_{initial}}$) in the solution in mm^3, which can be calculated from the equation as follows:

$$\eta_{separation} = \frac{m_{product} \times (\%v/v)_{product}}{m_{initial} \times (\%v/v)_{initial}} = \frac{m_{al_{product}}}{m_{al_{initial}}} \text{ x } 100 \quad (1)$$

3. Results and discussion

The results of the experiment performed above can be presented as follows:

1. The normal system (solar ethanol distillation without ultrasonic wave). The experiment investigated the effects of ethanol at various initial concentrations in the ethanol-water solution in the distillation performance. The details of the study can be given as follows:

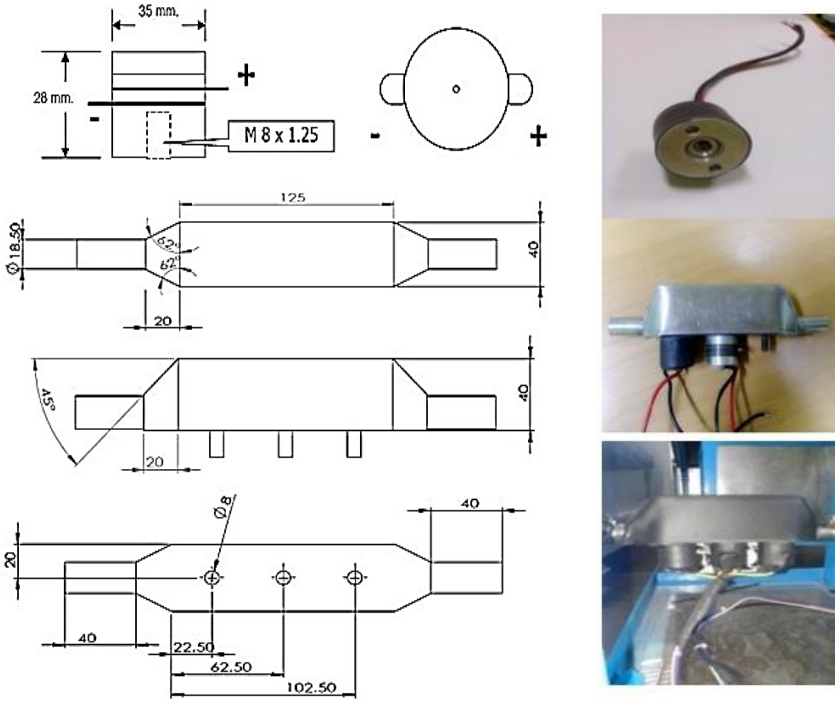

Figure 1 Schematic dimensions (mm) and installation position at the inlet area of the distillation tank for an ultrasonic transducer to improve solar ethanol distillation using an ultrasonic wave

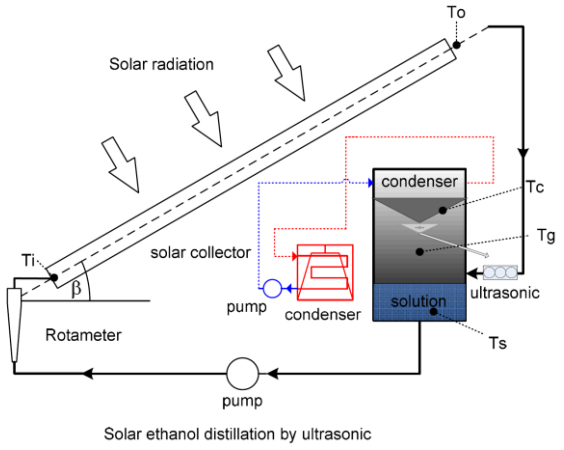

Figure 2 Schematic diagram of solar ethanol distillation using ultrasonication

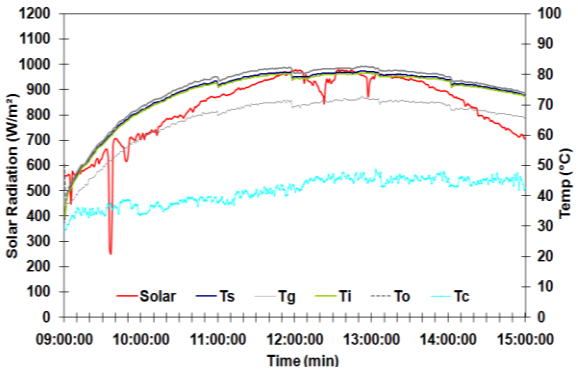

Figure 3 Solar radiation (18.03 MJ/m^{2}day) and temperature (ethanol 10%v/v)

Using Figure 3, it can be observed that the temperature at each point slowly varies with the solar radiation value from the accumulated heat of the ethanol-water solution, in which the outlet temperature of the solar collector (To), inlet temperature of the solar collector (Ti), and solution temperature (Ts) were similar at approximately 70-80°C between 11:00 – 14:00. The temperature in the distillation tank (Tg) was lower, i.e., approximately 60-70°C, and the temperature of the surface condensation in the tank (Tc) had the lowest temperature, thus resulting in the temperature difference between the evaporation surface and the condensation surface and subsequently creating mass and heat transfer. Using Figures 4 and 5, it can be clearly observed that the volume of the distillation varied based on the solution temperature in the distillation tank. Furthermore, the product concentration clearly had an inverse relationship with the amount of distillation. The product concentration decreased as the duration of distillation increased or the amount of distillation increased based on the batch system, and the product concentration was proportional to the remaining ethanol volume in the ethanol-water solution in the distillation tank.

2. The experiments on the ultrasonic waves in solar ethanol distillation were conducted to study the effects of ultrasonic waves and various initial concentrations on the ethanol-water solution in the distillation performances; the details of the study are can be given as follows:

Figure 6 demonstrates that the temperature at each point slowly varies with the solar radiation value from the accumulated heat of the ethanol-water solution, in which the outlet temperature of the solar collector (To), inlet temperature of the solar collector (Ti), and solution temperature (Ts) were similar at approximately 70-80°C between 11:00 – 15:00. Similar changing features are exhibited by the normal system as well. Figures 7 and 8 display the volume of distilled ethanol and its concentration

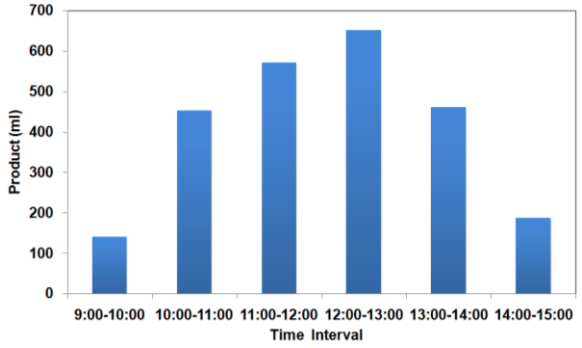

Figure 4 Distilled ethanol solutions from the ethanol-water solution (ethanol 10%v/v)

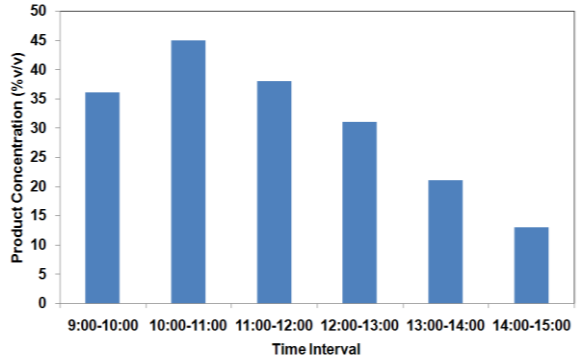

Figure 5 Distilled ethanol concentration per hours (ethanol 10%v/v)

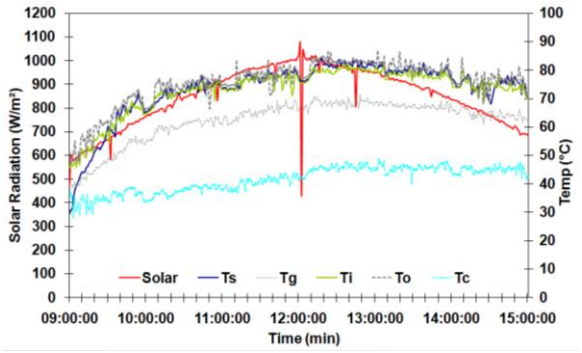

Figure 6 Solar radiation (18.39 MJ/m^{2}day) and temperature (ethanol 10%v/v)

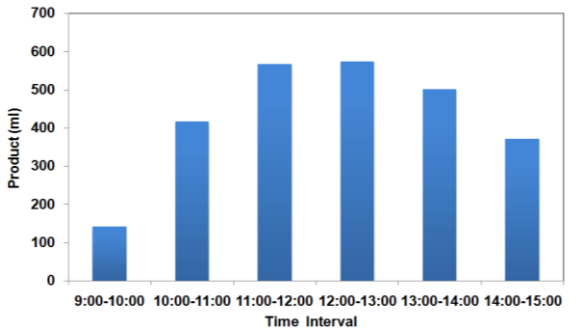

Figure 7 Distilled ethanol solutions from the ethanol-water solution (ethanol 10%v/v)

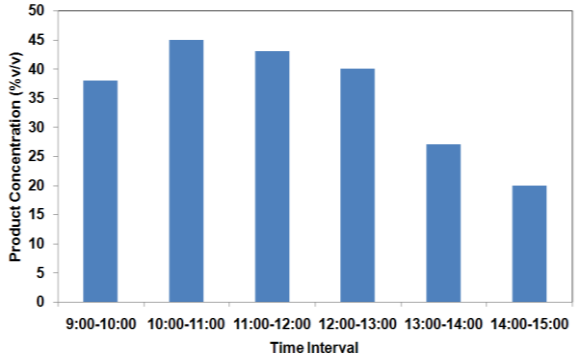

Figure 8 Distilled ethanol concentration per hours (ethanol 10%v/v)

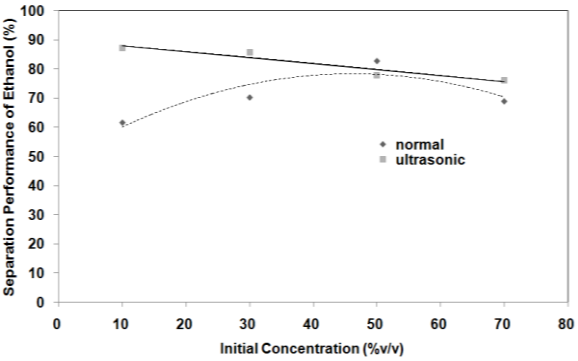

Figure 9 Comparison of separation performance as a function of the initial concentration

at various time intervals, and it can be observed that the distilled volume varies with the temperature of the solution. The concentration of the distilled solution inversely varied with the amount of distillation rate, which appears to be lower than that of the normal system, with a slight decrease due to the longer distillation period or higher distillation volume because the batch operation's characteristics are proportional to the remaining volume of ethanol in the ethanol-water solution.

It can be determined from Table 1 that the use of ultrasonic waves in the ethanol solar distillation caused the average concentration of the hourly distilled product to become higher than that of a normal system, where the distil rate or distil frequency are similar to or higher and vary with the initial concentration value of ethanol. The ethanol product, which was refined during 09:00 – 13:00, or the first 4 hours of hourly distillation, varied with the thermal heat obtained from the solar radiation in both systems. Furthermore, ultrasonic waves influencing the hourly concentration in the system had a remarkable increase during this period, which can be expressed as a quantity of the pure ethanol product from the distillation and the separation performance of the ethanol. The differences were primarily found between 11:00-12:00 in terms of the initial concentration of ethanol that was less than 50%v/v (10%v/v and 30%v/v). Subsequently, the hourly concentration, pure ethanol volume and separation performance of ethanol in the normal system decreased rapidly compared to the system that used ultrasonic waves varying with the initial concentration value. By correlating pure isolated ethanol in the distillation product to pure ethanol in various initial ethanol concentrations in the distillation tank, the separation performance of ethanol was revealed to be 87.18, 85.77,

Table 1 Comparison of product volume, product concentration, pure ethanol and separation performance between an ultrasonic system and a normal system

Initian 10%v/v	normal system (18.03 MJ/m^2 day)			Ultrasonic 30 kHz system (18.39 MJ/m^2 day)			Separation performance	
	Product (ml)	Product (%v/v)	Ethanol (ml)	Product (ml)	Product (%v/v)	Ethanol (ml)	normal	ultrasonic
9:00-10:00	140	36.00	50.40	141	38.00	53.58	5.04	5.36
10:00-11:00	452	45.00	203.40	415	45.00	86.75	20.34	18.68
11:00-12:00	570	38.00	216.60	565	43.00	242.95	21.66	24.30
12:00-13:00	650	31.00	201.50	573	40.00	229.20	20.15	22.92
13:00-14:00	460	21.00	96.60	500	27.00	135.00	9.66	13.50
14:00-15:00	186	13.00	24.18	370	20.00	74.00	2.42	7.40
total	**2458**	**25.00**	**614.50**	**2564**	**34.00**	**871.76**	**61.45**	**87.18**
Initian 10%v/v	**normal system (18.18 MJ/m^2 day)**			**Ultrasonic 30 kHz system (19.23 MJ/m^2 day)**			**Separation performance**	
	Product (ml)	**Product (%v/v)**	**Ethanol (ml)**	**Product (ml)**	**Product (%v/v)**	**Ethanol (ml)**	**normal**	**ultrasonic**
9:00-10:00	263	52.00	136.76	310	68.00	210.80	4.56	7.03
10:00-11:00	760	63.00	478.80	640	72.00	460.80	15.96	15.36
11:00-12:00	748	68.00	508.64	1050	70.00	735.00	16.95	24.50
12:00-13:00	925	54.00	499.50	900	65.00	585.00	16.65	19.50
13:00-14:00	800	47.00	376.00	725	56.00	406.00	12.53	13.53
14:00-15:00	710	34.00	241.40	525	43.00	225.75	8.05	7.53
total	**4206**	**50.00**	**2103.00**	**4150**	**62.00**	**2573.00**	**70.10**	**85.77**
Initian 10%v/v	**normal system (18.58 MJ/m^2 day)**			**Ultrasonic 30 kHz system (18.96 MJ/m^2 day)**			**Separation performance**	
	Product (ml)	**Product (%v/v)**	**Ethanol (ml)**	**Product (ml)**	**Product (%v/v)**	**Ethanol (ml)**	**normal**	**ultrasonic**
9:00-10:00	330	77.00	254.10	290	67.00	194.30	5.08	3.89
10:00-11:00	890	81.00	729.90	1050	80.00	840.00	14.42	16.80
11:00-12:00	1166	82.00	956.12	950	80.00	760.00	19.12	15.20
12:00-13:00	1240	79.00	979.60	1200	78.00	936.00	19.59	18.72
13:00-14:00	1000	74.00	740.00	1150	73.00	839.50	14.80	16.79
14:00-15:00	740	65.00	481.00	550	65.00	357.50	9.62	7.15
total	**5366**	**77.00**	**4131.82**	**5190**	**75.00**	**3892.50**	**82.64**	**77.85**
Initian 10%v/v	**normal system (18.39 MJ/m^2 day)**			**Ultrasonic 30 kHz system (19.04 MJ/m^2 day)**			**Separation performance**	
	Product (ml)	**Product (%v/v)**	**Ethanol (ml)**	**Product (ml)**	**Product (%v/v)**	**Ethanol (ml)**	**normal**	**ultrasonic**
9:00-10:00	300	82.00	246.00	790	85.00	671.50	3.51	9.59
10:00-11:00	800	87.00	696.00	800	87.00	696.00	9.94	9.94
11:00-12:00	1300	85.00	1105.00	1150	87.00	1000.50	15.79	14.29
12:00-13:00	1350	83.00	1120.50	1190	87.00	1035.30	16.01	14.79
13:00-14:00	1150	81.00	931.50	1380	86.00	1186.80	13.31	16.95
14:00-15:00	900	78.00	702.00	960	83.00	796.80	10.03	11.38
total	**5800**	**83.00**	**4814.00**	**6270**	**85.00**	**5329.50**	**68.77**	**76.14**

77.85 and 76.14% for solar ethanol distillation using ultrasonic waves at initial ethanol concentrations of 10, 30, 50 and 70%v/v, respectively. Furthermore, the normal system had a separation performance for ethanol of 61.45, 70.10, 82.64 and 68.77% at an initial ethanol concentration of 10, 30, 50 and 70%v/v, respectively. By contrasting the separation performance trend of ethanol with the initial concentration, it was discovered that the use of ultrasonic waves in the solar distillation of ethanol was more likely to have an initial concentration of ethanol lower than 50%v/v that was constantly decreasing when the initial concentration became higher than 50%v/v; this result is unlike the normal system, which had its greatest ethanol separation performance at 50%v/v, as indicated in Figure 9.

Furthermore, the greater ethanol separation performance occurs when using ultrasonic waves in the ethanol distillation in addition to the difference in the boiling point temperature of the solution (ethanol-water); the use of ultrasonic waves at a specific frequency incurred a weaker bonding force of particles, thus accelerating the separation of the hydrogen bonding of the ethanol-water solution. The rise in the temperature of the solution caused a lower surface tension and thus greater evaporation substances. Additionally, the cavitation effect initiated the generation of small ethanol micro-droplets and water vapour. Particularly, the high vapour pressure of ethanol, which is greater than that of water, could separately vaporize itself from the ethanol-water solution, especially when the initial concentration of ethanol was lower than 50%v/v.

4. Conclusions

This experiment revealed that the use of ultrasonic waves in solar ethanol distillation was an alternative method for improving solar ethanol distillation with ultrasonic waves (30 kHz frequency). Additionally, the generated superior mass transfer could be enhanced, where the average concentration of the hourly distilled ethanol product was higher than that of a normal system at the same or higher distillation rate. The ultrasonic wave was able to separate ethanol from the solution through solar ethanol distillation, which was consistent with other studies [41-42]. The amount of pure ethanol product from each distillation batch was clearly larger than the amount of product from the normal system when the initial concentration of ethanol < 50%v/v, with an average of approximately 40% and 20% obtained for

an initial ethanol concentration of 10% v/v and 30%v/v, respectively. Therefore, solar ethanol distillation using an ultrasonic wave was able to eliminate 1 stage of refining solar ethanol distillation for obtaining a distillation product concentration of ethanol of approximately 80%v/v and higher compared to a normal system under identical conditions; the distillation rate varied with the solar radiation value in both systems.

Hence, due to the frequency (30 kHz), bubbles occurred from the cavitation phenomenon, thus accelerating the separation of the hydrogen bond of the ethanol-water mixture; furthermore, the high temperature from the solar radiation can be applied to the discrete ethanol distillation process. By applying a higher temperature to the solution, frequencies lower than 2.4MHz are applicable. Due to the aforementioned factor, a lower surface tension of the solution could be obtained; hence, the evaporation of the mixed solution became higher. This phenomenon altered the physical properties of the mixtures and enhanced the mass [43] and heat [44] transfer, thus offering a further exploitation to intensify the vapour–liquid separation. Nevertheless, this study is useful and serves as a good starting point for further work on the design of ultrasonic-assisted solar ethanol distillation systems, which are currently being conducted, thus offering a new approach to improve the process by adding ultrasonic equipment to the distillation system. Using the concept of low temperature distillation through the cavitation phenomenon changes the vapour–liquid equilibrium characteristics to enhance the ethanol-water separation using heat from solar energy, which are the driving forces behind the mass transfer in the distillation tank. Thus, a higher ethanol purity separation in a single stage distillation can be enabled by a non-pressure drop and a low temperature difference, which results in this system having less energy consumption and being suitable for renewable energy.

Due to the intriguing hypothesis and with no known research in this field, this study could be a framework for the future development of solar ethanol distillation. The frequency of the ultrasonic wave range and position to install the ultrasonic transducer are parameters should be developed to determine the optimization of the system in future studies.

5. Acknowledgements

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