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Research Article

Application of Pulse Electric Field for Chemical Extraction Process

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Abstract: This paper discusses the material and method of designing the electric circuits of Pulse Electric Field (PEF) hardware that can accommodate Direct Current (DC) voltage with modulation frequencies that could be controlled. The main circuit has several parts that are input, processor, and output. The keypad is used to set the frequency, the duty cycle, the number of Pulse with Modulation (PWM), and time variables. A microcontroller will process these parameters as the processor. The outputs consist of a display, separator, driver, and chamber. The separator is used to secure the processor. The driver is a voltage regulator for the circuit. A PEF chamber is used to treat the sample. The sample used in this study is 40 mL of water for hardware testing. The test procedure is using ± 128 VDC as the voltage source with a variant value of frequency, duty cycle, and time. This test aims to get the best value of these variables that produces optimum condition during the extraction process. Thus, it can be concluded that the hardware is able for the extraction of water-based processes. It can operate over a voltage range from 15 VAC to 128 VAC (up to 172 VDC after rectification), the frequency in 1 Hz to 5 Hz, duty cycle of 1 % to 5 %, and the treatment time in 10 s to 25 min. This PEF hardware design could be used for the microalgae as the water-based raw material by electric shock method.

Keywords: Electric shock, extraction, microalgae, microcontroller, Pulse Electric Field.

1. INTRODUCTION

Nowadays the usage of energy depends on fossil-fuel energy. As we know, that it is kind of non-renewable energy which is decreasing significantly. The main problem of biofuel development from the renewable natural feedstock is the depletion of fossil energy and greenhouse effect [1]. Palm oil is one of the most common raw materials used to produce biodiesel as biofuel in addition to soybean oil and sunflower oil. In Indonesia, the use of these raw materials for energy conversion contradicts the fulfilment of the food sector, although palm oil is the best biodiesel feedstock in quality and quantity to replace fossil diesel fuel [2].

To overcome this problem, cheap raw materials such as used cooking oil and palm oil distillate are being utilized. Also, microalgae recently explored as promising new biodiesel feedstocks [3]. Microalgae are simple cellular microorganisms that live in an aquatic environment. They need enough light, water, and CO_2 to bring photosynthesis in high biomass productivity [4]. They can be cultivated in extreme media, such as in wastewater, and CO_2 supplied from flue gas [5]. Meanwhile, the lipid content is potentially converted into biodiesel.

Conversion of microalgae into biodiesel (oil extraction) is a problem to be solved. Some methods that can be used for algal oil extraction include: mechanical, electrical and chemical methods [6]. In mechanical method, pressurized conditions are used to remove oil from the main cells of microalgae. In chemical methods, chemical solvents such as n-hexane [7] and CO_2 are used in supercritical conditions [8]. Both of these methods utilize dry microalgae as raw materials, which require high energy and take more time in the drying process. Electrical methods use electrical energy to move algal oil out of the algal cells. One of the proposed electrical methods is the Pulse Electric Field (PEF), which extracts algae oil by disrupting the cell wall of microalgae in an electric field [9].

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According to [10], PEF is a method that widely used in non-thermal food processing by using high-intensity electric shock. PEF was applied to the liquid material. The process is short between one microsecond to a millisecond with short pulses. The process of PEF is based on short pulse applications at high voltages (20 kV.cm^{-1} to 80 kV.cm^{-1}) to the food placed between two electrodes. PEF was categorized as a non-thermal process because the food was processed at room temperature or below for a few seconds. It can minimize the loss of any nutrients caused by heating.

The main purpose of PEF method is to extract the lipid content by applying an electric field to destruct the cell wall of microalgae. By using this technology, energy was obtained from a high voltage of source stored in one or more capacitors and released through the food material to produce electric fields required. The energy stored in the capacitor could be released quickly with a very high power. Therefore, the objective of this research is to design a PEF device for the water-based microalgae extraction process. The indicator of the PEF performance can be concluded by analyzing the sample behavior and device stability by varying the voltage input, switching frequency, and treatment time. The proposed design is laboratory scaled and expected to be used in the next research.

2. MATERIALS AND METHOD

This section explains the materials and method used to build PEF hardware. The PEF can accommodate Direct Current (DC) voltage with controlled frequencies. It is used for the water-based extraction process. The PEF system diagram design is shown in Fig. 1.

In Fig. 1, keypad is used for user input to set the variables and parameters that need to be adjusted in the PEF operation. These variables are frequency, duty cycle (t_{on} and t_{off}), the number of Pulse with Modulation (PWM) waveform, and treatment time. The next part is the PEF system processor that will process the Input variables and parameters. This study used AVR ATMEGA16 microcontroller as a processor which controls the voltage output waveform. Further, the last part is the outputs. This part consists of several sections. Liquid Crystal Display (LCD) used as an indicator for the user. The optoisolator is used to secure the processor circuit from overvoltage and short circuit. Next, the MOSFET gate driver is used to drive the N-Channel MOSFET and voltage through PEF chamber. PEF chamber is used to place the water-based sample for the extraction process. It is related to further studies that will apply the PEF hardware for the extraction process of the water-based sample. A 40 mL of sample is used for PEF hardware testing.

In hardware testing, the voltage value is fixed at ± 128 VDC with a variant value of frequency, duty cycle, and treatment time. This test aims to get the best value of these variables that produce optimum conditions during the water-based extraction process. The design and testing of PEF hardware is described in the next section.

3. RESULTS AND DISCUSSION

This section describes the process of hardware testing presented in several stages. These stages are the series of experiments that aim to produce PEF hardware that could be used for the water-based extraction process.

3.1. Design of PEF Chamber

The PEF chamber is designed at the first stage. The size of this chamber affects the calculation of the electric field needed for the extraction process and

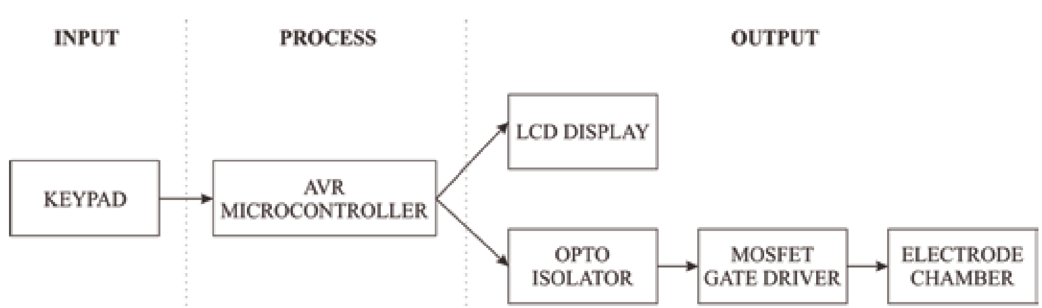

Fig. 1. PEF system diagram

determines the hardware to be used. This calculation is given by Equation (1) [11]:

$$E = \frac{V}{d}$$

Where E is the electric field strength, V is the voltage source, and d is the gap between two parallel plates. This PEF chamber consists of eight pieces of 100 mm × 180 mm x 1 mm stainless steel sheet . These are arranged vertically and placed in 165 mm × 145 mm × 42 mm acrylic containers that is shown in Fig. 2.

In PEF chamber, the distance between the plates is one mm and there is one mm thick glass that is placed between the plates. This glass is used as a translucent insulator and heat-resistor between the plates. According to Equation (1), it aims to get the electric field of 1.28 kV.cm^{-1} when the voltage passing through the plates is 128 VDC.

In the PEF chamber, eight plates are arranged alternately with the order of the electrode (-) and (+) so that the plates will be charged (-) in the end plate. This configuration is shown in Fig. 3.

Figure 3 shows that electrodes are marked in red and given a positive voltage, while the gray is connected to ground. The installation of PEF Chamber is shown in Fig. 4.

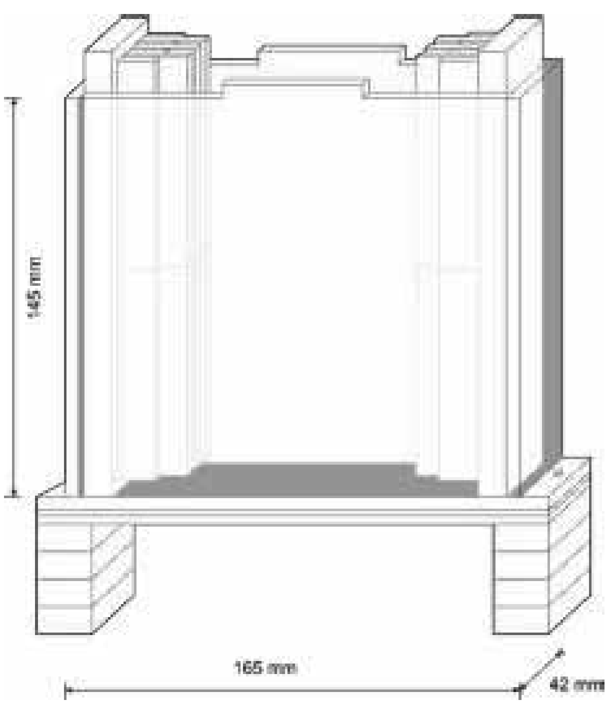

Fig. 2. Design of PEF chamber

The composition of the electrode plates is placed inside a three mm acrylic container.

3.2. Design of Transformer

In the electronic parts, the main step is to design the transformer by using two step-down transformers

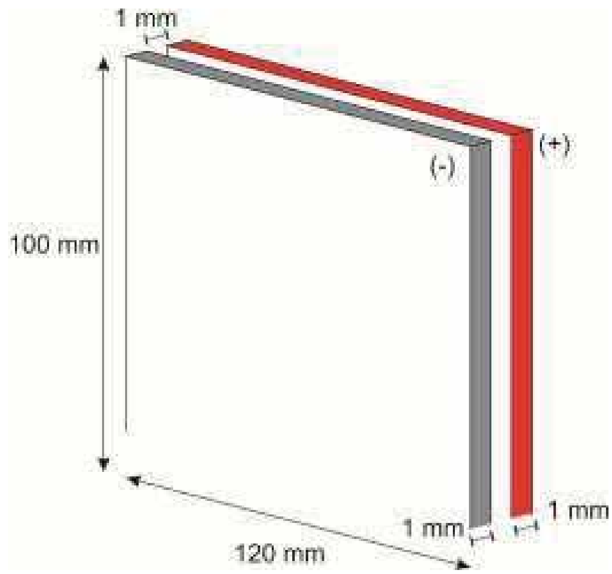

Fig. 3. Electrode and polarity

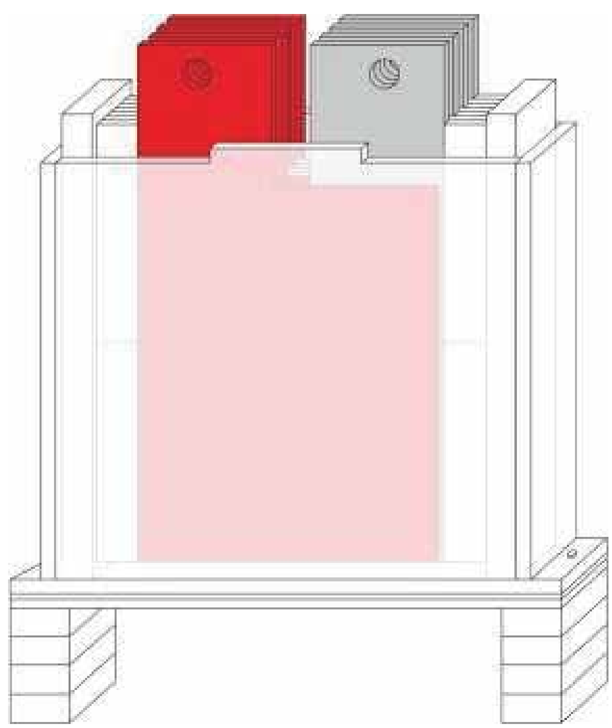

Fig. 4. PEF Chamber installation

32 V 5 A CT to produce the voltage as needed in the extraction process. Ampere meter is used as an additional instrument to determine the load current measurement.

Both transformers are connected in series to gain a larger voltage. This configuration produces two times the voltage which is generated by one transformer. The serial transformer circuit diagram is shown in Fig. 5.

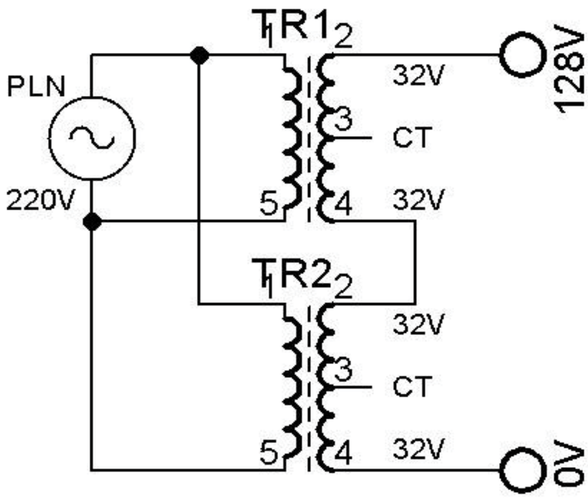

Fig. 5. Serial transformer circuit diagram

Fig. 5 shows how to obtains 128 VAC transformer output voltage with 5 A current. Thus, the maximum electric field can be applied 1.28 kV/cm (AC), assuming that there is no change in the voltage when rectified.

3.3. Design of Rectifier

The rectifier circuit consists of full-wave diode bridge used to cope with high loads. The circuit of rectifier is shown in Fig. 6.

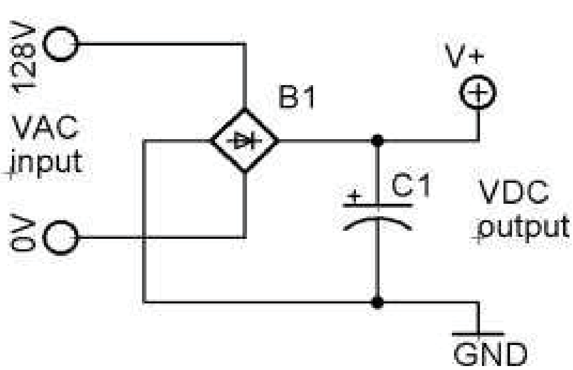

Fig. 6. Rectifier circuit diagram

The DC output voltage value generated may reach 172 VDC due to the capacitor added in this circuit.

3.4. Design of Processor and User Interface

The ATMEGA16 chip processor serves as a controller chip that sets a variable frequency, timer, and duty cycle. The user interface design is shown in Fig. 7.

Fig. 7. User interface design

The keypad is used to set a variable of input. LCD is added to display the variable and as a user interface.

3.5 Design of Separator and MOSFET Driver

This section serves to get the optimum performance and behavioral voltage control circuit in the PEF chamber. The separator section used two optocoupler TLP521 as a non-contacted connector between the controller and the driver that also functions as a conduit logic to MOSFET Gate Driver (MGD) circuit, as shown in Fig. 8.

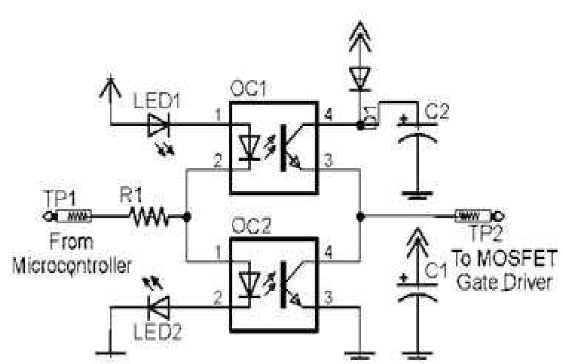

Fig. 8. Optocoupler separator circuit

In Fig. 8, OC1 and OC2 are two optocouplers working alternately by a square wave pulse with the voltage level of 5 V sent from PORTD.6 microcontrollers. When the wave of logic is one (high), then optocoupler OC1 would be active, and OC2 would be inactive. Otherwise, when the wave of logic is zero (low), then the optocoupler OC1 would be active, and OC2 would be inactive, and its run continuously. This process will generate the output waveform and become the input, but the level is boosted to 12 V and separated electronically from the input. Strengthening the voltage level has to be done, considering that the MGD components used requires 12 V voltage levels to work. The MGD circuit is shown in Fig. 9.

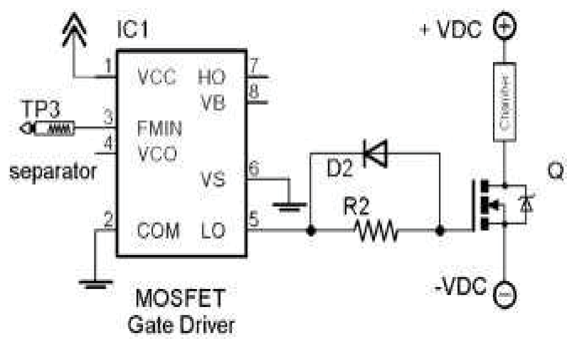

Fig. 9. MOSFET gate driver (MGD) circuit

The driver circuit in Fig. 9 only uses a single MOSFET. It merely uses part of the low side. The reason for using this configuration is that when two MOSFETs (high side and low side) parts are used, the part that cannot handle the load is that of the step-down transformer. Based on the results of previous trials, the high-side MOSFET part was frequently damaged.

3.6 Assembling PEF

Earlier described are compiled into a PEF device. The overall integration of the input part, processor, and output is shown in Fig. 10 and Fig. 11.

Figure 10(a) is an input voltage from the transformer 5 A; this input is used to generate a voltage of 128 V in the extraction process. Figure 10(b) is a power supply that provides power to the circuit. Figure 10(c) shows the part of the 5 A serial transformers circuit. Figure 10(d) is an interface, which is used to set parameters and to see the information on the LCD. Ampere meter is used to read the current value indicated in the Fig. 10(e). Fig. 10(f) is part of the rectifier that serves to rectify AC into DC voltage. Separator and MOSFET gate driver circuit are shown in Fig. 10(g) and Fig 10(h) shows a microcontroller as a processor. Figure 11 shows the assembled PEF unit and the PEF chamber.

Figure 11(a) is an assembled PEF unit as described before. Figure 11(b) is an oscilloscope, an additional instrument for measuring the frequency

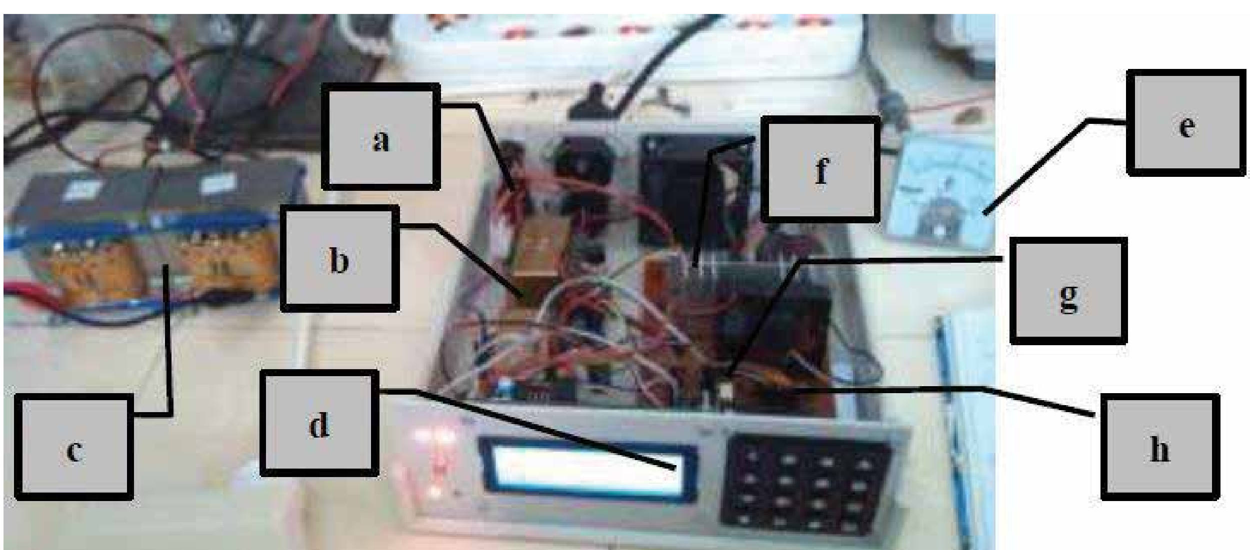

Fig. 10. PEF Assembly unit, **(a)** Input from transformer 5A, **(b)** Power supply, **(c)** Serial Transformer 5A, **(d)** Interface, **(e)** Ampere meters, **(f)** Rectifier, **(g)** Separator and driver, and **(h)** Microcontrollers

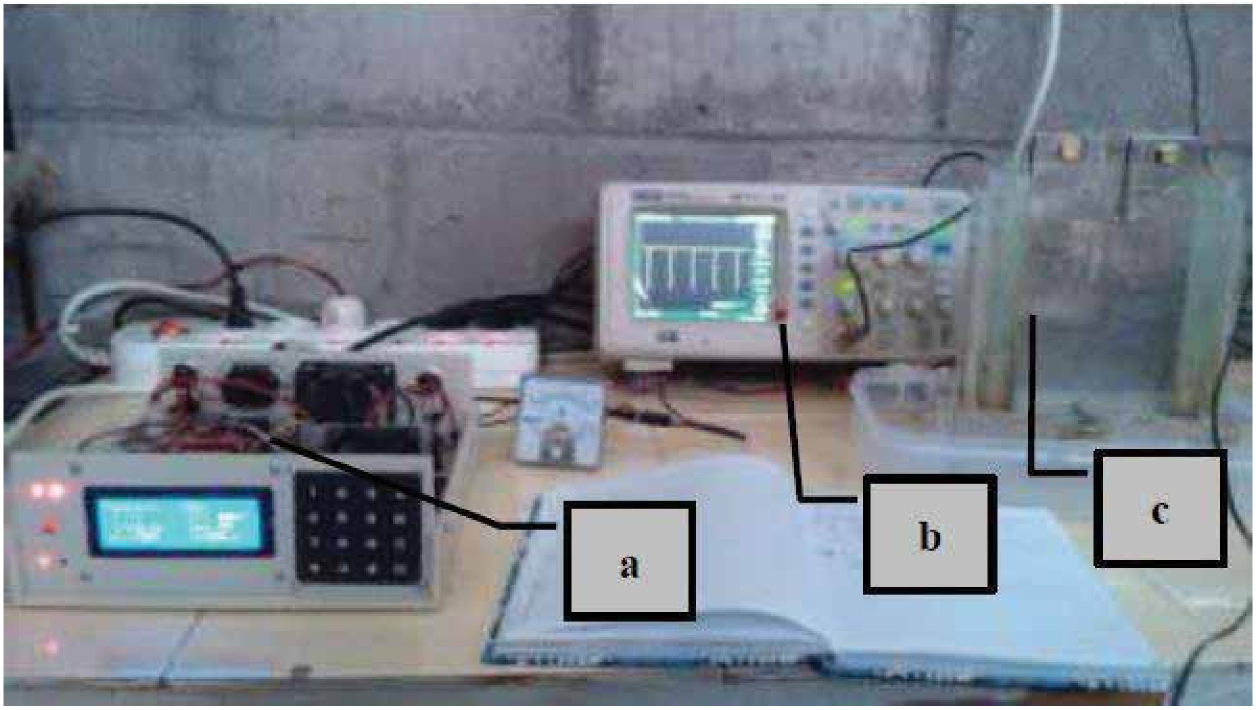

Fig. 11. Overall PEF set, **(a)** PEF assembled unit, **(b)** Oscilloscope, and **(c)** PEF chamber

used in the extraction operation. Fig. 11(c) is the PEF chamber, a place to put the sample for the extraction process. After PEF is assembled properly, then the experiment is made to test the ability of the designed PEF for the extraction process.

3.7 PEF Test

To test PEF, 100 mL of 7 % salt water as a sample was used. Then the tests were made for a variety of experimental variables with the voltage from 15 VAC to 128 VAC (up to 172 VDC after rectification), the frequency from 1 Hz to 8 Hz, the duty cycle from 1 % to 15 %, and treatment time from 10 s to 15 min, aiming to determine the value of the fine parameter for optimum operation condition.

The first test used various VAC input voltages intended to assess the device's performance against increasing input voltages. The data in Table 1 shows the results of the PEF testing.

This test was performed for 30 s for the increasing values of voltage. When the input is set to 15 VAC, the current measured is 5 A, the sample was unreacted and the device was in a stable condition. This condition happened until the input value was 32 VAC. After voltage was set to 64 VAC, device condition was stable, the voltage measured was 92 VDC with 6 A current, at this moment in the PEF chamber some bubbles began to appear. When the input voltage was raised to 128 VAC, the voltage rise to 180 VDC, and current was 8 A, where the device's condition was still steady and more bubbles appeared.

The second test was performed with varying duty cycle values, with the static input of 128 VAC and frequency of 1 Hz. The data in Table 2 shows the results of the second PEF testing.

From the data of the second experiment it could be seen that the changes in the duty cycle value brought changes to the current flowing. The output was stable in 172 VDC, where the device was relatively stable for each change made, but the sample on the PEF chamber was unreacted.

The third test performed using varying frequencies and duty cycle values, while input was static in 128 VAC with time treatment of 1 min. The data in Table 3 shows the results of the third PEF testing.

The last test performed using varying time of treatment, while input was static in 128 VAC, the

Table 1. PEF testing in frequency 1 Hz and 1 % duty cycle with time of treatment 30 s

AC Voltage (V)	Current (A)	DC Voltage (V)	Sample Behavior	Device Performance
15	5		unreacted	stable
18	5		unreacted	stable
25	5		unreacted	stable
32	5		unreacted	stable
64	6	92	bubbles appear	stable
128	8	180	bubbles appear	stable

Table 2. PEF testing with 128 VAC, frequency 1 Hz, and time of treatment 30 s

Duty Cycle (%)	Current (A)	DC Voltage (V)	Sample Behavior	Device Performance
5	11	172	unreacted	stable
4	10	172	unreacted	stable
3	9	172	unreacted	stable
2	8	172	unreacted	stable
1	7	172	unreacted	stable

Table 3. PEF testing with 128 VAC and time of treatment 1 min

Freq. (Hz)	Duty Cycle (%)	Voltage (V)	Current (A)	Sample Behavior	Device Performance
1	1	172	7	unreacted	stable
2	2	172	7	bubble appears	stable
3	3	172	8	bubble appears more	stable
5	5	172	6	bubble appears more	stable

Table 4. PEF testing with 128 VAC, frequency 1 Hz, and 2 % of duty cycle

Time (s)	Voltage (V)	Current (A)	Sample Behavior	Device Performance
300	172	9	bubbles appear	stable
600	172	9	bubbles appear. water level rise pulsing as frequency	stable
900	172	9	bubbles appear. water level rise pulsing as frequency	stable
1200	172	9	bubbles appear. water level rise pulsing as frequency sample coagulates	stable
1500	172	9	bubbles appear. water level rise pulsing as frequency sample coagulates	stable

frequency was 1 Hz, and the duty cycle was 2 %. The data in Table 4 show the results of the last PEF testing.

The data from Table 3 and Table 4 shows that the device works steadily. Changes in the frequency and the duty cycle values give some effects on the testing tool, mainly the changes in the current passing through the circuit. The length of treatment time affects the extraction of the sample. From the experiments, it is known that the extraction process is marked by the emergence of bubbles in PEF chamber, a rise in water level, pulses in the frequency and the coagulated sample. This coagulated sample is the result of extraction performed by this device.

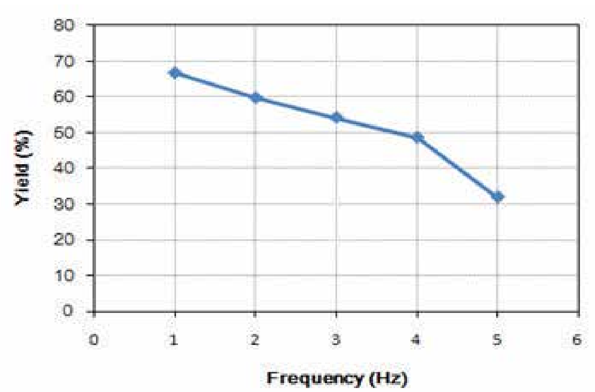

Fig. 12. Effect of frequency to yield of microalgae oil

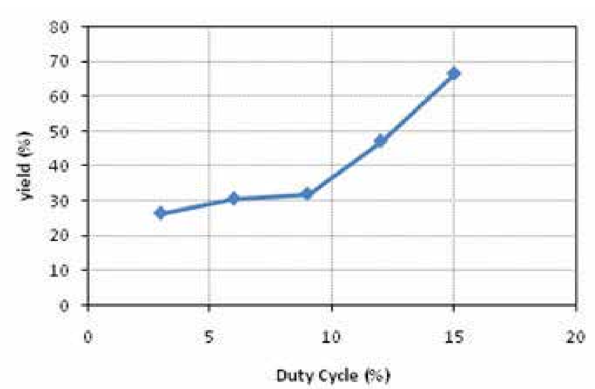

Fig. 13. Effect of the duty cycle to yield of microalgae oil

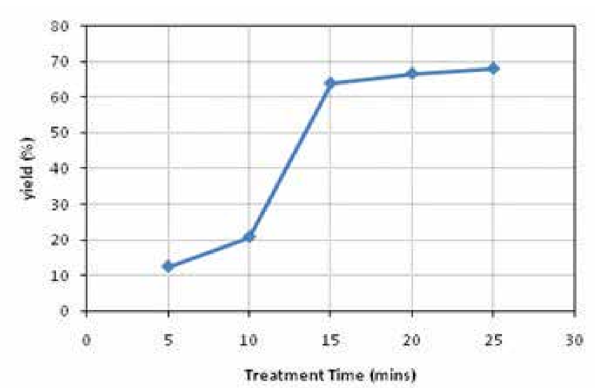

Fig. 14. Effect of time to yield of microalgae oil

The device can run well with no damage for various combinations of these variables. Therefore, this circuit can be used in the process of collecting, testing, and analyzing data. By using this design and vary the duty cycle, switching frequency, and the treatment time, the experimental result shows these variables can affect the extracted lipid amount [12]. Fig. 12, Fig 13, and Fig.14 show the experimental data of this effect.

The results concluded that the lipid yield would increase by enlarging the duty cycle and treatment time also reduces the switching frequency due to the device limitation as described before (1 Hz to 5 Hz frequency, 1 % to 5 % duty cycle, and 10 s to 25 minutes treatment time. However, the detailed analysis and mathematical modeling of this behavior data will be conducted in another research [13].

4. CONCLUSION

The PEF Hardware is designed to have the ability to do the water-based extraction processes. It can operate over a voltage range from 15 VAC to 128 VAC, the frequency from 1 Hz to 5 Hz, the duty cycle from 1 % to 5 %, and a treatment time from 10 s to 25 min.

5. FUTURE RESEARCH

In the future research, the PEF will be implemented into microalgae extraction processes, aiming to extract microalgae into biodiesel feedstock in the form of lipids.

6. ACKNOWLEDGMENTS

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Mada.

7. REFERENCES

1. Arvindnarayan, S., Prabhu, K.K.S., Shobana, S., Dharmaraja, J., & Pasupathy, A. Algal biomass energy carriers as fuels: An alternative green source. *Journal of the Energy Institute*, 90, 300-315 (2017).
2. Sudibyo, H., Pradana, Y.S., Samudra, T.T., Budiman, A., Indarto, & Suyono, E.A. Study of cultivation under different colors of light and growth kinetic study of *Chlorella zofingiensis* Dönz for biofuel production. *Energy Procedia*, 105, 270-276 (2017).
3. Suganya, T., & Renganathan, S. Optimization and kinetic studies on algal oil extraction from marine macroalgae *Ulva lactuca*. *Bioresource Technology*, 107, 319-326 (2012).
4. Demirbas, M.F. Biofuels from algae for sustainable development. *Applied Energy*, 88, 3473-3480 (2011).
5. Pradana, Y.S., Kusumastuti, Y., Rahma, F.N., & Effendy, N. Chitosan Flocculation-sedimentation for Harvesting Selected Microalgae Species Grown in Monoculture and Mixed Cultures. *Chemical Engineering Transactions*, 56, 1549-1554 (2017a).
6. Pradana, Y.S., Sudibyo, H., Suyono, E.A., Indarto, & Budiman, A. Oil algae extraction of selected microalgae species grown in monoculture and mixed cultures for biodiesel production. *Energy Procedia*, 105, 277-282 (2017b).
7. Shin, H.Y., Ryu, J.H., Bae, S.Y., Crofcheck, C., & Crocker, M. Lipid extraction from *Scenedesmus sp.* microalgae for biodiesel production using hot compressed hexane. *Fuel*, 130, 66-69 (2014).
8. Santana, A., Jesus, S., Layyaroz, M.A., & Filho, R.M. Supercritical carbon dioxide extraction of algal lipids for the biodiesel production. *Procedia Engineering*, 42, 1755-1761 (2012).
9. Nafis, G.A., Mumpuni, P.Y., Indarto, & Budiman, A. Combination pulsed electric field with ethanol solvent for *Nannochloropsis sp.* extraction. *AIP Conference Proceedings*, 1699, Art. Num. 30021, DOI: 10.1063/1.4938306 (2015).
10. Apriliawan, H. *Laban Electric: Alat Pasteurisasi Susu Kejut Listrik Tegangan Tinggi (Pulsed Electric Field) Menggunakan Flyback Transformer* [Tool Pasteurization of Milk with High Pulsed Electric Field using Flyback Transformer], Jurusan Teknik Pertanian, Fakultas Teknologi Pertanian Universitas Brawijaya, Malang, Indonesia (2010) (in Bahasa Indonesia).
11. Carl, R.N. *Work and Voltage: Constant Electric Field*, Department of Physics and Astronomy, Georgia State University (2001).
12. Sejati, P., Aditama, F., B., Budiman, A. Pulsed Electric Field (PEF) Assisted Extraction of Microalgae Tetraselmis Chuii Sp. for Biodiesel Feedstock. Regional Conference in Chemical Engineering, Yogyakarta (2014).
13. Sejati, P.A., Pradana, Y.S., Kurniawan, A., Budhijanto, and Budiman, A. Modeling of Algal Oil Extraction from Tetraselmis sp. Using Pulsed Electric Field (PEF). International Conference on Engineering and Technology for Sustainable Development, Yogyakarta (2017).