Design of a High-Voltage Pulse Generator in a Pulsed Electric Field for the Pasteurization Process of Randu Honey

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Abstract

PEF applied to the honey pasteurization process is a non-thermal method for preservation using short pulses of electricity to inactivate microorganisms such as spores and fungi by minimizing adverse effects on food quality attributes. Honey preservation is heating the honey particles, which must gather around microscopic air bubbles and tiny crystals that act as aggregation nuclei [1]. Applying PEF offers consumers high-quality assurance, predominantly liquid or semi-liquid foods like honey nectar. PEF in food is better than other processing because this technology reduces adverse changes in food's sensory and physical properties [2], [3], [4], [5]. The PEF process is through a short pulse of high voltage electric field (HVEF), which flows between the two electrodes to the stirring rod while distributing the honey liquid in a vessel [6], [7]. Another advantage of applying HVEF in the PEF system is that it deactivates microorganisms and enzymes at low temperatures, and maintaining product nutrition will make the product quality, safe, and fresh. The processing time is shorter so that the loss of input energy due to the heating process can be reduced [8], [9], [10], [11]. Damage to microorganism cells and bacterial membranes occurs when a high-voltage of more than 20kV pulse time of 100-200 ns is applied [12], [13].

1 Introduction

Non-thermal technologies like PEF are being developed alongside the growing interest of consumers in nutritious fresh food products and the demand for environmentally friendly processing technologies [14], [15]. The advantage of applying food preservation using PEF is that the food processing industry needs the most liquid or semi-liquid products in the future. To prevent rapid disintegration and structural or functional changes in the food matrix, PEF uses an external electric field of medium to high intensity for a brief period. This method is energy efficient. However, the commercial exploitation of PEF for the food industry is still facing obstacles because it needs to develop energy-efficient equipment and study potential applications in several food products [4], [9], [16], [17]. Parameters in PEF are electric field strength, pulse count, and processing chamber. The electric field strength on the PEF depends on the level of the applied pulse strength [18]; in the case of pasteurization of honey at a capacity of 80 liters for small-scale businesses, where the PEF is mounted on a stirring rod which also functions to stir the liquid honey in the vessel.

In contrast, the number of pulses depends on how many the length of time the process will take. It is necessary to adjust the HVEF level and set the treatment time to produce an electric field that has proven capable of activating microorganisms. The number of pulses multiplied by the pulse width, which depends on the pulse waveform, results in the treatment time [19]. The
high-voltage pulse generator is generated through several waveforms depending on the circuit to be developed [20],[21].

The development of modern PEF is based on conventional pulse power technology, in which the power at the load will determine the voltage, current, and average control required in the designed system [22],[23]. The design of the PEF begins by considering the desired field strength and flow rate range for the large processing volume and the conductivity of the fluid during processing. Another consideration is the significant change in flow rate and conductivity during operation. Designing PEF and constructing a pulsed power system that can adapt to these changes is a complex challenge. Therefore, the HVPG design on the PEF for the pasteurization process of honey liquid must be able to increase the effectiveness of its function on the condition that it includes high point, energy saving, and flexible circuit design. This design helps produce the efficacy of the inactivation of spores and fungi through an electric current applied to an electric field and provides planning in the timing of treatment during the pasteurization process. A high-voltage transformer (HVT) circuit produces higher efficiency with shorter rise times and rectangle pulses to increase the inactivation of spores and fungi [24],[25]. The installation of HVT in a quasi-resonant fly-back converter circuit simplifies the design. It functions more effectively by providing the advantage of generating higher pulse frequencies, resulting in shorter processing times [26],[27].

PEF modulation has three main components [28],[29]. The first is a DC power supply that transitions AC power from the utility to high voltage DC power; the second is a pulse modulator which converts this average power into short and high peak power pulses; and the third is the mechanism of the delivery device to the stirring rod, which functions as the PEF process is applied to food. PEF modulation as bipolar (voltage + and – pulses) or monopolar (all + or all – pulses). PEF impedance varies due to processed foodstuffs in the form of semi-liquid or liquids. The variation in conductivity is an order of magnitude greater than the various characteristics of the food liquid. However, for one type of food, such as liquid honey, the conductivity can vary by 50-100% due to changes in the raw material. This variability required an impedance-matched modulation design [30],[31]—using pulse transformers and pulse-forming networks for consistent performance. A ‘hard switch’ in PEF modulation is a hard-switched solid-state switch or a hard drive power switch to switch the occurrence of full voltage on the system [32],[33]. The low impendence of the controller provides consistency of output voltage in the peak current range due to the conductivity of each variation of the processed food liquid [2],[34]. The HVT component of the PEF is emitted through a hollow metal rod made of stainless steel with a ferrite core. The electric sparks generated from the HVFEF are transformed into a food stir bar. Using ferrite cores is the best solution for a non-hazardous magnetic environment. It gives good results regarding electrical properties and magnetic resistance and is economically low-cost [35]. The applied electric field gap must be proportionate to the pipe diameter for the ferrite core to retain constant field strength. Due to this technical relationship between the mains voltage and pipe diameter, a larger pulse voltage is required to maintain the same field strength. The outer diameter of the pipe for placing the ferrite core is 5 mm, meaning ~200kV pulses (at 40kV/cm) as the nominal limit for hard-switched solid states. PEF modulation is designed to balance the main voltage and the needs of the honey pasteurization process.

This study aimed to design an HVPG circuit to support the PEF modulation using an HVT component and a microcontroller equipped with a voltage regulator and treatment time duration for the pasteurization of randu honey. Pulse programming on the microcontroller uses text programming on programmable logic control with CX-Programmer software according to the input time setting.

2 Method

2.1 Material

PEF research has been conducted to increase the generator circuit's and pulse wave's efficiency. The working principle of the designed pulse wave and generator circuit [36] is according to the principle of an enhanced pulse power supply based on a resonance circuit and a pulse transformer, as shown in Figure 1.

Fig. 1. Schematic diagram of an HVPG source

Figure 1 mainly consists of a DC voltage source (Vdc), a power switch (Q) and an anti-parallel diode, a tube (D), a resonant capacitor (C), a resonant inductance (Lr), and a diode (Dp) and resistor group (Rp). The freewheeling branch formed constitutes the step-up pulse transformer, the equivalent capacitance of the output load (Ceq), and the parallel resistance (Rout). L Leakage is the leakage inductance of the transformer, Lm is the excitation inductance of the transformer device, and the transformer transformation ratio is n. The maximum efficiency of an RLC circuit can reach 40 to 50%, while that of an RC circuit is 38% [37]. Some of the pulse waveforms with the highest efficiency are rectangular pulses with a maximum efficiency of up to 100% and a damped oscillator of 52% [38]. When comparing energy performance, square pulses have the highest energy efficiency since they minimize the pulse rise time. The choice of values for the resistor and
A switching circuit is a high voltage pulse generator (HVPG) to generate high voltage pulses. The microcontroller system is programmed using CX-Programmer software. The microcontroller is a high voltage step-up transformer that can control the output voltage through the keypad. The PWM pulse duty cycle settings are regulated through the microcontroller. The working process is displayed on the LCD screen and includes controlling the processing time during pasteurization.

The microcontroller provides three output signals. The keypad settings are displayed on the LCD using the first output. The second output controls the voltage and output, and the third manages the processing time. The voltage regulator is connected to the microcontroller’s output to turn on the relay in the voltage control circuit. The voltage control circuit utilizes the relay component circuit, with each relay coupled to a rectifier circuit. Design specifications controlled high voltage in the range of 20–40 kV with 5 kV scale increments. This PEF system requires five relay circuits connected to a rectifier circuit. The benefit of this circuit is the suitability of the resulting voltage for the HVT to obtain the appropriate output level. The third output is where the microcontroller is connected to the driver and switching circuit to separate the HVT and the microcontroller so that it is helpful to control the processing time and produce a 50% duty cycle. The microcontroller circuit is a mechanical drive and a data processing hub. This mechanism has four ports for LCD, keypad, switching circuit, and voltage controller connections. The microcontroller will receive input data from the keypad, process and display it, which can be seen on the LCD screen, and activate the HVT. Based on the reference datasheet, the capacitors in the voltage regulator circuit are 4700 µF, 20 nF, and 10 nF. The design of the HVT driver circuit can be adjusted to the process time controller circuit. The microcontroller system generates a pulse voltage during the selected time as input data set through the keypad. The input of the driver circuit with a potentiometer of 3.7 kΩ and 2.2 kΩ is a microcontroller output. The purpose of the OT transformer is to isolate the HVT from the microcontroller circuit.

Stainless steel plates with a 4 mm thickness are used in the vessel’s design during the pasteurization process. The shape of the treatment room is in the form of a vessel tube equipped with an opening and closing valve at the bottom. The output inlet valve is made of stainless steel with a diameter of 2.2 mm. The vessel’s dimensions are 45 cm high, 52 cm outside diameter, 48 cm inside diameter, and 4 cm thick vessel filled with synthetic oil and stainless steel 304 material. Synthetic oil is filled as much as 14 liters into the vessel wall as a heat conductor, with the heat source coming from two heating rods. After reaching the desired synthetic oil temperature in the vessel, the vessel is filled with honey at 240°C or room temperature, heated to 700°C gradually, and needed 60 minutes. The capacity vessel can accommodate liquid honey of up to 80 liters. The schematic of the pasteurization process using PEF is shown in Figure 3.

![Schematic design block diagram of PEF](image)

**Figure 2: Schematic design block diagram of PEF**

Figure 2 can be explained as follows (a) the use of a microcontroller type ATMEGA8535 on a PEF device to control the processing time of honey liquid; (b) the maximum value of HVPG in the PEF system is 35 kV; (c) setting the input data processing time can be set through the keypad and displayed on the liquid crystal display (LCD) screen; (d) constant high-voltage pulse frequency; (e) the keypad is useful for setting the specified production period in minutes in 10-second increments; (f) a microcontroller system to regulate the pulse-receiving driver in driving the switching components; (g) power transistor and output transformer (OT) used for switching components as a connecting switch between HVT and the microcontroller functioning as a regulator; (h) HVT is a high-voltage step-up transformer with a maximum output of 100 kV which serves to increase the voltage; (i) HVT output voltage through the switching circuit is a high-voltage pulse dependent on the output pulse; (j) the result of high-voltage pulses at both electrodes is fired into the honey liquid stirring rod whose position is in the middle of the vessel; (k) the capacity of the vessel in the design of the honey liquid pasteurization process is 80 liters.

### 2.2 Methods

The ATMEGA8535 microcontroller, as a control unit for PEF devices, helps reduce the number of external components and costs. The advantage of this microcontroller is that it has complete facilities and is available in the market. Programming on the microcontroller is programmed using CX-Programmer software. The microcontroller functions as a controller, stabilizing a fixed frequency and a constant pulse voltage, along with the timer. A timer is set through the keypad to determine the processing time and switching components’ on and off timeout. Pulse is the output of the microcontroller and is the PWM method. The microcontroller sends block wave pulses to the switching components.

The resulting output voltage depends on the PWM pulse from the microcontroller, which has a 50% duty cycle. Through the HVT input controller, the microcontroller controls the output voltage. Therefore, in this system, the higher the input to the HVT, the higher the output voltage. The output voltage and processing time are entered as input data through the keypad. PWM pulse duty cycle settings are regulated through the microcontroller. The working process is displayed on the LCD screen and includes controlling the processing time during pasteurization.
3 Results and discussion

3.1 High voltage pulse generator test

The voltage regulator circuit produces an output voltage as needed and generates a pulse signal at 30kHz, activating the HVT driver and switching circuit. The microcontroller is set to produce a square-shaped signal with a processing time setting [40]. The processing time is set to 60 minutes; after 60 minutes, the control will turn "off" and the microcontroller will produce a square pulse. The HVT needs to be controlled by a signal with a frequency of 30 kHz to produce the highest possible high-voltage output. At that point, the microcontroller will turn on the driving circuit and the 40kHz HVT switching signal. The measuring instruments used for HVPG inspection consist of Philips PE-PE154000 DC Power Supply 40V-3A, Hantek 6022BE Digital Oscilloscope Portable PC Based 2 Channels, Fluke 80K-40 High Voltage Probe, and Fluke Digital Multimeter. The results of measuring the output voltage of the microcontroller are connected to the switching and driver circuits, as shown in Figure 3.

![Fig. 3. Schematic of the honey pasteurization process](image)

The pulse generator circuit produces a pulse count of 30k pulses per second. Determination in the processing time setting for 60 minutes with the number of pulses emitted to the stirring rod of 30k pulses per second. The number of delivered pulses increases with processing time. HVPG testing is a check of the entire electronic circuit of an HVPG.

This test involves connecting an HVPG to a stirring rod and measuring the average voltage and current flowing into the honey liquid. Measurements were made using a Fluke 80k-40 High Voltage Probe with an attenuation of 1000 times, a Hantek 6022BE Digital Oscilloscope Portable PC, and a Fluke Digital Multimeter. The results of measuring the voltage and current circuits are based on the voltage variations described in Table 1.

**Table 1. Measurement of the voltage and current circuit from the test results**

<table>
<thead>
<tr>
<th>No.</th>
<th>Voltage setting (kV)</th>
<th>Voltage measured (kV)</th>
<th>Current Measured (mA)</th>
<th>Voltage error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>17.31</td>
<td>240.32</td>
<td>13.44</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>22.81</td>
<td>226.28</td>
<td>8.76</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>30.00</td>
<td>200.00</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>37.61</td>
<td>177.65</td>
<td>7.45</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>44.94</td>
<td>162.92</td>
<td>12.36</td>
</tr>
</tbody>
</table>

The percentage of voltage error from the measurement of the pulse generator circuit between the set voltage and the measured voltage is the largest value is 13.44%, and the smallest value is 0% at the output voltage of 30kV.

3.2 Test the Characteristics of the Nutrient Content of Pasteurized Randu Honey

Testing the honey liquid in this step is the first step in testing the pasteurization process using PEF. To determine the effectiveness of using PEF in the honey pasteurization process, the test uses a voltage of 30kV and a processing time of 60 minutes until the honey temperature is 24°C. Testing of pasteurized honey results consists of water content and organoleptic at laboratory tests adjusted according to the Standard Nasional Indonesia (SNI) [41] and information from the legislation regarding honey criteria and standards [42]. The legislation does not always follow the complexity of the variety of honey farmers produce. The parameters of real honey and not being processed further fail to meet the criteria for the composition of standard norms set by state institutions. Still, not least, fake honey has parameters in the criteria set per statutory standards [43],[44],[45]. Beekeepers sometimes complain about market inspection organizations’ inaccurate assessments of their products, which force them to pay fines for naturally occurring variations from certain features that particular mono-floral types of honey have.
The pasteurized honey liquid comes from the nectar of the randu flower (Cheiba pentandra). The reason for using opium honey is that this honey is mostly consumed by most people as a mixture of traditional herbs or consumed directly, and the price is lower. The physical characteristics of randu honey are that the color of the liquid is light brown, it tends to be clear, and it has a sweet and slightly sour taste. If cotton honey is harvested in the summer, the water content is less than in the rainy season. Some people are used to consuming opium honey and will feel a distinctive aroma. Testing the water content of the honey content is a consideration that shows the success of the pasteurization process. The results of honey pasteurization were compared before and after going through the SNI data standard. The organoleptic test of the results of the pasteurization process involves trained panelists regarding the characteristics of honey through the sense of smell. This test is to evaluate the characteristics of the pasteurizer.

Laboratory tests for the water content of randu honey per 100 ml of the test sample showed the results before the pasteurization process was 26% b/b as 21% b/b, there was a significant change in the decrease in water content of 19.23% and the SNI required is a maximum of 22% b/b means that honey is suitable for consumption. The heating process significantly changes the honey moisture content, while PEF does not contribute to the reduction of honey's water content until SNI standards are below 22% b/b. Figure 4 shows the changes in the water content of randu honey before and after the pasteurization process.

Fig. 5. The water content in randu honey before and after pasteurization

The heating stage of the liquid honey slowly reaches a temperature of 70°C, and the heating stops to reduce the water content. The PEF process is continued in liquid honey up to 24°C without changing the water content reached during heating. The decrease in water content in randu honey is made possible by the heating process due to the emergence of an electric field. PEF is applied to liquid or semi-liquid foods using short pulses at high voltages (20–30kV/cm).

Organoleptic tests on randu honey consist of color, scent, and flavor. Before and after using PEF, color, scent, and flavor did not change as significantly. Although PEF is a non-thermal process because the food is processed at room temperature for several minutes, it also minimizes the loss of nutrients due to the preheating process.

4 Conclusion

The design of an HVPG circuit on PEF supports honey pasteurization treatment with the smallest error voltage of 0% at a set voltage of 30kV. This test is before and after the pasteurization process using PEF on randu honey with a processing time of sixty minutes from one hundred twenty minutes the process, the number of pulses emitted to the stirring rod of 30k pulses per second of 80 liters capacity vessels. Laboratory tests on the water content per 100ml as 21% b/b underwent significant changes and required the standard SNI, a maximum of 22% b/b. The organoleptic test, including smell and taste, did not change, meaning that it is suitable for the consumption of honey, according to SNI. PEF protects and maintains the smell, taste, and nutritional content of randu honey.

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