Development and Performance Evaluation of a Microcontroller Pulsed Magnetic Field Machine for Assisting Cellular Foods Freezing

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Abstract— Cellular foods have a short shelf-life due to the high water contents and activities of microorganisms. The water content is magnetized when exposed to electromagnetic field, which is beneficial to freezing. Although, magnetized water contained in cellular foods benefits freezing, but pulsed magnetic field machine available generates irregular wave patterns that are not promising to modern days freezing market. Therefore, the current study focuses on development and performance evaluation of a microcontroller pulsed magnetic field (MPMF) machine for assisting cellular foods freezing. The MPMF technology consists of four main components including the magnetic field treatment chamber (120 mm x 90 mm x 60 mm), four electromagnets, a step down transformer, a rectifier, capacitors, diodes, and a timer. The machine was operated at a voltage range and current of 2, 5, 7, 9, 11, 13 V, and 2.00, 12.60, 20.70, 28.60, 34.90, 38.60 A, respectively. The performance evaluation carried out on the machine includes magnetic field strengths and wave patterns. The results showed that the magnetic field strength varies between 9.15 to 42.96 T, and the wave patterns obtained were regular and satisfactorily. The effect of the machine on the quality of cellular foods can be investigated for further studies.

Keywords— Electromagnets, microorganisms, treatment chamber, rectifier, water, wave patterns

1 Introduction

Cellular foods such as mango, pear and apple contain high water content that can be magnetized when acted upon by a magnetic field, and the act is beneficial to their freezing (Arteaga *et al*., 2022; Jha *et al*., 2017; and Panayampadan *et al*., 2022). Freezing in-conjunction with magnetic field (known as magnetic field-assisted freezing; MFAF) has great potentials to promote freezing process by influencing the physical property and thermal property of water contained in cellular foods (Kang *et al*., 2020; and Tan *et al*., 2019). Otero *et al*., (2016) and Zhang *et al*. (2021) reported that physical properties including viscosity and surface tension of food models change when passes through low magnetic field. In another study by Pang and Deng (2010), optical properties (i.e. infrared, Raman, visible, and ultraviolet) of water change under magnetic field 14T. The changes inhibit ice nucleation, and promote fast freezing, which is beneficial to the preservation of cellular foods (Mok *et al*., 2015; Purnell *et al*., 2017; Rodríguez *et al*., 2019; and Tang, *et al*., 2020).

However, the application of magnetic field to cellular foods freezing takes root in natural scenario where magnetic field occurred almost everywhere on the earth surface, surrounded with field up to 65 mT (Jha *et al*., 2017; and Tang *et al*., 2020). Zhang *et al*. (2021) reported the phase behavoir of confined water under the action of magnetic field 10 T. Their findings revealed that the homogenous magnetic field causes a shift of freezing temperature from -3.15 °C to -8.15 °C, indicating that the crystallization of ice is induced by decreased viscosity. Low viscosity supports fast freezing, and preserves quality of cellular foods. Magnetic field intensities (up to 100 mT) had evidently promoted freezing of fresh-cut mango, that was supercooled at -5°C, maintaining its original quality for up to 7 days (Kang et al., 2021). Panayampadan et al. (2022) observed a reduction in phase transition time (77 min 35 s) and drip loss value (4.47%) of guava that was frozen by magnetic field-assisted freezing at 7 mT when compared to control (without magnetic field) samples. According to Tan et al. (2019), the freezing point of avocado puree was decreased from -1.2 to -6 °C, under magnetic field at 4 mT and 50 Hz, which indicated that the freezing was enhanced. Enhancement of freezing (i.e. decrease in freezing point) of avocado puree have also been reported (Tan et al., 2019). Iwasaka *et al*. (2011) reported that pulsed magnetic field (PMF) of up to 325 T/s at 6.5 mT causes more uniform grains in food model than the samples frozen without PMF. The findings hypothesized that a time-varying magnetic field is one of the factors which promote food freezing.

Despite all the numerous benefits on magnetic field in food freezing and preservation, very little works have been reported on the development of pulsed magnetic field technique for assisting cellular foods freezing. Most literatures reported on theoretical analysis where the field patterns obtained were irregular, due to 'Lorenz force' generated, and a dipole moment from the earth surface, causing inconsistent results during MFAF process. Whereas, the design procedure, which is the basic requirement in the development of electromagnetic field device is not presented, therefore the need for this study. The aim of study is to develop and perform evaluate the mpmf machine for assisting cellular foods freezing.

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Section A- AGRICULTURAL ENGINEERING & RELATED SCIENCES
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2 Materials and Methods

Materials used included galvanized steel plate, copper wire, rectangular plate, triangular electromagnet cores, bolts and nuts. Other materials used are resistors, inductors, rectifiers, digital multimeter (HIOKI DT4282, Japan), Wattmeter (Model 380940, EXTECH Instruments, USA) and Gauss meter (Model GM-2, ALPHALAB INC., USA).

2.1 Design of Machine

2.1.1 Design Considerations and Assumptions

The criteria considered in the design of the MPMF machine included four (4) electromagnets, material of construction and size of the treatment chamber. Other considerations included the desire to make the magnetic cores steel and the treatment chamber a galvanized steel to prevent shock and ensure good frozen quality, respectively. The assumptions made in the design process included: zero or negligible field strength on the earth surface, 400 numbers of turns of wire. This number of turns is assumed, in practice, to take care of possible losses such as eddy loss, air gap loss and copper loss (Yusuf, 2017). The design considerations are given in Table 1. Figure 1 shows the conceptual view of the MPMF machine for assisting cellular foods freezing

Table 1. Design considerations of the PMF machine

Parameters	Value
Magnetic field density in between the 4 coils	0.5-100 T
Length of the treatment chamber	12 cm
Breath of the treatment chamber	9 cm
Height of the treatment chamber	6 cm
Core length	6cm
Core breadth	6cm
Frequency	20 – 2000 Hz

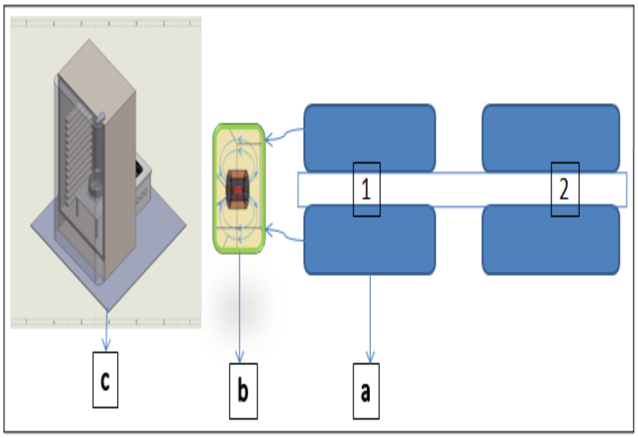


Fig. 1: Conceptual view of the MPMF machine for assisting cellular foods freezing;
Labels: 1-2: Treatment compartments; a: Electromagnets (4 in number); b: Treatment chamber; c: Freezing machine

2.1.2 Description of the Machine

The MPMF machine was developed at Kwara State University (KWASU), Malete, Nigeria (51° 27' 49.144'' N 19° 13' 4.303'' E). It mainly consists of a rectangular treatment chamber unit (400 mm x 450 mm x 200 mm) made of aluminum square pipes and a step-down transformer unit. The treatment unit has one covered stationary treatment box (120 mm x 90 mm x 60 mm) made of aluminum for holding the cellular foods to be frozen. The four electromagnets (two on each side) are properly arranged along the two sides of the treatment chamber, a step-down transformer (from 220 V). Others components include rectifiers, capacitors, copper wires, timer and a microcontroller containing one actuator (MOSFET). The transformer has tapings for selecting different values of voltages (2.42 – 13.34 V). The plug has a fuse that protects the machine against damage when there is fluctuation in current. Figure 2, 4 and 5 show the pictorial view, orthogonal and exploded views of the MPMF machine.

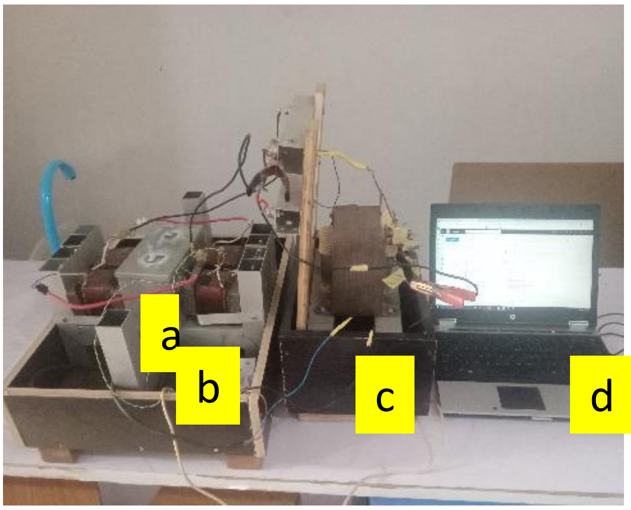


Fig. 2: Pictorial view of the MPMF machine:
Labels: a- Treatment chamber unit; b- Microcontroller box; c- Step-down transformer unit, and d- Data acquisition unit

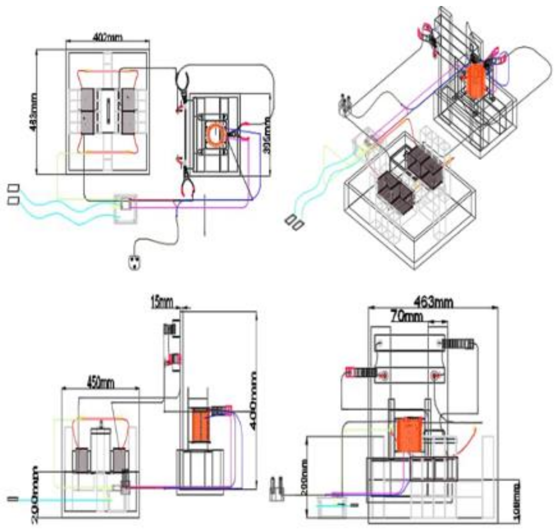
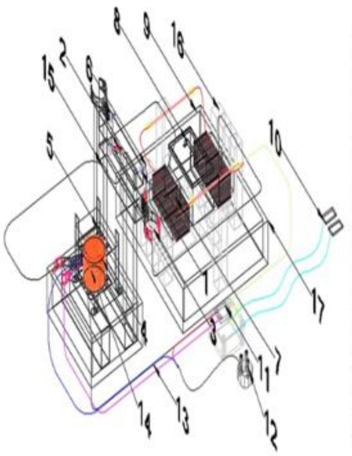


Fig. 3: Orthogonal and isometric view of the MPMF machine



PARTS LIST		
ITEM	QTY	PART NAME
1	4	Electromagnets
2	1	Capacitor
3	4	Capacitor switch
4	4	Step down platform
5	6	Step down voltage terminals
6	2	Crocodile clip
7	4	Diodes
8	1	Treatment chamber
9	2	Wire connectors
10	2	Magnetic sensors
11	1	Microcontroller
12	1	Mains plug
13	2	Voltage connectors
14	1	Step down transformer
15	1	Step down transformer frame
16	6	Aluminum platform
17	1	Wooden frame

Fig. 4: Exploded view of the MPMF machine

2.1.3 Design Procedure

The design procedure is categorized into five stages viz: (1) microcontroller circuit, magnetic, and treatment area specifications, (2) materials selection, (3) design winding (core) structure, (4) design of the microcontroller and (5) experimental determination of magnetic field. In the first stage, details specifications of the microcontroller circuit physical (wire and switches), and logical topology (currents, voltages and frequency), magnetic (volt-amps rating, voltage ratios, DC and peak currents, and inductances, actuator, amplifier and MOSFET), and of treatment area, where the induced current acted upon, were specified. The second stage involves selection of materials, based on the cost, safety of the food materials to be processed and allowable loss factor (Ajiboye *et al*., 2021). In the third stage, design winding of the cores as well as follow up winding design was performed according to Ajiboye *et al*. (2021) and Odewole *et al*. (2023). However, stage four involves the design of the microcontroller circuit, while stage five involves the performance evaluation of the machine. Figure 5 illustrates the design flow chart for the MPMF machine.

2.2 Working Principles of the MPMF Machine

The working principle of the MPMF machine is based on electromagnetism that induces electromotive force (EMF). The EMF is known as a magnetic field strength. Figure 6 shows the circuit diagram of the MPMF machine. From figure 6, the step-down transformer (TR1) is connected to the mains in other to step down the voltage from 220 V to various levels of switches, inducing electromagnets (L1 – L4) arranged along the lengths of the treatment chamber where the cellular foods will be placed. In order to achieve permanent or static magnetic field, the current will only pass through the rectifier before getting to the treatment chamber connected to the transformer. The diode is for the protection of the transformer and its components. A timer connected to the machine sets treatment time (5, 10, 15, 20, and 25 min) for each voltage input. The operation of the machine stops automatically at the end of the pre-set time. The automatic stoppage of the machine makes it unique and user friendly.

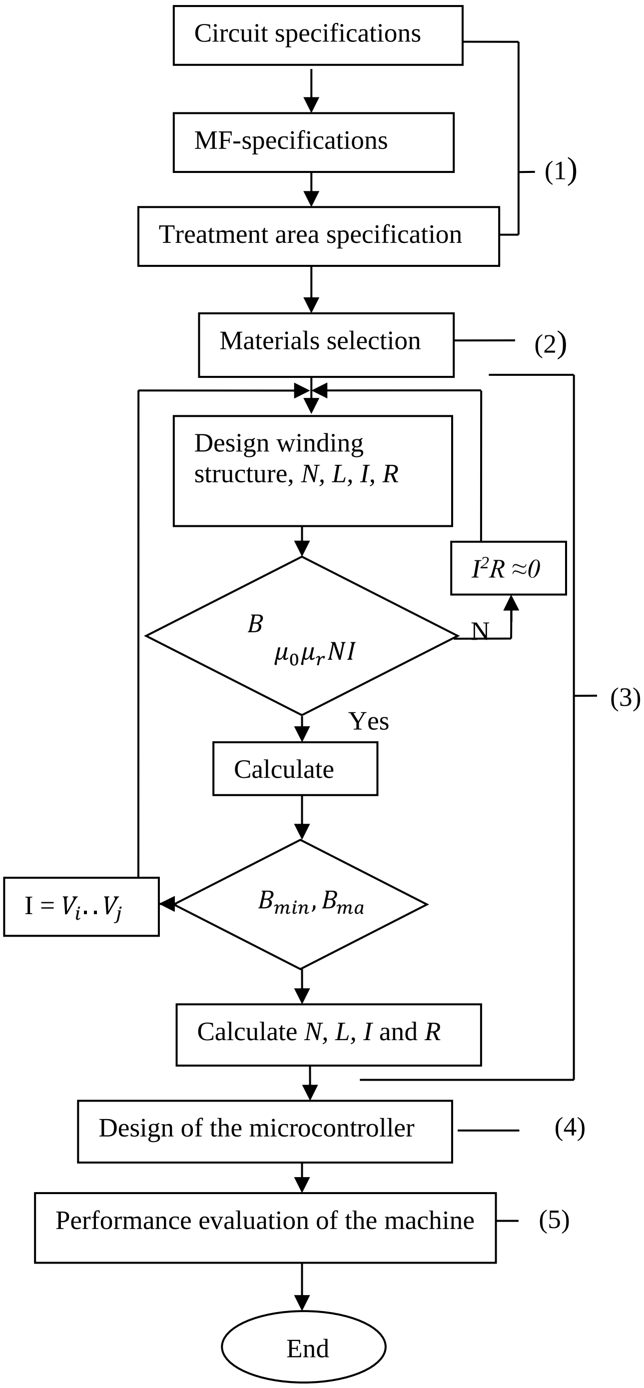


Fig. 5: Design procedure for MPMF machine

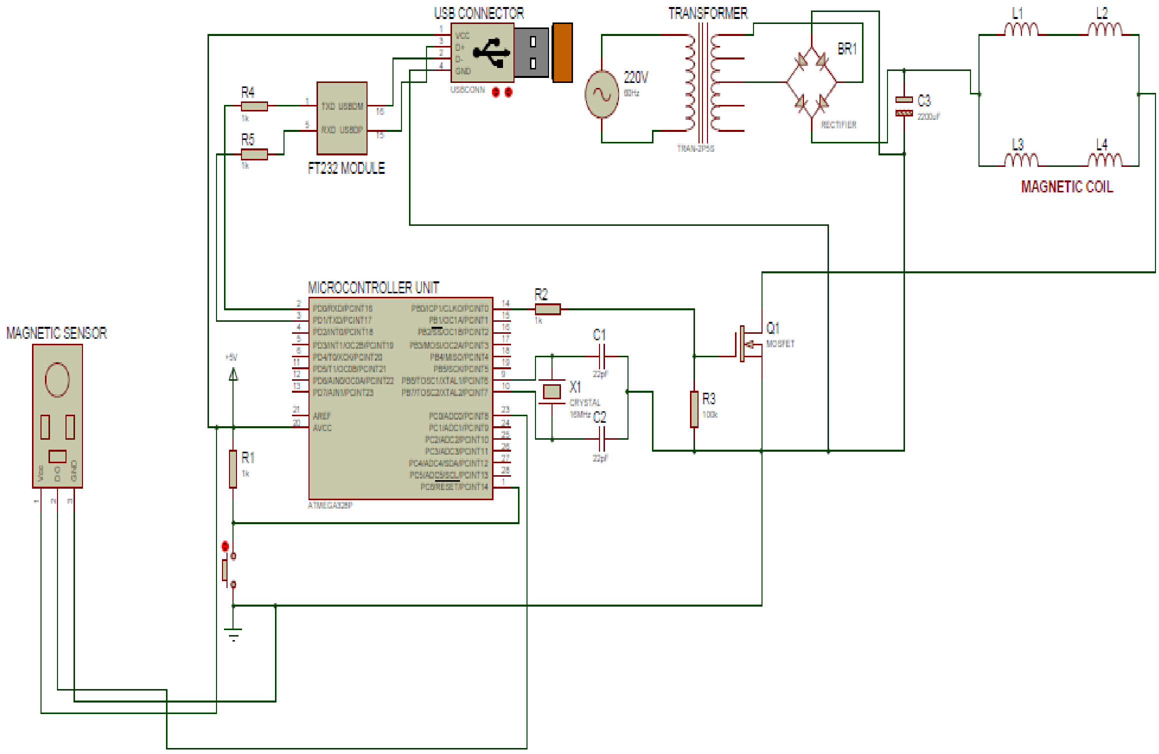


Fig. 6: Electrical circuit diagram of the MPMF machine for assisting cellular food freezing

2.3 Performance Evaluation of the MPMF Machine for Assisting Food Freezing

Performance evaluation of the MPMF machine was done after its fabrication and instrumentation using standard methods. Immediately, after connecting the transformer unit and the treatment chamber unit together, the current and voltage values of the mains were recorded as initial values. The current was allowed to flow in a way that ensured the electromagnets achieved N-S poles arrangement in the opposite direction; and the poles of the electromagnets were confirmed with the standard bar magnet (Odewole et al., 2023). Settling of the PMF was done on the transformer unit. The current and voltage, magnetic field strength and power consumed were measured with the Multimeter, Gauss meter and Wattmeter respectively. The wave patterns were recorded on the data acquisition machine (computer). The readings were repeated five (5) times and the average values were recorded in a tabular form, while pulsed magnetic field wave patterns were plotted graphically.

3 Results and Discussions

Tables 2 show the measured values of parameters during the performance evaluation of the PMF machine. As seen in Table 2, an increase in the values of source voltage (when the transformer unit was not connected to the pretreatment chamber unit) from 2.42 to 13.34 V led to increase in voltage readings (when the transformer unit was connected to the pretreatment chamber unit), current, and power and magnetic field strength. Thus, voltage readings, current, power and magnetic field strength increased from 1.32 to 8.24 V, 2.00 - 38.60 A, 120 – 350 W and 9.15 – 42.96 T respectively with increase in source voltage from 2.24 to 13.34 V. The values obtained were in agreement with Odewole *et al*. (2023). The range of values of the PMF produced by the device are suitable for preserving fruits and vegetables such as blueberry (Arteaga et al., 2022), cucumber (Zhang et al., 2021), and mango (Kang et al., 2021). More so, power generated by the device is adequately sufficient and safe for electromagnetism in terms of voltage and currents utilization (Bird, 2007). Generally, PMF device utilized high currents and low voltage readings. This is in agreement with Bird, (2010), who postulated that the use of alternating (low) current had high capability to transmit power when compared with direct (high) current. Also, low current usually leads to low heating effect and less power requirement.

Table 2. Measured parameters of the MPMF machine

Voltage source (V)	Voltage readings (V)	Current (A)	Power (W)	Magnetic field strength (T)
2.42	1.32	2.00	120.00	9.15
4.84	2.22	12.60	180.00	14.30
7.24	3.20	20.70	220.00	20.58
9.01	4.52	28.60	250.00	27.20
11.49	5.66	34.90	300.00	36.32
13.34	8.24	38.60	350.00	42.96

Note: Source Voltage: No load voltage of the Step- down Transformer of the MF device; Voltage Readings: On-load voltage obtained from the device (same for current and power); Mains Voltage: 220 V.

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Furthermore, PMF intensities have similar patterns trend. These observations did not mean that they will have the same effect when applied to freezing, even though they have similar trends in term of the wave patterns (Odewole *et al*., 2023). Thus, it is suggested that freezing experiments be conducted on the technique to ascertain the effect of different magnetic strength on the final quality. Figures 7 (a), 7(b) and 7(c) show the wave patterns of the MPMF machine at 2 V, 7 V, and 13 V, respectively.

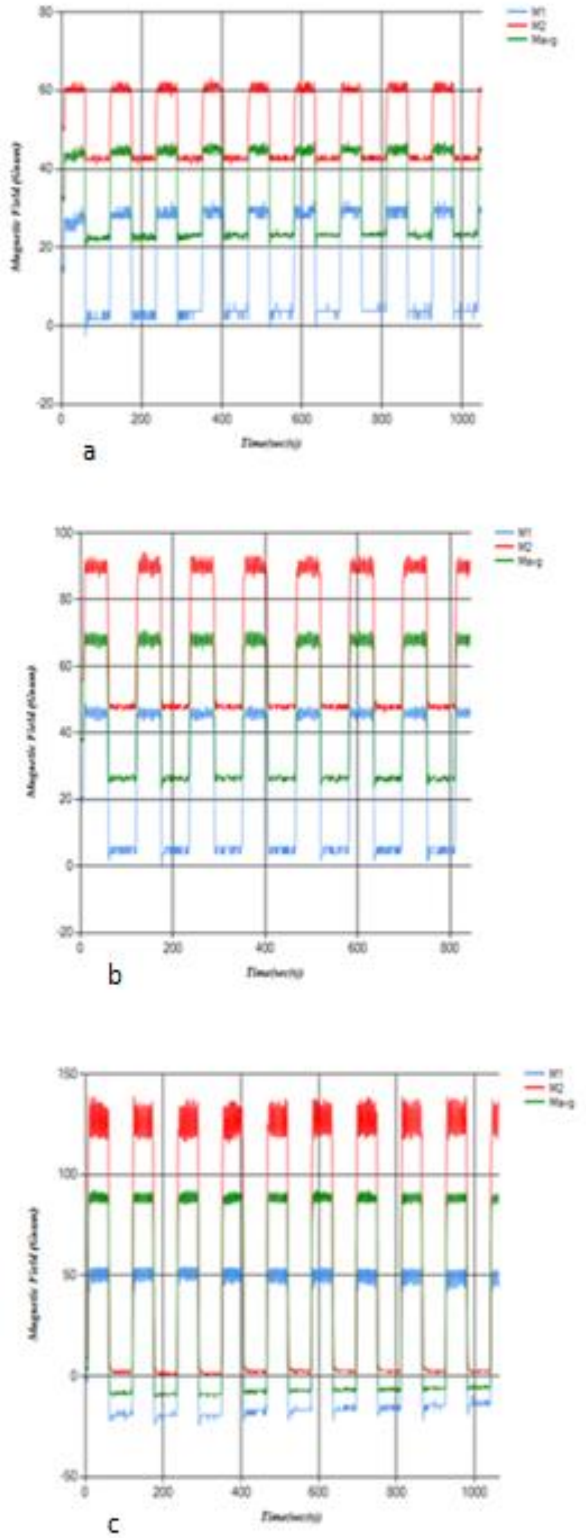

Fig. 7: Wave pattern of the MPMF (a) at 2 V, (b) at 7 V, (c) at 13 V

4 Conclusion

A microcontroller pulsed magnetic field machine that can be applied to assist cellular foods freezing was developed and the performance based on the field strength and wave patterns of the machine were evaluated. The machine was able to generate satisfactorily controlled pulsed wave patterns at different field strengths and voltage readings. The machine can be applied to assist freezing of cellular foods for further studies.

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