MICROWAVE MILK PASTEURIZATION SYSTEM USING COAXIAL SLOT RADIATOR

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UNIVERSITI TEKNOLOGI MALAYSIA

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DEDICATION

This thesis is dedicated to my beloved father and mother, who sacrificed their lives for a better future for their son. May Allah reward them with best rewards in this life and thereafter (Amin). It is also dedicated to my beloved wife, my beloved son Yasir, my beautiful and beloved daughters: Sarah and Lara, and to my beautiful and beloved niece Ronza (May Allah protect them from all evils).

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ABSTRACT

Microwave heating is a volumetric heating and free-fouling process which can save billions of dollars caused by periodic cleaning procedures of heat exchangers in the current dairy industry. The current milk microwave pasteurization method results in non-uniformity in the temperature distribution, which compromises the pasteurization quality. This thesis aims to improve the uniformity of microwave heating using a low-power coaxial slot antenna for the application of milk pasteurization. Initially, the relative complex permittivity of cows' raw milk is measured using a Keysight 85070E dielectric probe over a temperature, T ranging from 25 °C to 75 °C with an interval of 5 °C and a frequency ranging from 0.2 GHz to 6 GHz. The measurement results of relative complex permittivity are modeled using a modified Debye relaxation model and their values are used in the simulation for radiator design. A coaxial slot radiator is designed and optimized using the COMSOL Multiphysics simulator by considering the radiator sunk into the 100 mL of cows' milk for pasteurization. The radiator's performance is optimized by adjusting the slot length and slot position on the monopole radiator. At radio frequency of 2.45 GHz, the slot length of 2.4 mm and slot position at 4.7 mm from the end tip of the radiator provide optimized impedance matching, Z_{in} of $51.54 - j0.3\,\Omega$, which is close to ideal impedance, Z_{in} of $50\,\Omega$. The monopole slot radiator is fabricated using a semi-rigid RG405U cable with a SubMiniature version A (SMA) connector. The antenna is fed with 2.45 GHz magnetron based microwave generator, which is implemented and calibrated. The reflection coefficient, $|S_{11}|$ of the radiator with generator system in 100 mL of cows' raw milk, is measured across a temperature ranging from 25 °C to 85 °C using a portable radio frequency (RF) reflectometer and a lab heater. The measurements of $|S_{11}|$ show readings higher than -45 dB at 25°C and higher than -25 dB at 85 °C. The temperature distribution generated from the radiator in 100 mL of cows' raw milk at processing powers of 100 W, 125 W, and 150 W are simulated using COMSOL and measured using an infra-red (IR) thermal imaging camera and two thermocouple sensors mounted on a 3D-printed holder. The measured temperature distributions show a significant improvement in temperature uniformity with a maximum temperature difference, ΔT of 3.4 °C, 2.3 °C, and 2.2 °C for power usage of 100 W, 125 W, and 150 W respectively. With a maximum temperature difference, ΔT of 24.1 ± 1 °C, milk microwave batch pasteurization improved by up to 89.2% compared to previous non-uniformities. The collected cows' raw milk samples are then placed in pre-sterilized containers and processed inside biosafety cabinet II for pasteurization quality assessment based on aerobic plate count (APC) tests and to investigate the heating effects on milk's nutrition at power usage of 100 W according to the physiochemical properties tests using the Master Eco ultrasonic milk analyzer. The APC tests show the technique's ability to eliminate milk micro-organisms with a 5-log reduction of the microbial population after 7 min, 6 min, and 5 min at microwave powers usage of 100 W, 125 W, and 150 W respectively. The measured milk's physiochemical properties show similar heating effects on protein, solid-non-fat, and fat and fewer effects on density, dry matter (DM), and lactose compared with previous studies on conventional milk microwave batch pasteurization.

ABSTRAK

Pemanasan gelombang mikro adalah proses pemanasan isipadu dan bebas daripada pencemaran serta menjimatkan kos berbilion-bilion dolar untuk pembersihan penukar haba secara berkala dalam industri tenusu semasa. Walau bagaimanapun, pempasteuran gelombang mikro susu semasa mempunyai isu ketidakseragaman dalam taburan suhu yang akan menjejaskan kualiti pempasteuran. Tesis ini bertujuan untuk menambahbaik keseragaman pemanasan gelombang mikro untuk aplikasi pempasteuran susu dengan menggunakan antena slot sepaksi berkuasa rendah sebagai sumber pemanasan untuk pempasteuran susu tersebut. Pada mulanya, kebolehtelapan kompleks relatif susu mentah lembu telah diukur dengan menggunakan prob dielektrik Keysight 85070E, yang melingkupi julat suhu antara 25 °C hingga 75 °C dengan selang 5 °C dan julat frekuensi antara 0.2 GHz hingga 6 GHz. Hasil pengukuran ketelusan kompleks relatif dimodelkan dengan menggunakan model santaian Debye yang dimodifikasi dan nilainya digunakan dalam simulasi untuk reka bentuk radiator. Radiator slot sepaksi telah direka bentuk dan dioptimumkan menggunakan penyelaku COMSOL Multiphysics dengan mempertimbangkan rendaman radiator tersebut ke dalam 100 mL susu lembu untuk tujuan pempasteuran. Prestasi radiator tersebut dioptimumkan dengan menyesuaikan panjang slot dan kedudukan slot pada radiator eka-kutub. Panjang slot 2.4 mm dan kedudukan slot pada 4.7 mm dari hujung radiator memberikan nilai pemadanan impedans Z_{in} bersamaan $51.54 - j0.3\,\Omega$ pada 2.45 GHz, di mana menghampiri nilai impedans unggul Z_{in} iaitu $50\,\Omega$. Antena slot eka-kutub tersebut difabrikasi dengan menggunakan kabel RG405U separuh tegar dengan penyambung SubMiniature version A (SMA). Antena tersebut disambungkan dengan penjana gelombang mikro berasaskan magnetron yang diaplikasi dan dikalibrasi pada 2.45 GHz. Pekali pantulan, $|S_{11}|$ radiator dengan sistem penjana dalam 100 mL susu mentah lembu diukur pada julat suhu antara 25 °C hingga 85 °C dengan menggunakan reflektometer frekuensi radio (RF) mudah alih dan pemanas makmal. Pengukuran $|S_{11}|$ menunjukkan bacaan lebih tinggi daripada −45 dB pada 25 °C dan lebih tinggi daripada −25 dB pada 85 °C. Taburan suhu yang dihasilkan daripada radiator dalam 100 mL susu lembu pada kuasa pemprosesan 100 W, 125 W, dan 150 W telah disimulasi dengan menggunakan penyelaku COMSOL dan diukur menggunakan kamera pengimejan terma inframerah (IR) dan dua penderia termogandingan yang dipasang pada pemegang tercetak 3D. Taburan suhu yang diukur menunjukkan bahawa penambahbaikan yang bererti dalam keseragaman taburan suhu dengan sisihan suhu maksimum, ΔT 3.4 °C, 2.3 °C, dan 2.2 °C untuk penggunaan kuasa masing-masing pada 100 W, 125 W, dan 150 W. Peningkatan sebanyak 89.2% prestasi keseragaman taburan suhu dicapai berbanding kaedah lama pempasteuran gelombang mikro susu yang mempunyai sisihan suhu maksimum, ΔT 24.1 ± 1 °C. Sampel lembu susu mentah yang dikumpulkan kemudian diletakkan di dalam bekas yang disteril dan diproses di dalam kabinet biokeselamatan II untuk tujuan penilaian kualiti pempasteuran berdasarkan kepada ujian kiraan plat aerobik (APC) dan kajian kesan pemanasan terhadap susu pada penggunaan kuasa 100 W berdasarkan ujian fisiokimia menggunakan penganalisis susu ultrasonik Master Eco. Ujian APC menunjukkan bahawa teknik kajian ini mampu mengurangkan mikroorganisma dalam susu dengan pengurangan populasi mikrob 5-log selepas 7 min, 6 min, dan 5 min untuk penggunaan kuasa gelombang mikro masing-masing pada 100 W, 125 W, dan 150 W. Sifat fisiokimia susu yang diukur menunjukkan kesan pemanasan yang hampir sama terhadap kandungan protein, pepejal-bukan-lemak, dan lemak dam susu. Tetapi, hanya menunjukkan sedikit kesan pada ketumpatan, bahan kering (DM), dan laktosa dalam susu selepas menjalankan pempasteuran berbanding dengan kajian pempasteuran susu gelombang mikro konvensional yang terdahulu.

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LIST OF ABBREVIATIONS

ALP - Alkaline Phosphatase

APC - Aerobic Plate Count

BEM - Boundary Element Method

CCP - Colloidal Calcium Phosphate

CFU/mL - Colony-forming unit per mL

CNC - Computer Numerical Control

COVID-19 - Coronavirus disease 2019

CUT - Come Up Time

DC - Direct Current

DM - Dry Matter

DOL - Direct On Line

EMF - Electromagnetic Field

FAO - Food and Agriculture Organization

FAs - Fatty Acids

FDM - Finite Difference Method

FDTD - Finite Difference Time Domain

FVM - Finite Volume Method

HHST - Higher Heat Shorter Time

HPP - High Pressure Processing

HTST - High Temperature Short Time

ICNIRP - International Commission on Non-Ionizing Radiation Protection

IoTs - Internet of Things

IR - infrared

ISM - Industrial Scientific and Medical

ITU - International Telecommunication Union

LTLT - Low Temperature Long Time

MAPS	-	Microwave coaxial Antenna based Pasteurization System
MCMC	-	Malaysian Communications and Multimedia Commission
MoM	-	Method of Moment
MT	-	*Mycobacterium Tuberculosis*
PC	-	Personal Computer
PCA	-	Principle component Analysis
PEC	-	Perfect Electric Conducting
PEEM	-	Partial Element Equivalent Method
PEF	-	Pulse Electric Field
PML	-	Perfect Matched Layer
PMO	-	Pasteurized Milk Ordinance
PTFE	-	Polytetrafluorethylene (Teflon)
RF	-	Radio Frequency
SAR	-	Specific Absorption Rate
SE	-	Standard Error
SMA	-	SubMiniature version A connector
SNF	-	Solid Not Fat
SPC	-	Standard Plate Count
SPLC	-	Spiral Plate Count
TAGs	-	Triacylglycerols
TDT	-	Thermal Death Time
TE	-	Transverse Electric mode
TEM	-	Transverse Electromagnetic Mode
TLM	-	Transmission Line Method
TM	-	Transverse Magnetic mode
TS	-	Total Solids
TV	-	Television
UHF	-	Ultra High Frequency
UHT	-	Ultra High Temperature

UV	-	Ultraviolet
WHO	-	World Health Organization
WR430	-	Waveguide Rectangular 430

LIST OF SYMBOLS

ε - permittivity (F/m)

ε_r^*, ε_r - relative complex permittivity

ε_o - permittivity of vacuum (F/m)

$\varepsilon_r^{'}$ - real part of relative permittivity / dielectric constant

$\varepsilon_r^{''}$ - imaginary part of relative permittivity / loss factor

ε_∞ - optical permittivity

ε_s - static permittivity

ε_1, ε_2 - relaxation threshold permittivity

μ - permeability (H/m)

σ - conductivity (S/m)

f - frequency (Hz)

t - time (s)

T - temperature (C)

K - thermal constant (W/m.k)

ω - angular frequency (rad/s)

τ - relaxation time (s)

τ_1, τ_2, τ_3 - relaxation times (s)

$\varepsilon_\infty^{Milk}$ - optical permittivity of liquid milk

$\varepsilon_\infty^{Dried-Milk}$ - optical permittivity of milk powder

$\varepsilon_\infty^{water}$ - optical permittivity of water

D - penetration depth of electromagnetic waves (m)

$\mathbf{D}$ - antenna directivity (unity) or (dB)

D_{915} - penetration depth at 915 MHz (m)

D_{2450} - penetration depth at 2450 MHz (m)

D-value - decimal reduction time (min)

$\phi\,(t)$ - dielectric response function / decay function

c - velocity of light (m/s)

λ - wavelength(m)

λ_o - free space wavelength

λ_{eff} - effective wavelength

$\vec{E}$ - electric field / electric intensity

$|S_{11}|$ - reflection coefficient (dB)

Z_o - characteristic impedance (Ω)

Z_{in} - antenna input impedance (Ω)

$\mathrm{Re}(Z_{in})$ - real part of antenna input impedance (Ω)

$\mathrm{Im}(Z_{in})$ - imaginary part of antenna input impedance (Ω)

L_{slot} - the slot length for coaxial slot antenna (mm)

υ_{water} - water content of the milk

R^2 - coefficient of statistical determination

ΔV - rate of change (%)

V_1 - milk property before processing

V_2 - milk property after processing

$|V_1|$ - absolute value of initial property of milk

dB - decibel

f_R - relaxation frequency (Hz)

κ - first order rate constant

P_{MICRO} - microwave radiation power (W)

P_{DC} - magnetron DC input power

ΔT - temperature difference (C)

Δt - time difference (s)

$A_1, \beta_1, \beta_2, \beta_3$ - empirical constants

c - coupling factor (dB) / speed of light (m/s)

Q_e, P - absorbed microwave power

SAR - specific absorption rate (W/kg)

ρ - density kg/m^3

δP_{DC} - error in the DC input power of magnetron (W)

δP_{MICRO} - error in the output microwave power of MAPS

δP_{sensor} - error in the microwave power sensor measurement (W)

$N(t)$ - the population of the survived microorganisms

N_o - the initial population of microorganisms

C_p - specific heat capacity (kJ/(kg K))

E_{avg} - average electric field intensity (Vm^{-1})

EIRP - effective isotropic radiation power (W)

T_{inact} - inactivation temperature (°C)

$\mathrm{O-H}$ - oxygen and hydrogen bound

$\boldsymbol{STD}$ - the standard deviation

$\boldsymbol{r^2}$ - coefficient of determination

$\boldsymbol{r^2(adj)}$ - adjusted coefficient of determination

$\boldsymbol{SE}$ - the mean standard error

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Milk provides a wealth of nutrition benefits, such as protein, fat, and lactose. It also contains antibodies, which protect humans against infections [1]. A category of milk consumers prefer to drink raw milk rather than pasteurized milk for several health benefits claims as they perceived. These benefits are related to the nutrition and digestibility that would prevent allergies and heart disease [2, 3]. It is due to claims that heating may destroy the nutritional values of the milk. However, raw milk serves as an excellent growth medium for several microorganisms, including pathogenic bacteria that cause illnesses to most people who serve contaminated raw milk and its related products [4]. The risks imposed by consuming raw milk and its products can be reduced by heating. Hence, pasteurization is a thermal process that aims to eliminate the milk-borne pathogens, maintain nutrition and taste, and extend the product shelf life [5].

Consequently, the United States Food and Drug Administration (FDA) made pasteurization mandatory in the dairy industry [6]. A heat exchanger is equipment used to heat the milk based on the conduction heating concept. It is the standard pasteurization equipment used in the industrial sector due to its uniform thermal distribution [7]. Nevertheless, conduction heating causes overheating of milk molecules, resulting in milk residuals at the conducting surfaces. However, the fouling in the heat exchanger causes degradation in pasteurization quality and requires high maintenance cost [8]. The continuous demand for solving such problems enables emerging technologies to be involved. Microwave heating is one of the promising solutions which is used and adapted in certain countries. Microwave heating is rapid, which yields increased production and is inexpensive to maintain the operation. The principal feature of microwave heating is volumetric heating, where the heating mechanism relies on the interaction between material and applies microwave signals, which avoids the overheating of milk particles at the internal surfaces of heat exchanger pipes as in the conventional heating [9]. Currently, a microwave heating system is not applied as milk pasteurization in the dairy industry; due to the lack of uniformity in the thermal distribution of microwave heating, which lowers the product safety and quality [10]. This thesis presents a low-power applicator called coaxial slot antenna as a new microwave heating method for milk pasteurization based on a batch processing approach. Hence, the proposed coaxial slot radiator aims to overcome the non-uniformity in the thermal distribution in milk's current microwave batch pasteurization. Accordingly, it includes measurements and modeling of the temperature and frequency-dependent dielectric properties of cows' raw milk to be used to simulate microwave pasteurization. In addition, the microbial quality of the pasteurization process is assessed based on monitoring the aerobic plate count (APC) tests. At the same time, its impact on milk nutrition is investigated based on measuring the physiochemical properties.

1.2 Problem Statement

Milk includes high water activity and complex biochemical composition. Therefore, it serves as an excellent culture medium for the growth and multiplication of several kinds of microorganisms, including pathogenic bacteria [11]. It gets contaminated by several factors, such as cow herself, air, milking equipment, cleanliness of breading, containers, soil, feed, faeces, and grass [3, 12, 13]. Several milk-borne pathogens have been isolated from raw milk samples across different countries and decades, as reviewed in Table E.1. Therefore, pasteurization is a mandatory process, which requires heating raw milk to an inactivation temperature, T_{inact} for a certain amount of time to render it for human consumption (to ensure that the milk or its products are free of pathogens) without compromising its nutritional values [11]. In the current dairy industry, milk pasteurization processes are achieved using either plate or tubular heat exchangers. In such equipment, milk is heated based on conduction heating, where the pipes are the source of heating, which consequently causes accumulating of milk residuals inside the pipes as a result of overheating [14] after some operating hours [15], as shown in Figure 1.1. Fouling causes a lack of uniform temperature distribution, which decreases the quality and safety of milk products. Therefore, periodic cleaning of the heat exchanger (at least once per day) is a mandatory process to maintain heat transfer efficiency and product quality [16]. However, fouling mitigation practices cost approximately $26.85 billion annually [17, 18].

Figure 1.1: A cross-sectional view of heat exchanger shows severe deposits [19]

In contrast, microwave heating is a promising heating technology that can be effectively applied as an alternative to radically overcome fouling problems in conventional industrial pasteurization systems [10]. Microwave heating is volumetric heating and free-fouling process as the milk is heated based on the interaction between applied microwave signal and its molecules, while the container remains cold [20, 21]. Besides, the heating efficiency of microwave is higher than conventional heating, thereby maximizing product safety and maintaining quality [22, 23]. Existing research on milk microwave heating, however, [10], reveals significant non-uniformities in temperature distribution. Hence, the thermal variations in microwave heating lead to incomplete kill of harmful bacteria, which ends up with inferior quality products as addressed by several researchers [24–26].

In milk pasteurization, microwave heating is classified into two types; batch and continuous-flow heating methods. The batch method requires manually placing the food in the processing cavity, such as an oven chamber. In contrast, the continuous-flow process requires milk to be bumped into the tube from the inlet side of the cavity, pass through the radiation, and exit from the outlet side of the chamber as a processed product [22,27]. It is recommended to use multiple cascaded ovens with three magnetrons (for each) with a minimum net power of 2 kW to ensure uniform heating at the exit location, where such power is considered high, in order to achieve uniform temperature distribution in a continuous-flow microwave heating. Furthermore, it was discovered that increasing the flow rate of milk in the tube reduces the rate of microbial destruction, resulting in pasteurization failure [28, 29].

In contrast, in milk microwave batch pasteurization, different methods have been conducted to optimize the temperature uniformity, such as the mode stirrer, which is applied in both types of the processing [30], and the usage of a rotating turntable, which applies to several materials and has been extensively adopted in current domestic microwave ovens [31]. None of these solutions could solve the non-uniformity heating issue for milk pasteurization efficiently [32, 33]. A study on cow's milk microwave batch pasteurization using a modified domestic microwave oven was conducted [34]. It shows that even though there are different container types, different volumes of samples, and different applied microwave power were used, the results show no variations in the temperature uniformities with a mean maximum temperature difference, ΔT of 24.1 ± 1 °C. Therefore, this thesis aims to solve the non-uniformities of milk pasteurization using a low-power coaxial slot radiator as an isothermal heating radiator.

Dielectric properties are the main parameter and variable in the microwave heating mechanism, where the dielectric properties primarily represent the microwave power absorption. Therefore, proper dielectric measurements and modeling of the specimen under heat are essential in order to provide accurate data for microwave heating simulation for approximate determination of thermal-energy coupling, temperature rise, and distribution within the samples [35]. The dielectric properties of milk depend on several factors, namely operating frequency, temperature, milk density, thermal conductivity, and specific heat capacity [36]. Several studies were carried out to measure the dielectric properties of different milk [1,36–40]. Two of them concerned cow's milk [1, 40]. However, [40] measured the dielectric properties of cow's milk at a range of the pasteurization temperature from 25 °C until 75 °C with a step size of 10 °C for only two selected frequencies and modeled the measured dielectrics using an empirical polynomial regression rather than a Debye relaxation model. Likewise, for [1], where the measurements were achieved at a temperature of 5 °C and from 10 °C to 70 °C at single frequency, $f = 2.45$ GHz. In this thesis, the dielectric measurements are carried out at a range of pasteurization temperatures from 25 °C to 75 °C with a 5 °C interval and frequencies from 0.2 GHz to 6 GHz. Once the measured data is obtained, the data is fitted and represented using the Debye-relaxation model.

In addition, the incidence of pathogenic bacteria, so-called microbial load, in milk is an indicator for the microbial quality and safety of pasteurized milk [41, 42]. The pasteurization process is intended to eliminate the most heat-resistant pathogenic bacteria present in the raw milk [43], that is Coxiella burnetii, which will never be existed in all raw milk samples. Instead, measuring the logarithmic reduction in the population of microorganisms based on the aerobic plate count (APC) test (in a unit of colony-forming per milliliter CFU/mL) indicates successful pasteurization. The United States Food and Drug Administration (FDA) found that any thermal process that can achieve a 5-log reduction in the APC test can eliminate the most heat resistive pathogen of concern in food [44]. Besides, according to Grade "A" milk based on the Pasteurized Milk Ordinance (PMO), bacterial limits for pasteurized milk should not exceed 20×10^3 CFU/mL [6]. Therefore, the APC tests were conducted to investigate the quality of the pasteurization, the inactivation times, and inactivation kinetics of microorganisms in cows' raw milk.

Finally, milk undergoes several changes during thermal treatment, which results in the degradation of some nutritional content [45]. Both conventional conduction heating and microwave heating show effects on some of the milk's nutrition in terms of the physiochemical properties; dry matter (DM), solid-not-fat (SNF), total protein, lactose, fat, and other properties such as pH, density, and freezing point which are necessary to test the milk adulteration [46]. Therefore, milk's physiochemical properties were tested to analyse and compare the effect of previous studies on microwave milk pasteurization with the proposed microwave cow's milk batch pasteurization.

1.3 Research Objectives

The objectives of this study:

(i) To measure the relative complex permittivity of the cows' raw milk and express the relative complex permittivity using the Debye relaxation model (required parameter in the coaxial slot antenna design).

(ii) To design, optimize, and fabricate the coaxial slot antenna as a heating applicator and implement a microwave signal generator system based on the magnetron source required to feed the applicator.

(iii) To study the temperature distribution of the proposed microwave heating for cow's milk at the pasteurization temperature based on simulation and experimental measurements using both Infra-red (IR) thermal imaging camera and thermocouple sensors, then compare the temperature uniformity with previous studies on conventional milk microwave batch pasteurization.

(iv) To pasteurize cows' raw milk using proposed heating and assess the quality of microbial reduction of the pasteurization process based on the aerobic plate count (APC) tests.

(v) To analyze the effect of the pasteurization process on milk's nutrition by testing its physiochemical properties, namely pH, solid-not-fat (SNF), density, dry matter (DM), fat, protein, lactose, salt, and freezing point using an ultrasonic milk analyzer.

1.4 Scope of Work

This work aims to measure and model the relative complex permittivity of cows' raw milk using batch (vat) pasteurization. The measured relative complex permittivity is then used to simulate antenna performance during heating. Then, the microwave heating system is fabricated based on a coaxial slot radiator as a heating applicator. Then it was followed by assessing milk pasteurization quality using aerobic plate count tests (APC) and the corresponding impacts on physiochemical properties. The scope of this thesis is briefly presented as:

(i) Measure and model the dielectric properties of cows' raw milk under batch pasteurization. The measurements cover the frequency range of 0.2 GHz to 6 GHz and the temperature range of 25 °C to 75 °C with 5 °C interval. A combination of Debye, Cole-Davidson, and You's formulation was applied to model the temperature-dependent dielectric properties at the three dominated relaxation processes, and all statistical coefficients and parameters were provided accordingly. MATLAB programming is used for modeling the dielectric properties.

(ii) The dielectric constant and loss factor measurements were used to simulate microwave heating for optimum antenna design. COMSOL Multiphysics software was used to study the coaxial slot antenna's design, optimization, and performance. An RG405-U Semi-rigid RF coaxial cable is used in the design simulation and fabrication of antenna at 2.45 GHz for three processing powers, namely 100 W, 125 W, and 150 W. The heat transfer equation, which includes the coupled electromagnetic heating, is applied to obtain the temperature distribution through milk pasteurization.

(iii) The antenna design and optimization were carried out based on a single slot, where the effect of the variation in the slot length and location was achieved based on the minimum reflection coefficient, $|S_{11}|$ and optimum input impedance, Z_{in} matching.

(iv) The microwave coaxial antenna-based pasteurization system (MAPS) includes a coaxial slot antenna connected to a microwave signal generator. An industrial water-cooling magnetron was used to generate signals at $f = 2.45$ GHz. The system is tuned, tested, and calibrated based on a three-stub waveguide tuner (WR430), waveguide coupler (WR430), and $|S_{11}|$ parameter, respectively. The system is calibrated based on cows' raw milk collected from a local dairy farm in Johor Bahru, Malaysia.

(v) The sample volume used is the 100 mL glass beaker, which was used in the simulation's modeling to study the design optimization of the heating applicator and heating profile. It is also used in the experimental work, including temperature distribution measurements, pasteurization quality assessment using APC tests, and physiochemical properties investigation.

(vi) The temperature distribution was determined in the simulation using COMSOL software. The experimental measurements are monitored using a VarioCAM thermal imaging camera manufactured by Infra Tech. for surface temperature distribution. Two thermocouple sensors were used to monitor the depth temperature distribution in the length cross-section of a 100 mL glass beaker.

(vii) The bacterial count test (APC) is carried out to study the microbial control of the proposed microwave heating and assess pasteurization quality. Hence, the MAPS system is installed on the level 2 biosafety cabinet. Three processing powers were used for the APC test, namely 100 W, 125 W, and 150 W at a processing period of 0 min up to 7 min with 1 min of period steps. The APC test is conducted according to the Food and Drug Administration (FDA) standard of microbial analysis. The decimal reduction time of microorganisms or (D-value) is applied to calculate the pasteurization efficiency.

(viii) The physiochemical properties are carried out using Master Eco ultrasonic milk analyzer (manufactured by Milkotester) for samples processed in 100 W of MAPS processing power case. Pearson correlation matrix, rate of change ΔV, and principle component analysis (PCA) are used to interpret the findings and correlation, where R programming is used to achieve these calculations.

1.5 Contribution of Research Work

The highlighted outcomes of this work are listed as:

(i) The measured relative complex permittivity from 0.2 GHz to 6 GHz presents degradation in the dielectric constant as the temperature and frequency increase. Whereas the values of dielectric loss factor, ε_r'' are very high at frequencies below 2.0 GHz, where the effects of ionic conductivity exhibited. The relative complex permittivity is modeled based on Debye and modified Cole-Cole with three relaxation processes. All its parameters were optimized and gave good matching between predicted and measured data.

(ii) The simulation of effective antenna design gives higher impedance matching, $|S_{11}|$ = - 31.48 dB with antenna input impedance, $Z_{in} = 51.54 - j0.3\Omega$. The measurements of the reflection coefficient of total system impedance matching which is further tuned at $f_o = 2.45$GHz at a range of pasteurization temperature, show decreasing in the reflection coefficient as the temperature increasing, however, the $|S_{11}|$ at highest temperature, 85 °C gives −25 dB, which ensures maximum power transfer to the applicator during all pasteurization process.

(iii) The measurements of the temperature distribution on cows' raw milk samples show significant improvement in the temperature uniformity, with mean maximum temperature difference, ΔT of 2.6 ± 0.3 °C which is 89.2 % better than the uniformity of previous milk microwave batch pasteurization.

(iv) The microbial reduction test based on the aerobic plate count (APC) show total elimination of microorganisms after 7 min, 6 min, and 5 min of processing at 100 W, 125 W, and 150 W, respectively. All processed samples of cows' raw milk indicate the system's ability to achieve a 5-log reduction in the population of microorganisms, which ensures the microbial quality of the pasteurization process.

(v) The effects of the proposed heating on milk's nutrition show similar effects on the cow's raw contents of protein, solid-not-fat (SNF), and fat, as well as fewer effects on density, dry matter (DM), and lactose, when cows' raw milk is processed at 100 W for 7 min comparing with previous studies on milk microwave batch pasteurization.

1.6 Thesis Organization

Chapter 1 presents introduction and brief background of milk and the existing conventional and microwave pasteurization systems,research objectives, scope of work, the significance of the work, and the thesis organization.

Chapter 2 highlights the key issues and challenges concerning microwave pasteurization. The first section reviews the importance of milk pasteurization, outlines the current conventional pasteurization standards and equipment used, and describes the types of microwave heating. The second section reviews the previous studies that conducted experiments on milk microwave pasteurization and then quantifies the microwave non-uniformity for the batch milk pasteurization studies using the temperature difference, ΔT. The third section addresses the fundamentals of microwave heating; such as heating mechanisms, essential factors such as dielectric properties, microbial inactivation via microwave energy, and the standard regulations concerning the usage of microwave heating, such as the impacts on public and individual worker health and the interference with other communication systems. The fourth section discusses the significance of dielectric properties and modeling, as well as their role in the development of microwave heating. After that, it is followed by an evaluation of the previous research on the measurements and modeling of the cow's milk dielectric properties, particularly the relative complex permittivity. Following that, the fundamental concepts of microwave heating simulation were discussed. By reviewing prior studies based on conventional microwave oven-based pasteurization, the last section highlights the influence of microwave pasteurization on nutritional milk components, referred to as physiochemical characteristics.

Chapter 3 practically demonstrates the methodologies used to develop, study, and validate a microwave pasteurization system using a coaxial slot radiator. The first stage involves the measurements and modeling of the dielectric properties of cow's milk. The second stage presents the simulation methodology and optimization of the coaxial slot antenna utilizing the measured values of the milk's relative complex permittivities taken from the first phase. The simulation aims to optimize the coaxial slot antenna, calculate the radiation patterns, and simulate the effects of microwave energy on public health. The third stage includes fabrication of the coaxial slot antenna, implementation of microwave signal generator, study and improvement of impedance matching of the complete microwave heating system, and measurements and calibration of the generated microwave power. The main problem of microwave pasteurization is the temperature non-uniformity which causes pasteurization failure for pasteurized milk samples. Therefore, the fourth stage presents the measurement of the temperature distribution of the proposed microwave heating on the cow's milk samples of 100 mL, each using a thermal imaging camera and two thermocouples sensors. Milk microwave pasteurization is like other types of heating; it results in variation in the milk's nutritional components. Hence, the fifth stage presents the methodology used to measure the physiochemical properties of cow's raw milk. The final stage describes the statistical formulas and parameters used in different parts of the study.

Chapter 4 presents the results of the dielectric properties measurements and modeling, including the ionic conductivity, σ and depth of penetration, D. Then, it follows by the results of the temperature distribution with a comparison to highlight the optimization of the temperature uniformity as compared with previous works of microwave pasteurization. The results of pasteurization assessments based on aerobic plate count are presented. Then finally, the results of the impact of the proposed microwave pasteurization on milk nutrition are presented and compared with previous studies. Chapter 5 presents the conclusion of this research works, followed by recommendations for future work in this topic.

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