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EXPERIMENTAL INVESTIGATION AND NUMERICAL SIMULATION OF OHMIC HEATING FOR LIQUID FOOD PASTEURIZATION UNDER LAMINAR CONDITION

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

EXPERIMENTAL INVESTIGATION AND NUMERICAL SIMULATION OF OHMIC HEATING FOR LIQUID FOOD PASTEURIZATION UNDER LAMINAR CONDITION

By

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Pasteurization of liquid food - guava juice and soymilk by continuous ohmic heating within a temperature range of 30-90 ^{0}C, was performed in a 3-D non – axisymmetric ohmic heater. (Three stripe electrodes positioned along the walls and oriented 120^0 to the axis of the pipe), using 3-phase 50-60 Hz alternative voltages, with Delta connection.

A mathematical model describing the flow and thermal behavior of guava juice and soymilk solution in a continuous ohmic heating unit was developed. The equations for conservation of mass, momentum and energy and electric field distributions including temperature dependent electrical conductivities, thermo physical and rheological properties were solved using a commercial Computational Fluid Dynamics (CFD) software package (FLUENT 6.1) which was based on finite volume method of analysis. User defined functions (UDF's)

employed in the original platform (FLUENT 6.1), were used for the solution of scalar equations - electrical field model.

Thermo-physical and rheological properties of soymilk and guava juice were measured. Soymilk was found to be Newtonian and guava juice a Non Newtonian (power law n = 0.0.5978 and k = 0.117 Pa s^n). Measurements of electrical conductivities at various temperatures for guava juice and soymilk were carried out. These properties were then used as inputs for the CFD modelling.

The numerical calculation results have provided reasonable information for optimizing the design of ohmic heating cell geometry to improve the uniformity of the electrical and thermal fields across the heating cell in order to avoid over and under-processing of liquid foods.

The heating rate of soymilk was found to be higher than that of guava juice. The current density of both guava juice and soymilk was found to exceed the critical value. However, experimentally the soymilk, a protein solution, was found to rapidly deposit on the surface of the electrodes. No ohmic heating was conducted thereafter with the soymilk.

Temperature, flow pattern, electrical field distribution and the slowest heating zone (SHZ) during ohmic heating of both liquid foods (3D) were predicted. Experimental and simulated temperatures were in good agreement at different locations along the ohmic heating axis for guava juice, thus validating the CFD model and simulation.

The pasteurization calculations were done for guava juice (3.8 ^{0}brix) and soymilk (7.8±0.02 ^{0}brix) using the pathline of the highest velocity simulated from the CFD, and pasteurisation was adequately and rapidly achieved.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doctor Falsafah

PEMERIKSAAN EKSPERIMEN DAN SIMULASI BERANGKA BAGI PEMANASAN OHMIC UNTUK PEMPASTEURAN MAKANAN CECAIR DIBAWAH KEADAAAN LAMINER

Oleh

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Pempasteuran makanan cecair - jus buah jambu batu dan susu kacang soya melalui pemanasan *ohmic* berterusan di dalam julat suhu 30-90^{0}C , dapat disimulasi dan disahkan dengan penggunaan model 3-dimensi bukan simetrik (Tiga elektrod jejalur yang disusun sepanjang dinding dengan orientasi 120^0 ke arah paksi paip), menggunakan voltan-voltan alternatif tiga fasa antara 50-60Hz, menerusi sambungan Delta.

Satu model matematik, yang dapat menggambarkan aliran dan ciri termo jus buah jambu batu dan susu kacang soya dalam unit pemanasan *ohmic* berterusan, telah dibangunkan. Persamaan-persamaan keabadian bahan, tenaga dan momentum, dan penyebaran medan elektrik termasuk konduktiviti elektrik yang bergantung kepada suhu, sifat – sifat termofisik dan reologi dapat di selesaikan dengan

penggunaan pakej perisian komersial, iaitu *Computational Fluid Dynamics* (FLUENT 6.1) yang berasaskan keadah analisa isipadu makluk.

Fungsi-fungsi yang didefinisikan oleh pengguna dan tersediaada dalam landasan FLUENT 6.1, digunakan untuk penyelesaian persamaan *scalar* - model medan elektrik.

Sifat-sifat termofisik dan reologi bagi susu kacang soya dan jus buah jambu batu telah di ukur. Didapati susu kacang soya adalah *Newtonian* manakala jus buah jambu batu adalah bukan Newtonian (perundangan kuasa n = 0.0.5978 dan k = 0.117 Pa s^n). Pengukuran konduktiviti elektrik pada pelbagai suhu bagi jus buah jambu batu dan susu soya telah juga dijalankan. Sifat-sifat ini seterusnya digunakan untuk pemodelan CFD.

Keputusan perkiraan berangka telah memberi maklumat mengcukupi bagi tujuan mengoptimakan rekabentuk geometri sel pemanasan *ohmic* untuk meningkatkan keseragaman medan-medan elektrik serta termo diseberang sel pemanasan supaya dapat mengelakkan pemprosesan makanan cecair berlebihan atau berkurangan.

Kadar pemanasan susu kacang soya didapati lebih tinggi berbanding dengan jus buah jambu. Batu. Ketumpatan aliran bagi kedua-dua jus buah jambu batu dan susu kacang soya didapti melebihi nilai kritikal. Walaubagaimanapun, diperhatikan dalam eksperimen bahawa susu soya, satu cecair protein, memendap pada permukaan elektrod-elektrod dengan cepat. Selepas itu , tiada pemanasan ohmic dijalankan pada susu soya .

Semasa pemanasan *ohmic* bagi kedua-dua jenis makanan cecair, ciri-ciri suhu, corak aliran, pengedaran medan elektrik dan zon pemanasan paling pelahan dapat diramalkan dalam 3-dimensi. Persetujuan antara suhu-suhu eksperimen dan simulasi didapati baik pada lokasi-lokasi berbeza sepanjang paksi pemanasan ohmic bagi jus buah jambu batu, maka dapat mengesahkan model CFD dan simulasi.

Perkiraan-perkiraan pempasteuran bagi jus buah jambu batu (3.8 ^{0}brix) dan susu soya (7.8±0.02 ^{0}brix) dibuat mengikut garisan simulasi kelajuan tertinggi dari CFD, dan proses pempasteuran dapat dijayakan dengan memadai dan cepat.

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APPROVAL

I certify that an Examination Committee met on 7 May 2008 to conduct the final examination of Elzubier Ahmed Salih on his Doctor of Philosophy thesis entitled "Experimental investigation and numerical simulation of ohmic heating for liquid food pasteurization under laminar condition" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the student be awarded the (Name of relevant degree).

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DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

ELZUBIER AHMED SALIH ELFAKIE

Date

TABLE OF CONTENTS

LIST OF TABLES

LISTS OF FIGURES

NOMENCLATURE

The following is a list of definitions of the main symbols used in this thesis. SI units are considered in the study.

Symbol	Description	Unit
A	Cross- sectional surface area of the electrodes	[m^2]
AC	Alternating current	[A]
b	The coefficient of temperature dependent Electrical conductivity	[$^0C^{-1}$]
COP	Coefficient of performance	[dimensionless]
C_p	Specific heat of liquid food	[$J\ kg^{-1}\ ^0C^{-1}$]
D_T	Decimal reduction time	[min]
D	Diameter of the heating cell	[m]
dv_r/dr	Radial velocity gradient in the radial direction	[$ms^{-1}m^{-1}$]
$dv_r/d\theta$	Radial velocity gradient in angular direction	[$ms^{-1}m^{-1}$]
dv_r/dz	Radial velocity gradient in axial direction	[$ms^{-1}m^{-1}$]
dv_θ/dr	Angular velocity gradient in radial direction	[$ms^{-1}m^{-1}$]
$dv_\theta/d\theta$	Angular velocity gradient in angular direction	[$ms^{-1}m^{-1}$]
dv_θ/dz	Angular velocity gradient in axial direction	[$ms^{-1}m^{-1}$]
dv_z/dr	Axial velocity gradient in radial direction	[$ms^{-1}m^{-1}$]
$dv_z/d\theta$	Axial velocity gradient in angular direction	[$ms^{-1}m^{-1}$]
dv_z/dz	Axial velocity gradient in axial direction	[$ms^{-1}m^{-1}$]
dT/dr	Temperature gradient in radial direction	[$^0Cm^{-1}$]
$dT/d\theta$	Temperature gradient in angular direction	[$^0Cm^{-1}$]
dT/dz	Temperature gradient in axial direction	[$^0Cm^{-1}$]
dV/dr	Voltage gradient in radial direction	[Vm^{-1}]
dV/θ	Voltage gradient in angular direction	[Vm^{-1}]
dV/dz	Voltage gradient in axial	[Vm^{-1}]

	direction	
$dP/d\theta$	Angular pressure gradient	[Pam^{-1}]
dP/dz	Axial pressure gradient	[Pam^{-1}]
dP/dr	Radial pressure gradient	[Pam^{-1}]
E	Voltage gradient or local electric field intensity	[Vm^{-1}]
EE	Electrical energy	[W]
EE_{acum}	Accumulated electrical energy	[W]
E_{loss}	Heating energy loss from the system	[W]
F	Number of minutes required to destroy a given number of organisms at a given temperature	[min]
F_O	Cumulative thermal lethality	[min]
f	frequency	[Hz]
G	Acceleration due to gravity	[$m\ s^{-2}$]
G_E	Acceleration due to electric field	[$g_E = E^{-2}\ bD^{-1}$]
H	Height of the heating cell	[m]
I	Current	[A]
J	Current density	[$A\ m^{-2}$]
K	consistency index	[$Pa\ s^n$]
k	Thermal conductivity of liquid being heated	[$w\ m^{-1}\ k^{-1}$]
ln	Natural logarism	
LTH	Low temperature holding	[^0C]
L_e	Distance between electrodes	[m]
(L/A)	Ratio of distance between electrodes to diameter of heating cell	
L_{leth}	Lethality at specified time	[min]
L	Electrode length	[m]
$m^{\cdot}$	Volumetric flow rate	[$m^3 s^{-1}$]
mRT	Minimum residence time	[sec]
n	Flow behavior index	[dimensionless]
Po	power	[W]
P	Pressure	[Pa]
Q	Volumetric heating generation	[$w\ m^{-3}$]
RT	Residence time	[sec]
r	Radial position from center line	[m]

R	Resistance	[Ω]
T_{ref}	Reference temperature	[^{0}C]
TSS	Total soluble solids	[^{0}Brix]
t	Heating time	[sec]
t_b	Time of the process	[min]
T_{in}	Inlet fluid temperature	[^{0}C]
N_{surviv}	Number of organism survive the heat treatment	
T	Temperature	[^{0}C]
V	Voltage	[volts]
v_m	Mean velocity	[ms^{-1}]
v_θ	Angular velocity	[ms^{-1}]
v_r	Radial velocity	[ms^{-1}]
v_z	Axial velocity	[ms^{-1}]
Z	Number of ^{0}C required for the thermal death time curve to traverse one logarithmic cycle	[^{0}C]
r	Radial coordinate	[m]
z	Axial coordinate	[m]

Dimensionless quantities

Pr	Prandtl number	[$\nu/\alpha = C_p \mu k^{-1}$]
Gz	Graetz number	[$\rho V_m D^2 C_p k^{-1} L^{-1}$]
Gr_{pl}	Grashof number for power law fluid	[$g\rho^2 \Delta T \beta R^{1+2n} v_m^{2-2n} K^{-2}$]
Gr	Grashof number,	[$g \rho^2 \Delta T \beta D^3 \mu^{-2}$]
Gr_{El}	Electrical Grashof number	[$E^2 b \rho^2 \Delta T \beta D^2 \mu^{-2}$]
Re	Reynolds number	[$\rho v_m D \mu^{-1}$]

Greek symbols

ρ_{ref}	Reference density	[kg m^{-3}]
ρ	Density of liquid	[kg m^{-3}]
μ_a	Apparent viscosity	[Pa s]
τ	Shear stress	[Pa]
β	Thermal expansion coefficient	[$^0C^{-1}$]
θ	Angular coordinate	[m]
ν	Kinematics viscosity	[$\mu \rho^{-1}$]
α	Thermal diffusivity	[$k \rho^{-1} C_p^{-1}$]
γ	Shear rate	[s^{-1}]
σ	Electrical conductivity	[Sm^{-1} or $ohm^{-1}m^{-1}$]
σ_0	Electrical conductivity of the fluid food at reference temperature	[Sm^{-1} or $ohm^{-1}m^{-1}$]

ΔT	Difference between inlet and out let temperature	[^{0}C]
μ	Newtonian viscosity	[Pa s]

Subscripts

ref	Reference value
El	elctrical
out	outlet
pl	Power law
m	avaraged
e	Electrode
in	inlet

CHAPTER 1

INTRODUCTION

1.1 Background

Thermal processing is an important method to extend the shelf-life of foods. However, some sensory - discoloration, flavor and textural changes as well as other physical and chemical changes - over-cooking, liquefaction, vitamin loss, caramelization and Maillard reactions are undesirable effects of thermal processing. Therefore, it is necessary to achieve optimal thermal processing to ensure both quality and safety of processed food (Erdogdu, 2000; Lund, 1977; Ramesh, 1995).

Alternatively, technologies based on electric field treatments of a food product have attracted attention from both academic and industrial communities because of high durability of treated products, technical simplicity and the ability to minimize food quality deterioration (Jeyamkondan *et al*., 1999). These technologies include (1) ohmic heating (2) pulsed electric field treatment and (3) microwave processing.

The ohmic heating concept is not new and was widely used in the 19th century to pasteurize milk. Apparently due to the lack of inert materials for the electrodes this technology was abandoned (Mizrahi *et al*., 1975). However the technology has recently gained new interest because the treated products are of superior quality compared to those processed by conventional technologies. This is mainly