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

ELZUBIER AHMED SALIH ELFAKIE

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By

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May 2008

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Pasteurization of liquid food - guava juice and soymilk by continuous ohmic
heating within a temperature range of 30-90 °C, was performed in a 3-D non –
axisymmetric ohmic heater. (Three stripe electrodes positioned along the walls
and oriented 120° 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 = 0.5978 and k = 0.117 Pa s\(^b\)). 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 °brix) and soymilk (7.8±0.02 °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 KEADAAN LAMINER

Oleh

ELZUBIER AHMED SALIH ELFAKIE

Mei 2008

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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°C, dapat disimulasi dan disahkan dengan penggunaan model 3-dimensi bukan simetrik (Tiga elektrod jejalur yang disusun sepanjang dinding dengan orientasi 120° 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 keadaan 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 mengelakukan pemprosesan makanan cecair berlebihan atau berkurangan.

Semasa pemanasan *ohmic* bagi kedua-dua jenis makanan cecair, ciri-ciri suhu, corak aliran, pengedaran medan elektrik dan zon pemanasan paling pelan 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 °brix) dan susu soya (7.8±0.02 °brix) dibuat mengikut garisan simulasi kelajuan tertinggi dari CFD, dan proses pempasteuran dapat dijayakan dengan memadai dan cepat.
ACKNOWLEDGEMENT

IN THE NAME OF ALLAH, THE BENEFICENT, THE MERCIFUL

Thanks are to Allah, Lord of the worlds, the Creator and Sustainer of the world. To Him, we belong and to Him, we will return. He can never be thanked enough and for giving me the strength and the patient to let this work be finished. I would like to take this opportunity to extend my thanks to all my main advisors: Dr. Ibrahim Omer Mohammed, Dr. Sergey Spotar, Assoc. Prof. Dr Thomas Choong Shean Yaw, member of my advisory committee Dr. Wan Abdullah Haj Wan, and Dr Chin Nyuk Ling for their cooperation and support. I am also grateful to them for assistance and guidance in completing this research. Acknowledgement is also due to Mr. Kamarulzaman (KPM), Mr. Razali, and Mr Soib from FSTM. Finally, this work could not have been completed without the love and support of my family. I thank my beloved mother, father, brothers and sisters, for their endless support. Special thanks are also extended to the University of Jezeera, Sudan for finance and support during my study and special thanks to Dr. Ismaieel Hassan Hussain (Vice chancellor of Jezeara University, Sudan) for his great help and support. Without their help after Allah S.W.T the project will not be completed. More thanks to Project Leader, Mr. Hishamuldin Jamaluddin and his Msc. student Faiza for their help in the experimental work and for purchasing the ohmic heating equipments. Finally, I would like to thank my beloved family, my wife Najat, my son Mohammed and daughter Deema, for their love, sacrifice, support, patience and encouragement throughout everything I have ever done.
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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Date: 25-9-2008
This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor Philosophy. The members of the Supervisory Committee were as follows:

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Faculty of Engineering  
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Date: 16 October 2008
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

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# NOMENCLATURE

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

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<tr>
<td>AC</td>
<td>Alternating current</td>
<td>([A])</td>
</tr>
<tr>
<td>b</td>
<td>The coefficient of temperature dependent Electrical conductivity</td>
<td>([^0C^{-1}])</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of performance</td>
<td>[dimensionless]</td>
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<td>(C_p)</td>
<td>Specific heat of liquid food</td>
<td>([J\ kg^{-1}\ 0C^{-1}])</td>
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<td>(D_T)</td>
<td>Decimal reduction time</td>
<td>([\text{min}])</td>
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<tr>
<td>D</td>
<td>Diameter of the heating cell</td>
<td>([\text{m}])</td>
</tr>
<tr>
<td>(dv_r/dr)</td>
<td>Radial velocity gradient in the radial direction</td>
<td>([\text{ms}^{-1}\text{m}^{-1}])</td>
</tr>
<tr>
<td>(dv_r/d\theta)</td>
<td>Radial velocity gradient in angular direction</td>
<td>([\text{ms}^{-1}\text{m}^{-1}])</td>
</tr>
<tr>
<td>(dv_r/dz)</td>
<td>Radial velocity gradient in axial direction</td>
<td>([\text{ms}^{-1}\text{m}^{-1}])</td>
</tr>
<tr>
<td>(dv_{\theta}/dr)</td>
<td>Angular velocity gradient in radial direction</td>
<td>([\text{ms}^{-1}\text{m}^{-1}])</td>
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<td>(dv_r/dz)</td>
<td>Axial velocity gradient in axial direction</td>
<td>([\text{ms}^{-1}\text{m}^{-1}])</td>
</tr>
<tr>
<td>(dT/dr)</td>
<td>Temperature gradient in radial direction</td>
<td>([^0C\text{m}^{-1}])</td>
</tr>
<tr>
<td>(dT/d\theta)</td>
<td>Temperature gradient in angular direction</td>
<td>([^0C\text{m}^{-1}])</td>
</tr>
<tr>
<td>(dT/dz)</td>
<td>Temperature gradient in axial direction</td>
<td>([^0C\text{m}^{-1}])</td>
</tr>
<tr>
<td>(dV/dr)</td>
<td>Voltage gradient in radial direction</td>
<td>([\text{Vm}^{-1}])</td>
</tr>
<tr>
<td>(dV/d\theta)</td>
<td>Voltage gradient in angular direction</td>
<td>([\text{Vm}^{-1}])</td>
</tr>
<tr>
<td>(dV/dz)</td>
<td>Voltage gradient in axial</td>
<td>([\text{Vm}^{-1}])</td>
</tr>
</tbody>
</table>
direction

\( \frac{dP}{d\theta} \) Angular pressure gradient \([\text{Pam}^{-1}]\)

\( \frac{dP}{dz} \) Axial pressure gradient \([\text{Pam}^{-1}]\)

\( \frac{dP}{dr} \) Radial pressure gradient \([\text{Pam}^{-1}]\)

\( E \) Voltage gradient or local electric field intensity \([\text{Vm}^{-1}]\)

\( EE \) Electrical energy \([\text{W}]\)

\( EE_{\text{acum}} \) Accumulated electrical energy \([\text{W}]\)

\( E_{\text{loss}} \) Heating energy loss from the system \([\text{W}]\)

\( F \) Number of minutes required to destroy a given number of organisms at a given temperature \([\text{min}]\)

\( F_0 \) Cumulative thermal lethality \([\text{min}]\)

\( f \) Frequency \([\text{Hz}]\)

\( G \) Acceleration due to gravity \([\text{m/s}^2]\)

\( G_E \) Acceleration due to electric field \([g_E = E^2 bD^4]\)

\( H \) Height of the heating cell \([\text{m}]\)

\( I \) Current \([\text{A}]\)

\( J \) Current density \([\text{A/m}^2]\)

\( K \) Consistency index \([\text{Pa s}^n]\)

\( k \) Thermal conductivity of liquid being heated \([\text{w m}^{-1} \text{k}^{-1}]\)

\( \ln \) Natural logarithm

\( L_{\text{T}} \) Low temperature holding \([\text{C}]\)

\( L_e \) Distance between electrodes \([\text{m}]\)

\( L/A \) Ratio of distance between electrodes to diameter of heating cell

\( L_{\text{leth}} \) Lethality at specified time \([\text{min}]\)

\( L \) Electrode length \([\text{m}]\)

\( m' \) Volumetric flow rate \([\text{m}^3\text{s}^{-1}]\)

\( m_{\text{RT}} \) Minimum residence time \([\text{sec}]\)

\( n \) Flow behavior index \([\text{dimensionless}]\)

\( P_0 \) Power \([\text{W}]\)

\( P \) Pressure \([\text{Pa}]\)

\( Q \) Volumetric heating generation \([\text{w m}^{-3}]\)

\( RT \) Residence time \([\text{sec}]\)

\( r \) Radial position from center line \([\text{m}]\)
Resistance [Ω]
Reference temperature [°C]
Total soluble solids [°Brix]
Heating time [sec]
Time of the process [min]
Inlet fluid temperature [°C]
Number of organisms survive the heat treatment
Temperature [°C]
Voltage [volts]
Mean velocity [ms⁻¹]
Angular velocity [ms⁻¹]
Radial velocity [ms⁻¹]
Axial velocity [ms⁻¹]
Number of ⁰C required for the thermal death time curve to traverse one logarithmic cycle [⁰C]
Radial coordinate [m]
Axial coordinate [m]
Prandtl number $[\nu/\alpha = C_p \mu k^{-1}]$
Graetz number $[\rho V_m D^2 \beta k^{-1} L^{-1}]$
Grashof number for power law fluid $[g \rho^2 \Delta T \beta R^{1+2n} \nu_m^{-2n} k^{-2}]$
Grashof number, $[g \rho^2 \Delta T \beta D^3 \mu^{-2}]$
Electrical Grashof number $[E^2 \rho_m^2 \Delta T \beta D^2 \mu^{-2}]$
Reynolds number $[\rho v_m D \mu^{-1}]$
Reference density [kg m⁻³]
Density of liquid [kg m⁻³]
Apparent viscosity [Pa s]
Shear stress [Pa]
Thermal expansion coefficient [⁰C⁻¹]
Angular coordinate [m]
Kinematics viscosity [μm²]
Thermal diffusivity [k ρ⁻¹ C_p⁻¹]
Shear rate [s⁻¹]
Electrical conductivity [Sm⁻¹ or ohm⁻¹ m⁻¹]
Electrical conductivity of the fluid food at reference temperature [Sm⁻¹ or ohm⁻¹ m⁻¹]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>Difference between inlet and outlet temperature [°C]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Newtonian viscosity [Pa s]</td>
</tr>
<tr>
<td>Subscripts</td>
<td>Description</td>
</tr>
<tr>
<td>ref</td>
<td>Reference value</td>
</tr>
<tr>
<td>El</td>
<td>Electrical</td>
</tr>
<tr>
<td>out</td>
<td>Outlet</td>
</tr>
<tr>
<td>pl</td>
<td>Power law</td>
</tr>
<tr>
<td>m</td>
<td>Averaged</td>
</tr>
<tr>
<td>e</td>
<td>Electrode</td>
</tr>
<tr>
<td>in</td>
<td>Inlet</td>
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</table>
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