HEFAT2010
7th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
19-21 July 2010
Antalya, Turkey

MODELING OF HEAT AND MASS TRANSFER FOR TEXTURE IMPROVEMENT IN MICROWAVE BOILED LENTILS

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ABSTRACT

Lentil is an excellent source of proteins and various micro nutrients such as vitamin A, potassium, B vitamins, and iron, and it provides fiber with no cholesterol and virtually no fat. Canadian red lentils were soaked in ambient water for different times ranging from 0-120 mins. The soaked lentils were boiled in a custom built microwave setup at 2450 MHz with different lentil to water ratio of 1:1, 1:1.5 and 1:2 for different durations of 20 mins, 40 mins and 1 hour. The mechanism of heat transfer and the fluid dynamics during microwave boiling of lentils were investigated. An empirical diffusion model was developed based on the assumption that there was no significant change in the bound moisture content due to protein denaturation. The rheological parameters of the boiled lentils were measured and compared. The parameters of soaking time, power density and boiling time were optimised for microwave boiling of lentils for better rheological quality. The model fits the data well and can be used to tweak the microwave boiling process of lentils to obtain desirable results.

INTRODUCTION

Lentil has 25% protein content and is primarily used in human diets as a source of protein. Lentil is also an excellent source of various micro nutrients such as vitamin A, potassium, B vitamins, and iron, and it provides fiber with no cholesterol and virtually no fat. Furthermore, when eaten with a cereal, lentils provides all the essential amino acids required for the human body in a balanced diet (Pulse Canada, 2009; Saskatchewan Agriculture and Food, 2003), and helps to control and prevent various metabolic diseases, such as diabetes mellitus and coronary heart disease and can help in weight management (Chung et al., 2008; Dilis and Trichopoulou, 2009; Leterme, 2002). Lentils do however contain anti-nutritional factors like indigestible oligosaccharides, α-galactosides, trypsin inhibitors etc. (Vidal-Valverde et al., 1994).

The different micro and macro nutrients of the lentils are significantly affected by different thermal processing techniques like oven drying, dry roasting, salt bed roasting, microwave heating, cooking etc. (Raghavan et al., 1974). Thermal processing reduces the anti-nutritional factors in lentil (Stewart et al., 2003; Vidal-Valverde et al., 1994).

Microwave cooking preserves nutrients in many food products especially those with a rich protein matrix (Gonzalez et al., 2002). The literature available on the effect of processing on various parameters of lentils does not provide any information on the thermodynamic and engineering aspects of the processes. The cooking time for pulses is significantly long, being about 30 – 40 minutes (Abdel-Gawad, 1993; Cenkowski and Sosulski, 1996), modeling and quantifying the thermodynamic and the fluid dynamic aspects of the thermal processing of lentils needs research. Therefore this study was conducted to investigate the heat and mass transfer during microwave boiling of lentils and develop empirical models based on the data. Thereby optimise the microwave boiling process for the better textural quality.

NOMENCLATURE

$C(t.\ x)$	Moisture concentration at distance x
D_{eff}	Effective moisture diffusivity
M	Moisture content
M_e	Equilibrium Moisture content
M_o	Initial Moisture Content
a	Equivalent half thickness of slab
E	Total Electric field intensity (V.m^{-1})
E_x	Electric field intensity x component (V.m^{-1})
E_y	Electric field intensity y component (V.m^{-1})
E_z	Electric field intensity z component (V.m^{-1})
H	Total Magnetic Field Intensity (A.m^{-1})
H_x	Magnetic field intensity x component (A.m^{-1})
H_y	Magnetic field intensity y component (A.m^{-1})
H_z	Magnetic field intensity z component (A.m^{-1})
f	Frequency of microwaves (Hz)
ε'	Dielectric constant

ε''	Dielectric loss factor
ε_0	Permittivity of free space ($F.m^{-1}$)
μ_0	Permeability of free space ($H. m^{-1}$)
P_{av}	Time average power dissipated (W)
P_c	Poynting Vector – power dissipated over unit area ($W.m^{-2}$)
ρ	Density of the material ($kg.m^{-3}$)
C_p	Specific heat capacity of the material ($kJ.kg^{-1}.K^{-1}$)
T	Temperature (K)
T_c	Temperature (℃)
K	Thermal conductivity ($W.m^{-2}.K^{-1}$)
Q	Power Source Term ($W.m^{-3}$)
V	Volume (m^3)
n	Unit vector normal to the surface
A	Cross sectional area of the waveguide
α & β	Arbitrary constants

MATERIALS AND METHODS

Canadian Red Dehulled Lentils (Figure 1) with an initial moisture content of 14% $_{\text{(Wet Basis)}}$ were soaked in ambient water (23°C) for different time intervals ranging from 0-120 minutes with increments of 30 minutes. 25 grams of the soaked lentils were boiled in a custom built microwave setup at 2450 MHz with different lentil to water ratio of 1:1, 1:1.5 and 1:2 for different durations of 20 minutes, 40 minutes and 1 hour using a power density of 3 W/g. The mechanism of heat transfer and the fluid dynamics during microwave boiling of lentils were investigated.

Figure 1: Canadian red dehulled lentils used in this study

Equipment:

An instrumented and computer controlled laboratory scale microwave (MW) oven (custom built in the laboratory) (Figure 2) was used this study. Its main components were: a 2450 MHz microwave generator (Gold Star 2M214, South Korea) with adjustable power from 0 to 750 W, waveguides, a three-port circulator, a manual three-stub tuner to match the load impedance, microwave couplers to measure forward and reflected power, a carbon load to absorb reflected power and a microwave cavity made of brass, (47 x 47 x 27 cm) in which the egg samples were processed. The wave guides were rectangular (72 x 35 mm) and TE10 mode of application was used.

The microwave generator (magnetron) produced microwaves with varying power densities based on the supplied power. The generated microwaves were guided using the waveguides into the microwave cavity via the above mentioned components in a sequence. The manual three-stub tuner was used to adjust the reflected power, thereby keeping it at the minimum possible value (<10% of the incident power). The temperatures were measured using fiber optic probes (Nortech EMI-TS series, Quebec City, Canada). The probes were connected to a data acquisition unit (Agilent 34970A, Santa Clara, USA) which was again connected to a computer. The entire setup was monitored and controlled using the HPVEE (Agilent, Santa Clara, USA) object oriented programming language.

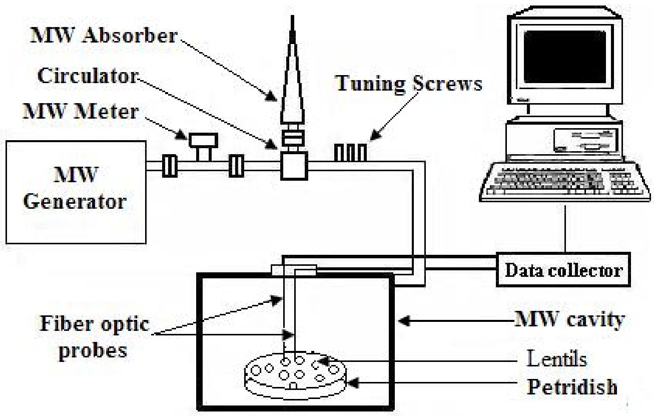


Figure 2: Experimental setup for microwave heating

Diffusivity Model:

Assuming that moisture diffused mainly through the seed coat of lens-shaped lentils, the moisture-absorption pattern can be described by Fick's Law of Diffusion for simplified slab geometry as in equation (1) (Crank 1986):

$$\frac{\partial C(t,x)}{\partial t} = \frac{\partial}{\partial x}\left[D_{\text{eff}}\left\{\frac{\partial C(t,x)}{\partial x}\right\}\right] \quad (1)$$

where, C(t. x) is the, t is time, and D_{eff} is the effective moisture diffusivity in lentils. A one dimensional approach is used here. It was assumed that moisture transport occurs only by diffusion and the corresponding diffusivity was calculated. Assuming a constant D_{eff} and, under a constant boundary condition at the surface of the lentils, $C(t, x = a) = M_e$, and an initial condition $C(t = 0, x) = M_o$, a general solution for the average moisture content, M, of the lentil can be determined using equation (2).

$$\frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\left[\frac{1}{(2n-1)^2}\, e^{\frac{-(2n-1)^2\pi^2 D_{\text{eff}}\, t}{4a^2}}\right] \quad (2)$$

where M_e is the equilibrium moisture content, and a is the equivalent half thickness of the slab. For red lentils, a is about 0.6 mm (Tang and Sokhansanj 1993).The moisture-absorption data for different initial moisture content produced by soaking for different intervals was fitted to equation (1) by adjusting the value of D_{eff} to minimize the sum of the squared differences between the estimated moisture contents and the experimental data. The goodness of fit was evaluated by the relative mean square errors (RMS) is given by equation (3)

$$RMS = 100\% \sqrt{\frac{1}{N} \sum_{i=1} \left(\frac{M_i' - M_i}{M_i'}\right)^2} \quad (3)$$

Electromagnetics:

The Maxwell's equations that govern the electromagnetic phenomena evolving in a given configuration resolved in 3D space were solved for the Electric field intensity (E) ($V.m^{-1}$) and Magnetic field intensity (H) ($A.m^{-1}$) (Dai, 2006). The dynamically changing dielectric constant ε' and loss factor ε" were calculated using equations derived from the measurement of dielectric properties.

The time average power dissipated (P_{av}) in each element in a dielectric material was obtained by integrating the poynting vector (P_c) over the closed surface S for each tetrahedral element (eqn. (4)) (Jia and Jolly, 1992).

$$P_{av} = -\frac{1}{2}\int_S P_c.dS \quad (4)$$

Where $P_c = E \times H$

Volumetric heat generation Q can be expressed in terms of power intensity in three orthogonal directions as shown in equation (2) (Lin *et al.*, 1989).

$$Q = \frac{\partial P_{av(x)}}{\partial V} + \frac{\partial P_{av(y)}}{\partial V} + \frac{\partial P_{av(z)}}{\partial V} \quad (5)$$

Where the suffixes x, y and z indicate time average power dissipated in the corresponding directions and V is the volume in which the heat is generated

Boundary conditions: (Fu et al. 2004)

Perfect Electrical Conductor (PEC) boundary condition (n x E = 0) was used for the walls of the cavity and Perfect Magnetic Conductor (PMC) boundary condition (n x H = 0) was used for the symmetry boundaries.

Boundary conditions at the port were taken as follows

$H_y = A \cos(\Pi x/\alpha) \cos(\omega t + \beta y)$ (6)

$E_z = (\omega\, \mu_0\, \alpha/ \Pi)\, A \sin(\Pi x/\alpha) \sin(\omega t + \beta y)$ (7)

$H_x = (\beta\, \alpha/ \Pi)\, A \sin(\Pi x/\alpha) \sin(\omega t + \beta y)$ (8)

Where the x,y and z indicate the corresponding axes and A is the cross sectional area of the waveguide, ω is the phase angle and α & β are arbitrary constants.

Heat transfer:

For an incompressible food material heated under constant pressure, the thermal energy equation is given by equation (9) (Zhou *et al.*,1995)

$$\rho C_p \frac{\partial T}{\partial t} = \nabla.(K\nabla T) + Q \quad (9)$$

Where ρ is the density ($Kg.m^{-3}$), C_p is the specific heat ($kJ.kg^{-1}.K^{-1}$) and K is the thermal conductivity of the material and T is the absolute temperature in Kelvin.

Mathematical Predictions:

The Partial differential equations (PDEs) were solved for the temperature values required for calculating the diffusion coefficient D using Finite difference method (Crank-Nicolson Method) with a 1D approach (Dai, 2006). MATLAB Version 7.5 (Mathworks, USA) was used to solve the PDEs and predict the temperature at any given time.

Rheological Properties:

The Advanced Rheometer AR2000 (TA Instruments, USA) was used to measure the apparent viscosity of the microwave cooked lentils and the results were compared.

RESULTS AND DISCUSSION

Soaking:

Figure 3shows moisture absorption percentage with time. Thus the lentils samples taken out at different soaking times resulted in different initial moisture contents. It is claear from the figure, that there was no significant ($P<0.05$) difference in moisture content of the lentils after 60 mins of soaking.

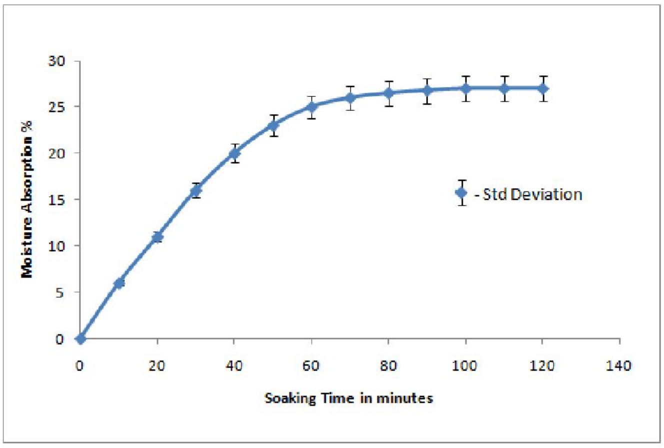


Figure 3: % Moisture absorption versus soaking time

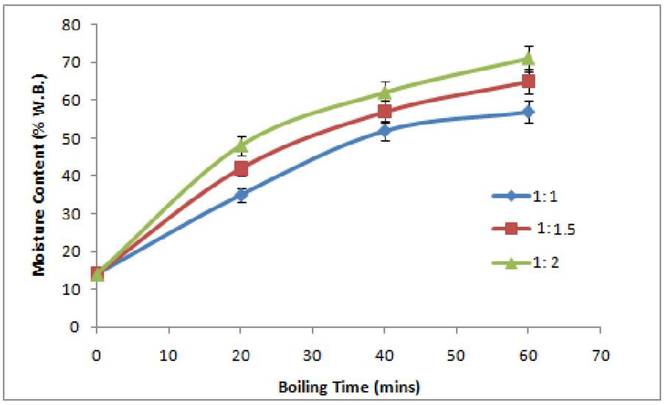
Diffusivity Model:

The diffusion model (Equation (3)) assumes that the moisture movement is driven by the moisture concentration differences. However, moisture normally exists in food materials with three phases: bound water, liquid water, and water vapor (Pang 1996). These three phases are subject to different driving forces. Liquid water may be driven by capillary action (Spolek and Plumb 1981) or water potential (Cloutier and Fortin 1993). Bound water may be driven by chemical potential (Stanish 1986), and water vapor may be driven by vapour pressure difference.

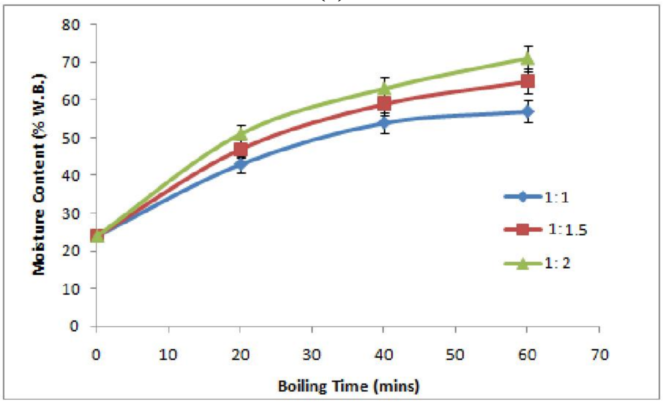
$$D = 2.07 \cdot 10^{-5} \exp\left(-\frac{2577.5\,[K]}{T}\right) \quad [cm^2/s] \tag{3}$$

where T is the absolute temperature.

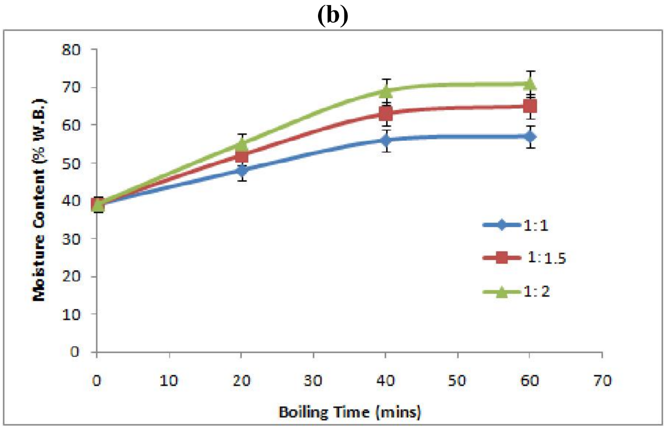
Figure 4 shows the actual moisture content change in lentils with boiling time. Soaking times longer than 60 mins were not taken into account as there was no significant increase in the moisture content for higher soaking times.



(a)



(b)



(c)

Figure 4. Moisture content of the lentils vs MW boiling time after soaking for (a) 0 mins (b) 30 mins (c) 60 mins

Longer the soaking time, smaller the difference in moisture content with respect to the lentil:water ratio. Similarly irrespective of the initial moisture content, the final moisture content is affected only by lentil:water ratio. The maximum moisture content after 60 mins of boiling remained constant. Also the predicted moisture content is in good agreement with the actual data (Figure 5).

Crank (1986) explained the deviation between the model prediction and the measured values from the experiment to be related to the "non-Fickian" or "anomalous" sorption. Therefore, part of the prediction deviation of the model for this experiment may come from the non-Fickian behavior. Despite the above limitations, this diffusion model based on Fick's law showed successful for the moisture absorption process in boiling lentils.

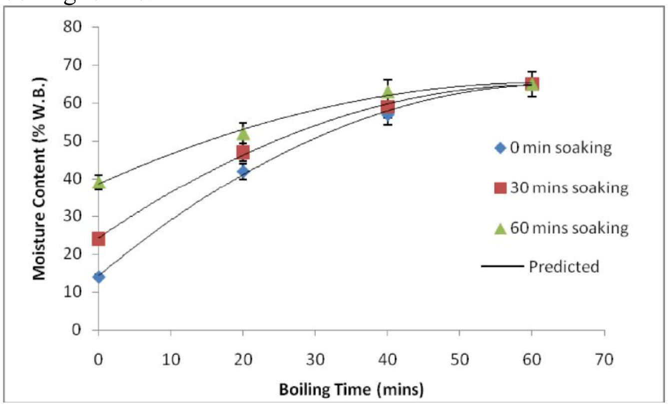


Figure 5: Actual and Predicted moisture content of lentils for different soaking times for 1:1.5 lentil to water ratio.

The lentil to water ratio of 1:1.5 was found to be the optimal as the lentils started charring after 40 mins of boiling for higher ratios and the lentils completely lost their structure and became a colloidal suspension after 40 mins of boiling for lower ratios.

Rheological properties:

Figure 6 shows the variation of apparent viscosity with r.p.m for lentils boiled in the microwaves for 40 mins with 1:1.5 lentil to water ratio. 40 mins of boiling time was found to be optimal as the lentils retained their structure but could be readily mashed and had maximum viscosity for any given lentil to water ratio. Jasim et al. 2009 found similar results for high pressure processed lentils. Also it is clear that the viscosity of the boiled lentils decreased with the soaking time as some of the soluble proteins and starch migrate into the water used for soaking.

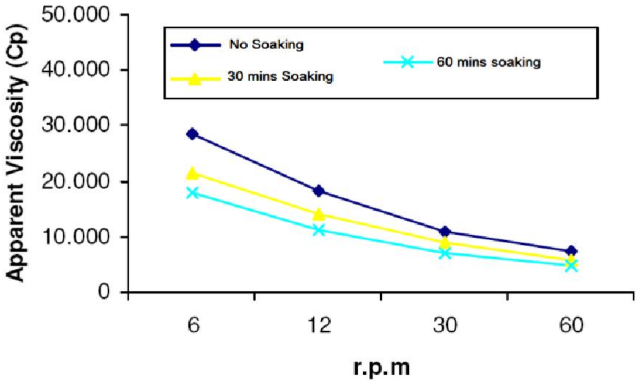


Figure 6: Apparent viscosity of lentils boiled in the microwaves for 40 mins with 1:1.5 lentil to water ratio.

CONCLUSION

Longer the soaking time, smaller the difference in moisture content with respect to the lentil:water ratio. Similarly irrespective of the initial moisture content, the final moisture content is affected only by lentil:water ratio. The maximum moisture content after 60 mins of boiling remained constant. Also the predicted moisture content is in good agreement with the actual data. The viscosity of the boiled lentils decreased with the soaking time as some of the soluble proteins and starch migrate into the water used for soaking. The lentil to water ratio of 1:1.5 and a cooking time of 40 mins was found to be the optimal.

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