7-2012

A coupled mathematical model for simultaneous microwave and convective drying of wheat seeds

Mohamed Hemis
University Center of Khemis Ain Defla

Ruplal Choudhary
Southern Illinois University Carbondale, choudhry@siu.edu

Dennis G. Watson
Southern Illinois University Carbondale, dwatson@siu.edu

Recommended Citation

Hemis, Mohamed, Choudhary, Ruplal and Watson, Dennis G. "A coupled mathematical model for simultaneous microwave and convective drying of wheat seeds." *Biosystems Engineering* 112, No. 3 (Jul 2012): 202-209. doi:10.1016/j.biosystemseng.2012.04.002.

A coupled mathematical model for simultaneous microwave and convective drying of wheat seeds

Mohamed Hemis[1], Ruplal Choudhary[2,*], Dennis G. Watson[2]

[1]University Center of Khemis Miliana, Ain Defla, Algeria
[2] Department of Plant, Soil and Agricultural Systems, MC 4415, Southern Illinois University Carbondale, Carbondale, IL 62901, USA
*Corresponding Author: Ruplal Choudhary, MC 4415, Southern Illinois University Carbondale, Carbondale, IL 62901, USA. Email: choudhry@siu.edu, Phone: 618 203 1017, Fax: 618 453 7457

Abstract

Faster drying techniques are preferred to prevent spoilage of harvested wheat seeds. Microwave (MW) drying may be used as an alternate technique for faster drying of crops with efficient utilization of time and energy. The objective of this study was to develop a mathematical model to simulate the drying condition of wheat seeds during drying in a MW oven. A coupled mathematical model was developed for simultaneous MW and convective drying of wheat seeds in a domestic MW oven, resulting in a system of non-linear equations. Wheat samples with initial moisture levels of 15 to 25% wet basis were dried under MW power ranging from 245 to 910 W for 3 min. The temperature and the relative humidity of drying air was 23 ºC and 27%, respectively. The results revealed that the rate of drying increased with increase in the initial moisture content of wheat seeds. The germination percentage of wheat seeds decreased with the increase of the MW power at each initial moisture content. The predicted temperature of grain during drying with the MW power at 910 W was within the range of 65-70ºC. The experimental results of moisture content of wheat seeds undergoing MW drying were in good agreement with the moisture content of wheat seeds predicted by the coupled mathematical model.

Keywords: microwave drying, convective drying, mathematical modeling, coupled model, wheat seeds.

Nomenclature

A :area, m^2
C : Specific heat of dry air (J kg^{-1} K^{-1})
C_p :Specific heat of grain (J $kg^{-1}.K^{-1}$)
C_v: Specific heat of vapor (J kg^{-1} K^{-1})
C_w: Specific heat of water (J kg K^{-1})
D: Diffusion coefficient of moisture in grain (m^2 s^{-1})
E_{ad}: activation energy (J g^{-1} Mol^{-1})
GI :geometric index
H_v: Latent heat of vaporization (J kg^{-1})
K: Drying constant
k: thermal conductivity of grain (W m^{-1} K^{-1})
k_m: mass transfer coefficient (m s^{-1})
L :half-thickness or radius, (m)
m: moisture content of grain in microwave model (kg [water] kg^{-1} [grain db])
M : Grain moisture content in convective model (kg [water] kg [grain db])
m_e :Equilibrium moisture content in microwave model (kg [water] kg^{-1} [grain db])
M_e: Equilibrium moisture content in convective model (kg [water] kg^{-1} [grain db])
P: power, (W)
P_0: surface power, (W)
R_g: gas constant (J g^{-1} mol^{-1} K^{-1})
RH: Relative humidity (%)
t :Time (s)
t :time, s
T: temperature, C
T_a :Air temperature (C)
T_p: Grain temperature (C)
u: Inlet air velocity (m s^{-1})
V: volume, m^3
W : Absolute humidity of air (kg [water] kg^{-1} [dry air])
x: spatial coordinate, m

Greek symbols

α : attenuation factor, m
ε' : dielectric constant (dimensionless)
ε'' : dielectric loss (dimensionless)
ε : void fraction
λ: wavelength, m
ρ : density, kg m^{-3}
ρ_p : Density of the product (grain) (kg m^{-3})
ρ_a : Density of dry air (kg m^{-3})
σ : Specific surface per unit volume of grain bed (m^2 m^{-3})
ξ : Convection heat transfer coefficient (W m^{-2} C^{-1})

Subscripts

a : air

e : equilibrium
i : position index
inc : incident
ini : initial
n : time index
p : product
sat : saturation
t : total
w: water

1. Introduction

Wheat is one of the most important food crops in North America, with its use as a major ingredient in a variety of food including bread, cake, pasta and pastry. The world wheat production in 2009-2010 was 685.4 Mt and the US wheat production during the same year was 60.3 Mt (USDA-WASDE, 2011). Harvested wheat requires rapid drying for safe storage to prevent respiration, germination, mould damage, and insect infestation. Commonly, hot air is used for drying of wheat in bins or continuous dryers, but low thermal conductivity of grains and case hardening of kernels hinder the efficiency of the process. Microwave (MW) drying has been previously investigated by several researchers as an efficient means of drying wheat seeds as well as wheat grains for food and feed purposes (Campaňa et al., 1986; Campaňa et al., 1993; Manickavasagan et al., 2007; Warchalewski et al., 1998; Vicaş and Mintaş, 2011).
The elevated temperature and time of exposure of wheat during the drying process may adversely affect its end use in the case of grains and germination in the case of seeds. Campaňa et al. (1986) studied the effects of MW irradiation on the germination of wheat. They reported that the use of a temperature below 65ºC does not damage the gluten of wheat, which may be responsible to conserve the viability of wheat seeds. The physical, chemical and baking properties of wheat dried with MW energy were also investigated by Campaña et al. (1993). They found that the baking quality was negatively affected by MW energy, and time of exposure.

The evaluation of wheat grain odour and colour following gamma and MW irradiation was studied by Warchalewski et al. (1998). They found that the sensory evaluation of a grain odour proved that applied treatments with MW energy did not cause significant changes in the grain odour and the total colour difference between MW irradiated samples and the control seed, which were exposed to gradual increases in temperature. Considering examined properties of the grain it can be concluded that both treatments will not change grain quality in terms of odour and colour when extreme doses and irradiation time used in this process are avoided.

Manickavasagan et al. (2007) used a laboratory scale, continuous type, industrial MW dryer (2.45 GHz) to study the germination of wheat grains from uneven MW heating. They compared the percentage of germination of wheat collected from hot-spot and normal heating zones after MW treatment. They observed that at all moisture and power levels, germination percentages were significantly lower for samples collected from hot spots than those from the normal heating zone.

Vicaş and Mintaş (2011) studied the effects of thermal treatment with MW on the germination of wheat seeds to find the optimum formula between applied energy and material humidity so that the material can be dried without its structure being affected. They concluded that the use of a constant temperature and constant humidity had a great influence on the germination rate of wheat and the use of an air stream is very important to eliminate the water from the grain and to avoid the hot spots, so there could be a uniform temperature in the whole mass of the product. The combination of MW energy and convective air drying may eliminate the disadvantages associated with the application of each method alone.
Mathematical models of convective drying of wheat were reported by Aregba et al. (2006). Hemis et al. (2009) used a coupled heat and mass transfer model for the prediction of drying characteristics of wheat under convective air drying. The MW drying model which was developed by Campanone et al. (2001, 2005) was used by Hemis et al. (2011) for wheat seeds. The MW model was able to predict the drying characteristics of granular crop products. However, the MW drying model used by the above authors did not include parameters of drying air, change in density of air, change in thermal conductivity of the dried product and the effect of relative humidity on the drying process. In this study, we attempted to combine convective air drying model with the MW model because the MW ovens have fans that move air through the oven. Accordingly, a coupled model was developed in this study by coupling the models for mass and energy balance in MW drying with the mass and energy balance in convective air drying. Our objective was to develop a realistic model of MW drying by coupling the mathematical model of MW drying and convective drying to predict the drying characteristics of US soft red winter wheat.

2. Mathematical Modeling

2.1 Microwave drying:

To model the MW drying, a mathematical model described by Campaňa et al. (2001) and used by Hemis et al. (2011) was adopted in this study. The mathematical model was developed based on the following assumptions in the MW modeling: (1) uniform initial temperature and moisture distribution in a wheat kernel, (2) temperature dependent thermal and dielectric properties of wheat kernel, (3) fixed kernel volume and bulk density, (4) convective boundary conditions, (5) moisture migration by diffusion, and (6) elliptical geometry of kernels.

The energy balance during MW drying can be expressed as (Campanone et al., 2005):

$$V\rho Cp\frac{\partial T}{\partial t} = V\left(\nabla k \nabla T\right) + P \tag{1}$$

where, ρ is the bulk density of wheat (kg m^{-3}), C_p is specific heat capacity (J kg^{-1} K^{-1}), T is temperature (°K), t is time (s), k is thermal conductivity of wheat (W m^{-1} K^{-1}), V is wheat kernel volume (m^3) and P is the MW power absorption by wheat (W).

Equation 1 can be expressed in terms of generic product shape index called GI (0 for slabs, 1 for infinite cylinders and 2 for spheres) as follows:

$$V\rho Cp\frac{\partial T}{\partial x} = V\frac{\partial k}{\partial x}\frac{\partial T}{\partial x} + Vk\frac{\partial^2 T}{\partial x^2} + VGI\frac{k}{x}\frac{\partial T}{\partial x} + P \tag{2}$$

where, x is the radial coordinate.

In order to solve the above equation, the following assumptions for the boundary conditions were taken:

$$t = 0 \qquad T = T_{ini} \qquad 0 \le x \le L \tag{3}$$

$$x = 0 \qquad -k\frac{\partial T}{\partial x} = 0 \qquad t > 0 \tag{4}$$

$$x = L \qquad -k\frac{\partial T}{\partial x} = \xi(T - T_a) \tag{5}$$

Where, L is half-thickness (m), T_{ini} is initial temperature (°K), ξ is heat transfer coefficient (W m^{-2} K^{-1}), T_a is ambient temperature (°K).

The absorption of MW energy was calculated by Lambert´s law governed by the following equation given by Swami et al. (1982):

$$P = P_o e^{(-2\alpha(L-x))} \tag{6}$$

Where, P_o is the power at the surface (W) which was determined by calorimetric method (Lin et al., 1995) for each power level. The determined powers (P_o) were 910, 490, and 245 W for P10, P5, and P3 power levels, respectively. These P_o values were used in solving the mathematical model. α is the attenuation factor which is a function of the dielectric constant ε' and loss factor ε'' given by Nelson et al. (2000):

$$\alpha = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon'\left[(1+\tan^2\delta)^{1/2} - 1\right]}{2}} \tag{7}$$

$$\delta = \tan^{-1}\left(\varepsilon''/\varepsilon'\right)) \tag{8}$$

λ is the wavelength of MWs in free space with λ = 122.4 mm at 2450 MHz frequency and T_a=20°C.

The thermal and dielectric properties of wheat were obtained from literature and are shown in Table 1. To predict the moisture content profile of wheat during MW drying, a microscopic mass balance equation was developed based on the assumption of moisture migration from inner part of grain by diffusion process. The governing equation is:

$$\frac{\partial m}{\partial t} = \nabla(D\nabla m) \tag{9}$$

The boundary conditions applied to solve Eq. (9) are:

$$t = 0 \qquad m = m_{ini} \qquad 0 \le x \le L \tag{10}$$

$$x = 0 \qquad \frac{\partial m}{\partial x} = 0 \qquad t > 0 \tag{11}$$

$$x = L \qquad -D_w \frac{\partial m}{\partial x} = k_m^{'}(m - m_e) \qquad t > 0 \tag{12}$$

where, m and m_e are the moistur content at a given time t and equilibrium moisture content, respectively (kg [water] kg^{-1} [dry matter]). k_m is mass transfer coefficient (m s^{-1}).

The equilibrium moisture content of wheat for MW modelling was calculated by the following equation given by Salek et al. (1984):

$$m_e = \frac{m_1 + m_2 - m_3^2}{m_1 + m_2 - 2m_3} \tag{13}$$

where, m_1, m_2 and m_3 are the moisture content values at times t_1, t_2 and t_3, respectively. The time intervals are equally spaced such that $0.5(t_1+t_2)=t_3$.

The diffusion coefficient of wheat was calculated from the following equation given by Aregba et al. (2006):

$$D = D_0 Exp(-\frac{E_{ad}}{R_g(T_p + 273.16)}) \tag{14}$$

where, D_0 is the pre-exponential factor for diffusion which is equal to 7.68x10^{-3} m^2 s^{-1}, E_{ad} is the activation energy of diffusion for the wheat which is equal to 51080 J g^{-1} mol^{-1} and R_g is gas constant which is equal to 8.314511 J g^{-1} mol^{-1} K^{-1}.

2.2 Convective Drying model:

With convective drying by air, there are four major parameters which affect the drying behaviour of grain in a deep bed, namely, grain moisture, air humidity, grain temperature and air temperature. These parameters vary with drying time and bed height. In the case of a static deep bed drying, following assumptions were made:

1. Uniform gain temperature and negligible heat conduction between grain kernels;

2. Negligible heat transfer between dryer walls and surrounding atmosphere;

3. Constant bulk density and heat capacities of grain and drying air;

4. No moisture migration between grains;

5. Thin layer drying equation describing the moisture evaporation from grain is known;

6. Constant air velocity and constant air pressure.

This model uses a system of partial differential equations composed of three coupled equations governing conservation of mass, energy of air, energy of grain and a fourth thin-layer grain drying kinetic equation.

The equation of conservation of mass

$$\rho_a \varepsilon (\frac{\partial W}{\partial t} + u \frac{\partial W}{\partial x}) = -(1 - \varepsilon)\rho_p \frac{\partial M}{\partial t} \tag{15}$$

with

$$\begin{aligned} T_a &= T(x,t); \\ T_p &= T_p(x,t); \\ M &= M(x,t); \\ W &= W(x,t) \end{aligned}$$

The equation of energy for air:

$$\rho_a (C + C_v W)\left(\frac{\partial T_a}{\partial t} + u\frac{\partial T_a}{\partial x}\right) = \frac{\xi\sigma(T_p - T_a)}{\varepsilon} \tag{16}$$

The equation of energy for the product:

$$\rho_p (C_p + C_w M)\frac{\partial T_p}{\partial t} = \frac{\xi\sigma}{1-\varepsilon}(T_a - T_p) - (H_v + C_v(T_a - T_p))\frac{\rho\varepsilon.u}{1-\varepsilon}\frac{\partial W}{\partial x} \tag{17}$$

The equation of mass conservation was used in the absence of condensation, corresponding to the criterion:

$$W < W_{sat}(T_s) \tag{18}$$

If the above criterian was not satisfied, then the absolute humidity (W) was taken as the saturated absolute humidity ($W_{sat}(T_s)$) at the same temperature.

Lewis (1921) had proposed that the rate of drying was directly proportional to the difference between the moisture content of dried material and the equilibrium moisture content of the same material at equilibrium with the ambient air. Therefore, the equation of thin layer drying of wheat can be written as:

$$\frac{\partial M}{\partial t} = (T, W, M) \tag{19}$$

$$\frac{\partial M}{\partial t} = -K(M - M_e) \tag{20}$$

$$K = K(T) \tag{21}$$

$$M_e = M_e(W, T) \tag{22}$$

The drying process of wheat is governed by the kinetic equation of drying. The values of constants K and M_e were calculated by the Eqs. (23) and (24), respectively. These coefficients are functions of temperature and humidity of drying air.

For wheat, the value of K was taken from O'Callaghan et al. (1971) as:

$$K = 2000\exp\left(\frac{-5094}{T + 273}\right) \tag{23}$$

The equilibrium moisture content was determined using the modified Oswin Eq. (24) and the coefficients A, B and C for wheat were taken from Hemis et al. (2009):

A= 9.671×10^{-6}; B=0.0004; C=2.671;

$$M_e = \frac{(9.671\times10^{-6} + 0.0004T)}{(100RH - 1)^{(1/2.671)}} \tag{24}$$

2.3 Coupling the microwave and convective drying models:

Two models were coupled as follows: The final moisture content predicted by the MW model in the first time step was taken as the initial moisture content input for the convective model, and the equilibrium moisture content for the calculation of the MW model in the second step was taken from the equilibrium moisture content value predicted by the convective model. Mathematically, it can be expressed as:

$$\begin{array}{lll} t > 0 & M_{in} = m & 0 \le x \le L \\ t > 0 & m_e = M_e & 0 \le x \le L \end{array} \tag{25}$$

The system of non-linear partial differential equations obtained by coupling the two models with the use of Eq. (25), was solved using Crank-Nicolson finite differential method by developing a code in MATLAB (Version 8.4.0.471, R2008b, The MathWorks Inc, Natick, MA, USA).

3. Materials and methods

3.1 Samples preparation

An experimental study was conducted using a US soft red winter wheat of an initial moisture content of 12.4% wet basis (wb). Wheat was moistened with addition of a calculated amount of water and storied in a refrigerator in a moisture-tight bag to obtain three initial moisture contents of 15, 20 and 25% wb

3.2 Drying procedure

A domestic MW oven (GE, Turntable MW oven, Malaysia) with a frequency of 2.45 GHz was used to study the drying of wheat seeds. It had 1550 W of rated power and 910 W of absorbed power at the MW power level P10. A drying pan made of a Teflon petridish with 50 mm diameter and 15 mm height was suspended from a digital balance by a fine fishing wire to acquire its weight at different time intervals during drying (Fig. 1). The absorbed power was measured by the method, given by Buffler (1993), of temperature elevation of water contained in two one-litre beakers. Before starting the MW drying experiment, the absorbed power of the MW was determined at three levels: (1) high MW power level, P10; (2) medium MW power level, P5; and (3) a lower MW power level, P3.

The experiment included nine treatments consisting of three MW power levels (P10, P5 and P3) and three initial moisture contents (15, 20 and 25%wb), and the experiment was replicated three times. For each treatment, the time of drying was 180 s.

3.3 Germination test

From each drying treatment, 25 grains were placed in a Petri plate with filter paper and 10 ml of water was added. After 7 days, the number of germinated seeds was counted.

***3.4 Statistical analysis*:** The degree of fitness of the coupled model for prediction of moisture content was evaluated by coefficient of determination (R^2) values for each sample using the statistics function included in Microsoft Excel 2010.

4. Results and Discussions

4.1 Experimental results

Figure 2 shows the experimental results for MW drying of soft red winter wheat seed with initial moisture content of 15% (wb) at three power levels. As expected, the P3 had slower drying than the P5 and P10. Loss of moisture increased in proportion with the MW power level. The difference in moisture contents between power levels increased with increase in time. At the end of 180 s of drying, the initial moisture content was reduced to 12.0%, 5.8% and 0.5%, respectively.

Figure 3 shows the effect of experimental results of MW drying of soft red winter wheat seed with 20% (wb) initial moisture content. A similar effect of power level was observed with 15% wheat. The P3 power level had slower moisture loss than the P5 and P10. The effect of power level on moisture contents increased with increase in time. At the end of 180 s of drying, the initial moisture content of 20% was reduced to 16.5%, 12.0% and 9.0% respectively. The effect of power level was lower in this case compared to the sample with 15% initial moisture where the difference between final moisture contents at different power levels was higher.
Figure 4 shows the drying characteristics of wheat with 25% initial moisture content. Similar effect of MW power was observed for this sample as with the 15% and 20% samples. The final moisture content reached after 180 s of drying were 21.5%, 14.0% and 7.0% for the P3, P5 and P10 power levels respectively. Comparing the percentage reduction of moisture at P3 power level, the sample with initial moisture content of 15, 20, and 25 % had moisture loss of 80%, 82.5% and 86%. Thus the percentage water loss increased with increase in the initial moisture content of wheat.
Figure 5 shows the comparison of experimental value of moisture loss with the predicted values of moisture loss using the coupled model at the power level P3. The developed model predicted the moisture loss with a high coefficient of determination, i.e. the R^2 values of 0.91, 0.95 and 0.94 for samples with initial moisture content of 25, 15, and 20 % respectively. This clearly demonstrates that the developed model was able to predict the drying of wheat very well.

4.2 Simulated results of the coupled model of microwave drying and convective drying of wheat

The model predicted drying characteristics of wheat samples dried at power level P10 is shown in Fig. 6. This result was predicted by the model for a MW power of 910 W, sample volume of 0.000038 m^3 and absolute humidity of 0.0124 kg [water] kg^{-1} [dry air] at air velocity of 0.1 m s^{-1}.

All the samples reached equilibrium moisture content within 200 s. Figure 7 shows the model predicted relation between drying rate and moisture content as predicted by the coupled model. The shapes of these curves are significant and indicate that the drying rate increased rapidly with initial time until a peak constant rate period and then decreased slowly. The initial rate of rise of drying rate indicates initial heating period before water molecules started to evaporate from the sample. The peak drying rate was highest for the 25% initial moisture content sample, followed by the 20% and 15% initial moisture content samples. Figure 8 shows the comparison of drying characteristics of wheat seeds as predicted by the coupled model and the MW model, without considering the effect of convective drying by air. Compared to only MW, the coupled model predicted a slower drying than the MW drying. This may be due to the cooling effect of air taken into consideration with the coupled model. Thus it is expected that the combined MW and convective drying will be slower than MW drying without air circulation. Figure 9 shows the comparison of predicted temperatures of wheat by the two models at different times of drying. The coupled model predicted a lower temperature of wheat than the MW model. This shows that the temperature of the wheat undergoing MW drying can be controlled by supplying a controlled dose of convective air. This will help to protect the viability of seeds. The germination test conducted to test the viability of seeds revealed that the viability of wheat seeds was lost at MW powers P5 and P10. Only the MW power level P3 (245 W) had germination for all moisture levels. The percentage germination for 15%, 20% and 25% initial moisture sample was 36%, 12% and 8%, respectively. Thus it is recommended that the seeds should not be exposed for long periods of time in MW to preserve their viability. Within the parameters of this study, the power level P3 with an exposure time of less than 2 min is recommended for safe drying of soft red winter wheat.

5. Conclusion

The coupled model developed in this study predicted the behaviour of MW drying of soft red winter wheat very well. The drying rates increased with initial moisture content of wheat. The predicted temperature of wheat was lower in the case of coupled model than the isolated MW model. Higher MW power caused increased drying rate of wheat seeds but at higher power levels the viability of seeds were lost. Wheat dried using MW power levels P10 (910 W) and P5 (490 W) caused loss of wheat germination. Drying at P3 power level (245 W) gave good drying rate without causing germination loss. The simulated result showed that the use of MW power of 245 W (P3) is sufficient to dry the wheat in a MW oven without damaging the quality of this product.

Acknowledgement

Thanks to the University Center of Khemis Miliana for support given to Dr. Hemis to conduct this research study at Southern Illinois University. Wheat seeds were provided by the Southern FS, Murphysboro, IL, USA. Matlab software was provided by Dr. Lalit Gupta, Professor of Electrical Engineering, Southern Illinois University, Carbondale, IL, USA.

References

Aregba, A.W., & Nadeau, J.P. (2006). Comparison of two non equilibrium models for static grain deep bed drying by numerical simulation. *Journal of Food Engineering*, 77 (1), 27–40.

Buffler, C.R. (1993). Microwave cooking and processing. *Engineering fundamentals for the food scientist.* Van Nostrand Reinhold, New York, NY.

Campaňa, L.A., Sempe, M.E. and Filgueira, R.R. (1986). Effect of microwave energy on drying wheat. *Cereal Chemistry*, 63, 271-273.

Campaña, L.A, Sempé, M.E. & Filgueira, R.R. (1993). Physical, chemical and baking properties of wheat dried with microwave energy. *Cereal Chemistry*, 70, 760-763.

Campanone, L.A., Salvadori, V.O., & Mascheroni, R.H. (2001). Weight loss during freezing and storage of unpackaged foods. *Journal of Food Engineering*, 47, 69-79.

Campanone, L.A. & Zaritzky, N.E. (2005). Mathematical analysis of microwave heating process. *Journal of Food Engineering*, 69, 359–368.

Hemis, M., Bettahar, A., Singh, C. B., Bruneau, D. & Jayas, D. S. (2009). An experimental study of wheat drying in thin layer and mathematical simulation of a fixed-bed convective dryer. *Drying Technology*, 27(10), 1142-1151.

Hemis, M., Singh, C. B. & Jayas, D. S. (2011). Microwave-assisted thin layer drying of wheat. *Drying Technology*, 29(10), 1240-1247.

Lewis, W.K. (1921).The rate of drying of solid materials. *Journal of Industrial and Engineering Chemistry*, 13(5), 427-432.

Manickavasagan, A., Jayas, D.S. & White, N.D.G. (2007). Germination of wheat grains from uneven microwave heating in an industrial microwave dryer. *Canadian Biosystems Engineering*, 49(3), 23-27.

Nelson, S.O., Kraszewski, A.W., Trabelsi, S., & Lawrence, K.C. (2000). Using cereal grain permittivity for sensing moisture content. *IEEE Transactions on Instrumentation and Measurement*, 49(3), 470–475.

O'Callaghan, J.R., Menzies, D.J., & Bailey, P.H. (1971). Digital simulation of agricultural drier performance. *Journal of Agricultural Engineering Research*, 16(3), 223–244.

Salek, J., & Villota, R. (1984). A comparative study of whirling and conventional fluidized beds in their application to dehydration. I. Heat and mass transfer analysis. *Journal of Food Processing and Preservation*, 8(2), 73–98.

Swami, S. (1982). Microwave heating characteristics of simulated high moisture foods. MS Thesis. USA: University of Massachusetts.

Tavman, S., & Tavman, I.H. (1998). Measurement of effective thermal conductivity of wheat as a function of moisture content. *International Communications in Heat and Mass Transfer*, 25(5), 733–741.

USDA-WASDE. 2011. World agriculture supply and demand estimates. WASDE-501. Approved by the World Agricultural Outlook Board. United States Department of Agriculture. Available online: http://www.usda.gov/oce/commodity/wasde/latest.pdf. Accessed Dec. 18,2011.

Vicaş S., & Mintaş O. (2011). Parameter variation of wheat seeds dried in microwave field. *Journal of Electrical and Electronics Engineering,* 4(1), 237-240.

Warchalewski, J., Gralik, J., Zawirska-Wojtasiak, R., Zabielski, J., & Kuśnierz, R. (1998). The evaluation of wheat grain odour and colour after gamma and microwave irradiation. *Electronic Journal of Polish Agricultural Universities*, 1(1), #04. Available Online: http://www.ejpau.media.pl/volume1/issue1/food/art-04.html. Accessed Dec. 1, 2011.

Figure Caption

Fig. 1. Depiction of apparatus used in this investigation; (1) electronic balance; (2) Plate (Teflon) D=70mm; (3) domestic MW oven.

Fig. 2. Drying kinetics of winter soft wheat at 0.15 (kg [water] kg^{-1} [grain wb]) initial moisture content at three MW power levels (P3, P5 and P10).

Fig. 3. Drying kinetics of winter soft wheat at 0.20 (kg [water] kg^{-1} [grain wb]) initial moisture content at three MW power levels (P3, P5 and P10).

Fig. 4. Drying kinetics of winter soft wheat at 0.25 (kg [water] kg^{-1} [grain wb]) initial moisture content at three MW power levels (P3, P5 and P10).

Fig. 5. Comparison between predicted data by the coupled model and experimental moisture loss result during MW drying of wheat at three initial moisture content of 0.15, 0.20 and 0.25 kg [water] kg^{-1} [grain wb]

Fig. 6. Evolution of moisture content predicted by the coupled model under the conditions of power level P10 (absorbed power = 910W), volume of sample V = $0.000038m^3$, absolute humidity of air W=0.0124 kg [water] kg^{-1} [dry air], and velocity of air v = 0.1m s^{-1}. (mi = initial moisture content).

Fig. 7. Evolution of drying rate of wheat drying under the conditions of drying of MW power P10 at three initial moisture contents.

Fig. 8. Comparison between the predicted values of moistures content by the coupled model and MW model under the conditions of MW power level P10 (absorbed power = 910W), and initial moisture content of 0.20 kg [water] kg^{-1} [grain wb]

Fig. 8. Comparison between the predicted values of moistures content by the coupled model and MW model under the conditions of MW power level P10, initial moisture content 0.20 kg [water] kg^{-1} [grain wb].

Fig. 9. Comparison between the temperatures of wheat predicted by the coupled model and the microwave model under the condition of the MW power level P10 (absorbed power = 910 W).

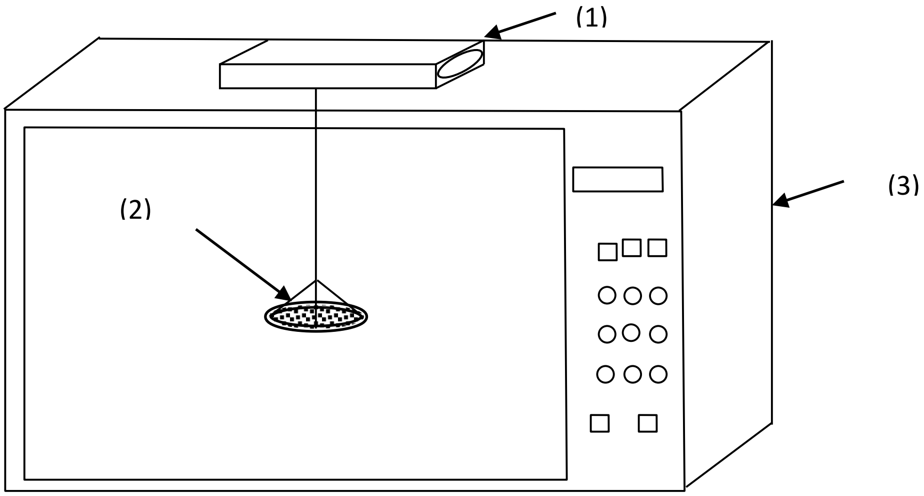

Fig. 1 Diagram of apparatus used in this investigation; (1) electronic balance; (2) plate (Teflon) D=70mm; (3) domestic MW oven

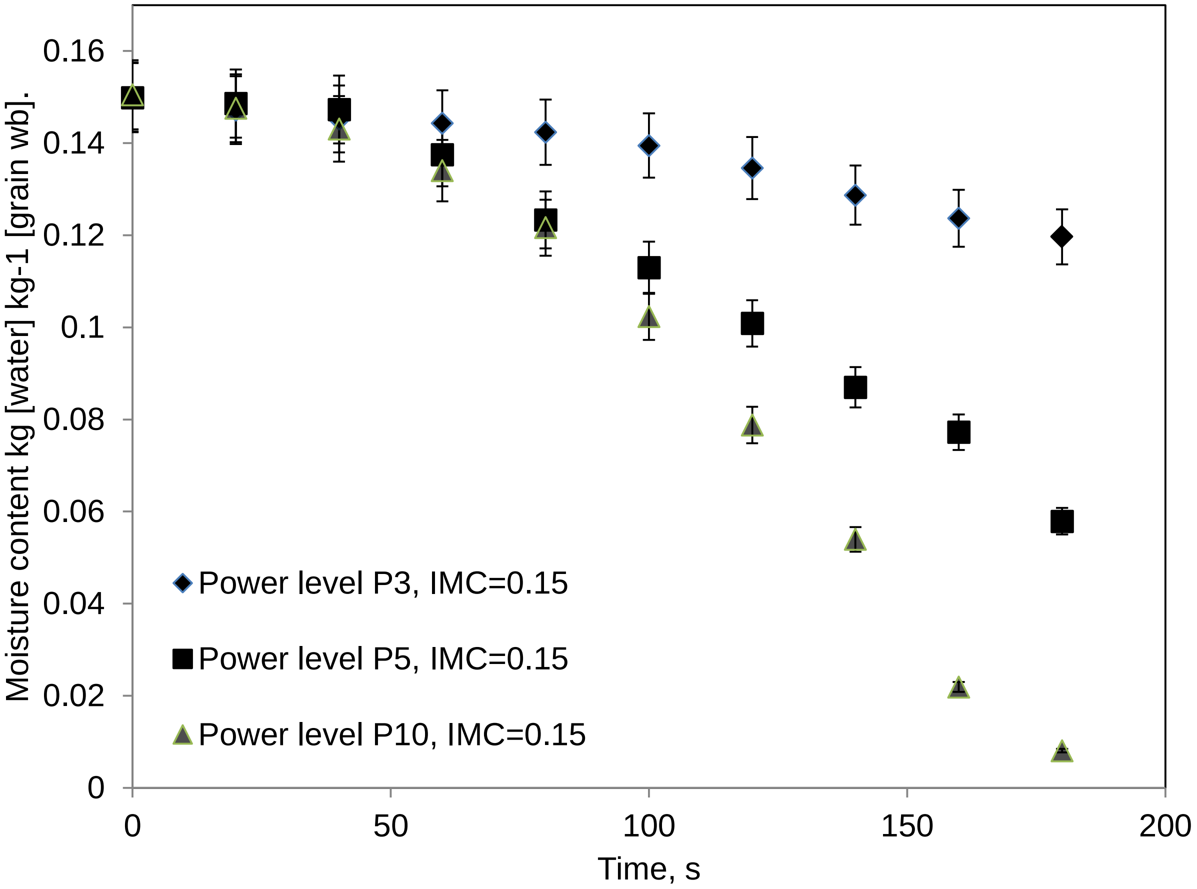

Fig. 2. Drying kinetics of winter soft wheat at 0.15 (kg [water] kg^{-1} [grain wb]) initial moisture content at three MW power levels (P3, P5 and P10). [IMC = initial moisture content].

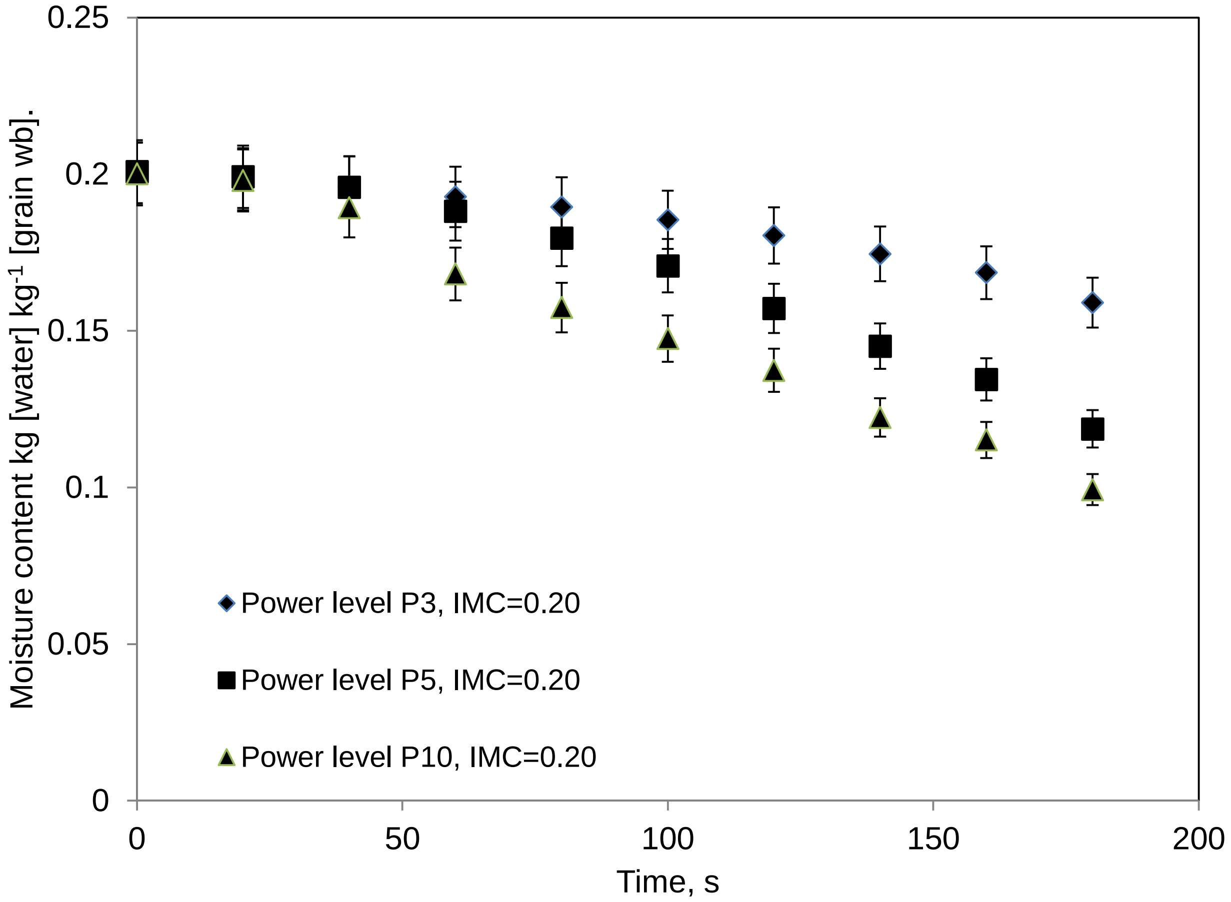

Fig. 3. Drying kinetics of winter soft wheat at 0.20 (kg [water] kg^{-1} [grain wb]) initial moisture content at three MW power levels (P3, P5 and P10). [IMC = initial moisture content].

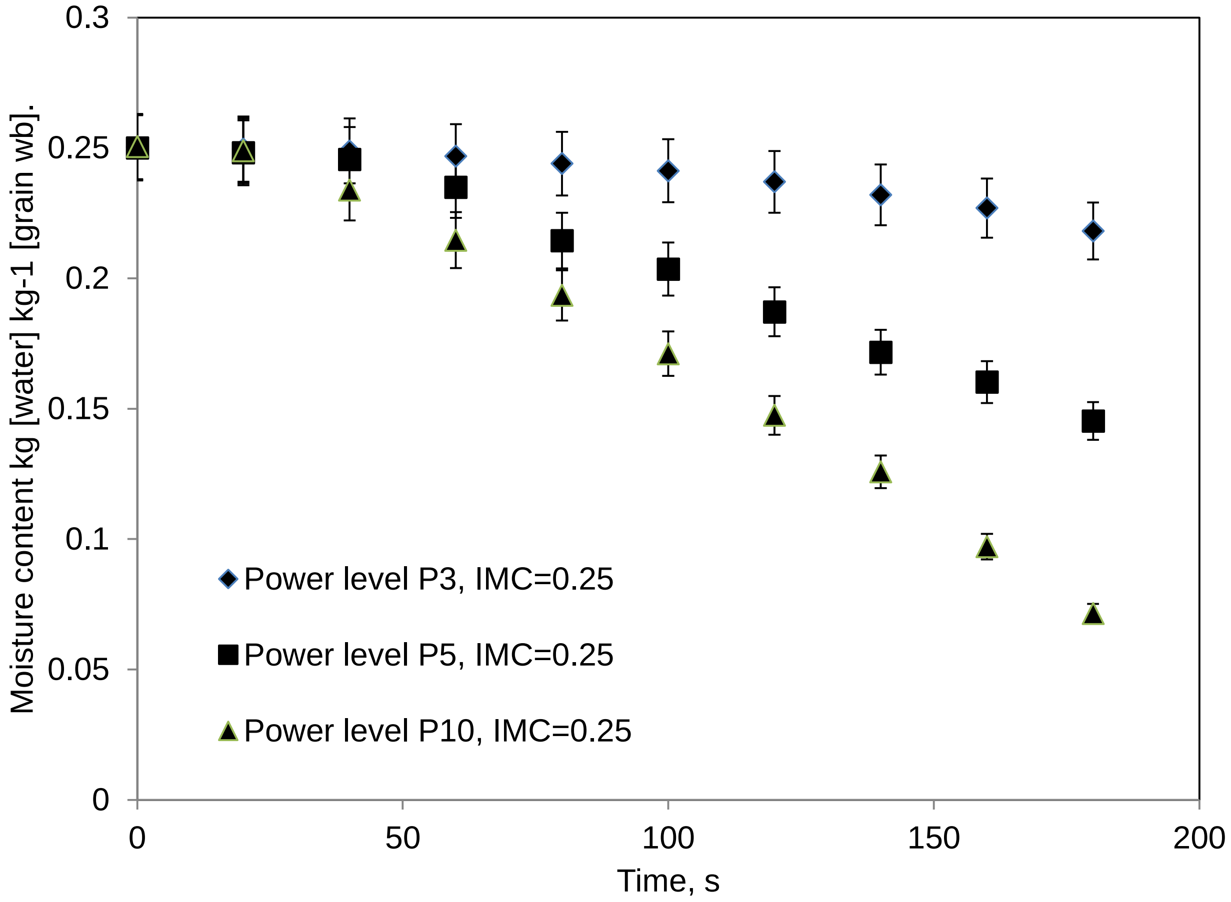

Fig. 4. Drying kinetics of winter hard wheat at 0.25 (kg [water] kg^{-1} [grain wb]) initial moisture content at three MW power levels (P3, P5 and P10). [IMC = initial moisture content].

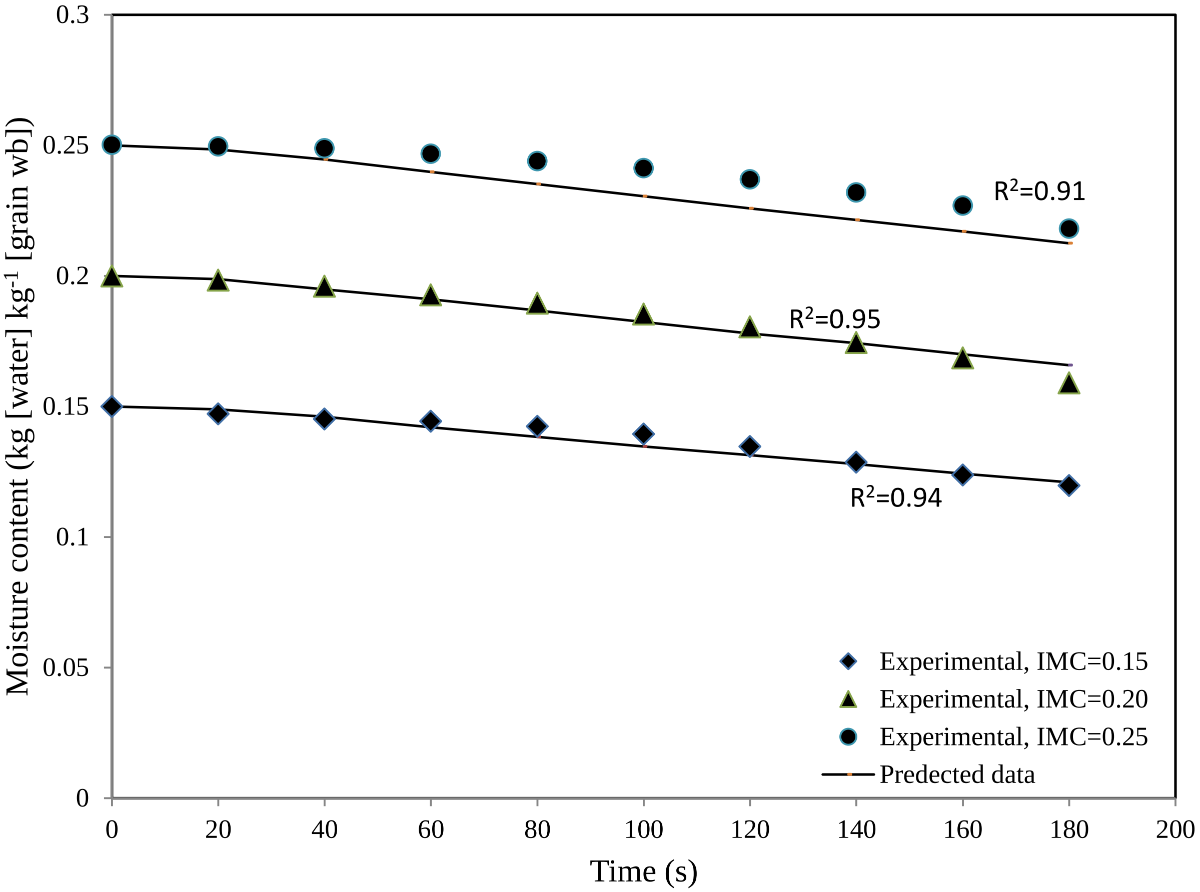

Fig. 5. Comparison between predicted data by the coupled model and experimental moisture loss result during MW drying of wheat at three initial moisture content of 0.15, 0.20 and 0.25 kg [water] kg^{-1} [grain wb]. [IMC = initial moisture content].

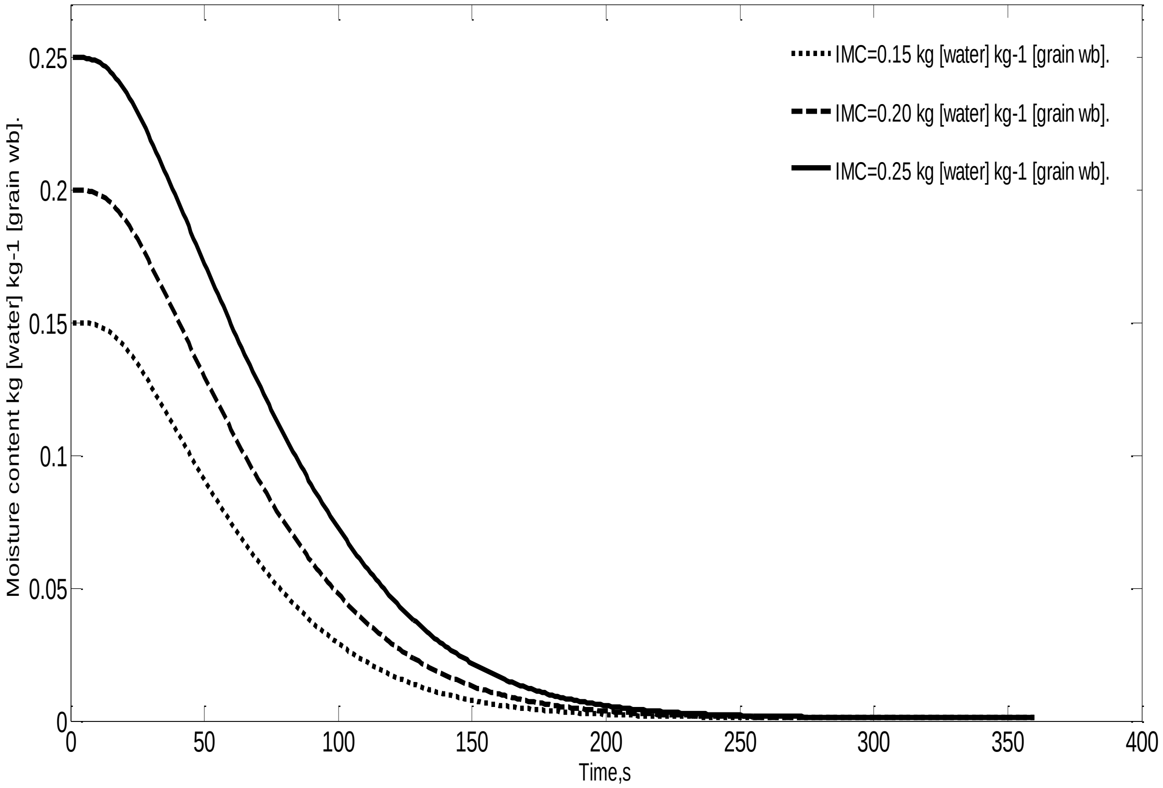

Fig. 6. Evolution of moisture content predicted by the coupled model under the conditions of power level P10 (absorbed power = 910W), volume of sample V = 0.000038 m^3, absolute humidity of air W=0.0124 kg [water] kg^{-1} [dry air], and velocity of air v = 0.1 m s^{-1}. [IMC = initial moisture content]. [IMC = initial moisture content].

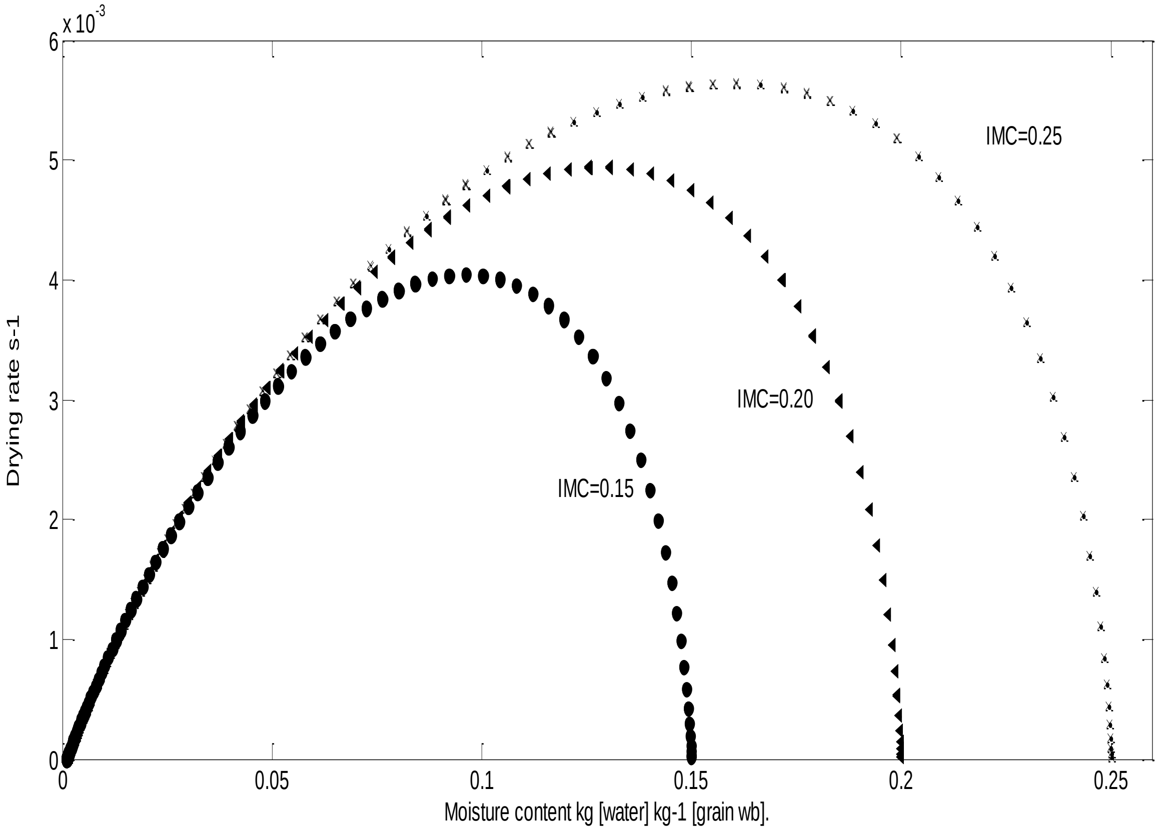

Fig. 7. Evolution of drying rate of wheat drying under the conditions of drying of MW power P10 at three initial moisture contents. [IMC = initial moisture content].

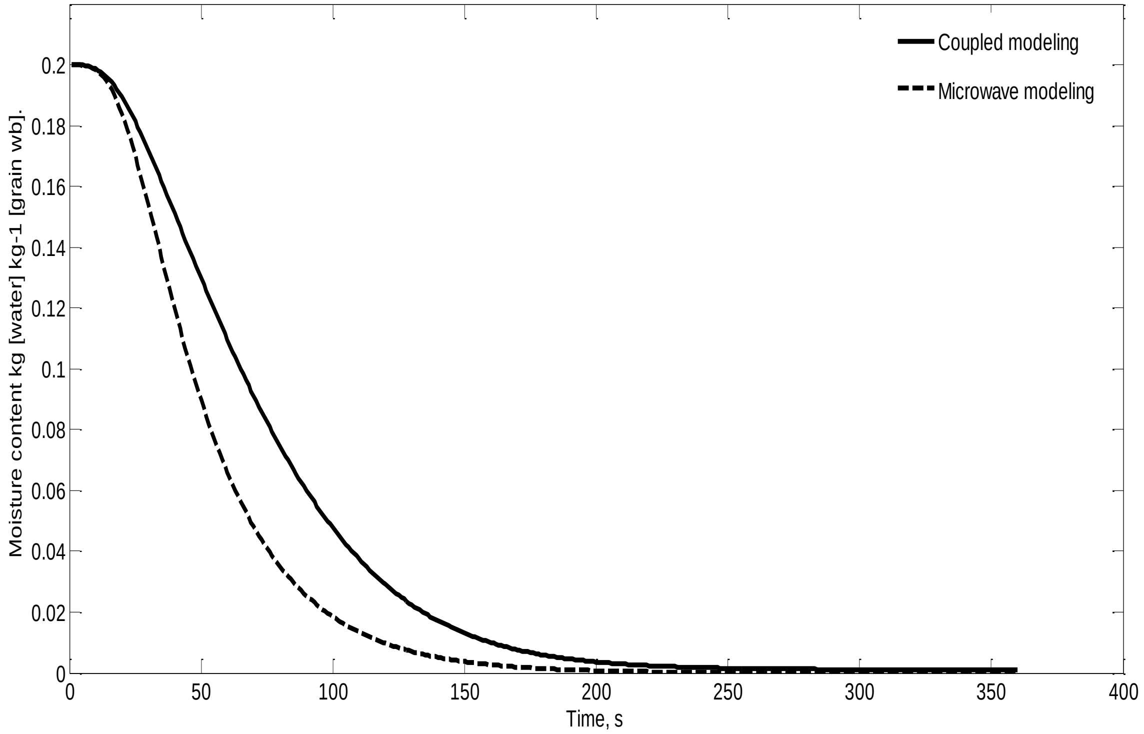

Fig. 8. Comparison between the predicted values of moistures content by the coupled model and MW model under the conditions of MW power level P10 (absorbed power = 910W), and initial moisture content of 0.20 kg [water] kg^{-1} [grain wb].

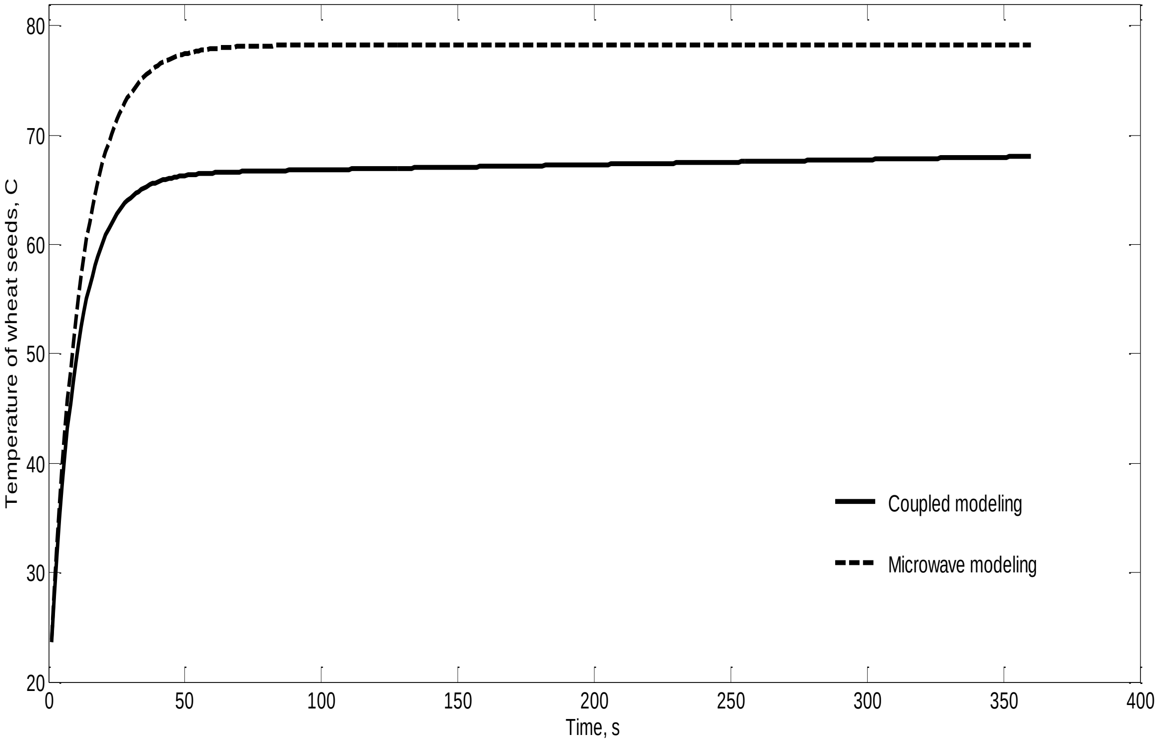

Fig. 9. Comparison between the temperatures of wheat predicted by the coupled model and the microwave model under the condition of the MW power level P10 (absorbed power = 910 W).

Table 1. Physical, thermal and electromagnetic properties of wheat

Property	Wheat characteristics	References
Bulk Density ρ (kg m^{-3})	800	This work
Thermal Conductivity k (W m^{-1} °C^{-1})	$k=0.14299+0.001264.m$	Tavman et al. (1998)
Specific Heat Cp (J (kg^{-1} ºC^{-1})	1300	Aregba and Nadeau (2007)
Dielectric Constant ε´(dimensionless)	2.89	Nelson et al. (2000)
Dielectric Loss Factor ε” (dimensionless)	0.35	Nelson et al. (2000)