Numerical Simulation of the Heat, Mass and Momentum Transfer during the Microwave Drying of Osmodehydrated Porous Material

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Abstract: Recent studies have been devoted to develop mathematical models to simulate food processing using the porous media approach. The aim of this study is to simulate the microwave drying of osmodehydrated food by means of modeling the mass, energy and momentum transfer using the porous media approach. Microwave drying involves complex physical mechanisms which should be taken into account in the complete mathematical model. Diffusion and convection, Maxwell-Stefan diffusion, Darcy's flow and conduction and convection were considered in order to model the mass transfer of liquid-water, water-vapor, pressure buildup and heat transfer, respectively. A complete and complex model was obtained and simulated using COMSOL Multiphysics software. In this manner, this paper presents a new application in food processing to model the microwave drying of osmodehydrated material using a porous media approach.

Keywords: Modeling, microwave-drying, porous-material, heat-mass-momentum transfer, osmodehydrated foods.

1. Introduction

Osmotic dehydration has the ability to protect food for further drying treatments, decreasing the losses in volatile compounds and the risk of chemical and physical changes (Arballo et al. 2012a). To complete the drying process and obtain a stable product, a further procedure such as microwave drying is necessary.

In recent years the microwaves have been used in the food processing industry as a result of the advantages with respect to conventional treatments: less environmental impact related to the use of clean energy and low energy consumption and short processing time, and saving in location space. In the food industry their uses include: thawing, pasteurization, sterilization, heating, blanching, cooking, baking and drying.

The above mentioned advantages are due to the microwaves have the ability to penetrate and heat within the materials. The microwaves are propagated in the form of an electromagnetic field that interact with the polar molecules (mainly water molecules) of the irradiated material and generate initially its heating (Campañone and Zaritzky 2005). When the microwave heating progresses, promotes the water vaporization and the removing of inner water is enhanced by increasing water-vapor pressure and forcing the vapor toward the surface (Datta and Anantheswaran 2001).

With respect to calculation of the increase in temperature it is necessary to obtain the absorbed microwave power inside the material due to the interaction between electromagnetic field and food. The Maxwell's equations describe the electromagnetic distribution inside the microwave ovens, empty or loaded. Nowadays, two modeling lines have been followed to predict the absorbed microwave energy inside the food: solving the Maxwell's equations (Dinčov et al. 2004) or the use the Lambert's Law which is an approximate description (Sanga et al. 2002).

Moreover, water migration during microwave drying is a complex phenomenon that involves different means such as diffusion of liquid-water and vapour, capillary flow, binary diffusion, and hydrodynamic flow produced by inner pressure buildup (Datta, 2007).

With the purpose to gain a better understanding about those complex phenomena involved in the microwave drying of osmodehydrated foods it is necessary to obtain a complete model and simulate the process under various conditions and additionally has to consider the change in dielectric properties due to osmotic pretreatment. In this way, the porous media models usually associate energy, mass, and momentum transport equations with all thermodynamic interactive fluxes. Several researchers have used this approach to model the microwave drying process (Salagnac et al. 2004; Datta 2007).

To model the changes in temperatures, moisture content and inner pressure during the microwave drying of food material is necessary to solve the mass, energy and momentum balances. These balances with their boundary conditions form a system of nonlinear partial differential equations that are highly coupled. Due to the complexity of the equations system it is necessary the implementation of a numerical technique, in the present work it will be used the finite element method implemented in COMSOL Multiphysics.

Taking into account the considerations expressed so far the objective of this research work is to develop a complete mathematical model to simulate the heat, mass and momentum transfer during the microwave drying of osmodehydrated foods.

2. Model Development

In the development of the mathematical model the food material can be considered as a combination of a solid matrix, an aqueous phase, and a gaseous phase (air and water vapour).

To simulate the microwave drying process a complete mathematical model has to allow solving the heat, mass and momentum transfer simultaneously, at the same time considering an internal vaporization due to the inner heat generation of microwaves. The following assumptions were made when developing the mathematical model:

. Constant pressure at the surface;

. Surface vapour flux by convection;

. Liquid water flux depends on total pressure and porous-media capillary forces;

. Vapour flux depends on pressure and gas binary diffusion;

. Thermal equilibrium between the phases;

. Non-equilibrium approach for vaporization rate;

. Changes in porosity and volume are neglected;

. Sample simplified geometry (2D-domain)

2.1 Multiphase mass transport in porous media

During microwave dehydration process, the mass conservation equation for the different phases include the following fluxes: capillary (liquid-water and water-vapour) and convective (liquid-water, water-vapour and air). Porous media model also include the phase change between the liquid and vapour phase of water through the entire domain (Datta, 2007).

$$\frac{\partial C_w}{\partial t} + u_{w,me}\nabla C_w + C_w \nabla u_{w,me} = \nabla\left(D_{w,eff}\nabla C_w\right) - I \quad (1)$$

$$\frac{\partial C_v}{\partial t} + u_{g,me}\nabla C_v + C_v \nabla u_{g,me} = I + \\ + \nabla\left(S_g \varepsilon \frac{C^2}{\rho_g} M_w M_a D_{g,eff}\nabla x_v\right) \quad (2)$$

$$\frac{\partial C_g}{\partial t} + \nabla\left(\rho_g u_g\right) = I \quad (3)$$

2.2 Momentum transfer in porous media

The rate of different fluxes inside the porous media is calculated by Darcy’s law (Ni et al. 1999).

$$u_i = -\frac{k_{in,i}\, k_{r,i}}{\eta_i}\nabla P \quad (4)$$

The liquid-water and gas linear velocity could be defined as:

$$u_{i,me} = \frac{1}{\varepsilon S_i} u_i \quad (5)$$

2.3 Heat transfer in porous media

The energy conservation equation accounts for convection due to movement of different phases inside the porous media, conduction of heat, phase change and a heat source term that considers the absorbed energy from the microwaves (Rakesh et al. 2012).

$$\rho_{eff} Cp_{eff} \frac{\partial T}{\partial t} + \sum_{i=w,v,a} \nabla\left(C_i u_{i,me} Cp_i T\right) \\ - Cp_w T \nabla\left(D_{w,eff}\nabla C_w\right) = \nabla\left(k_{eff}\nabla T\right) - \lambda I + Q_{micro} \quad (6)$$

where effective physical properties are considered as follows:

$$\rho_{eff} = (1-\varepsilon)\rho_s + \varepsilon S_g \rho_g + \varepsilon S_w \rho_w \quad (7)$$

$$Cp_{eff} = (1-\varepsilon)Cp_s + \varepsilon S_g \omega_v Cp_v + \\ + \varepsilon S_g \omega_a Cp_a + \varepsilon S_w Cp_w \quad (8)$$

$$k_{eff} = (1-\varepsilon)k_s + \varepsilon S_g \omega_v k_v + \\ + \varepsilon S_g \omega_a k_a + \varepsilon S_w k_w \quad (9)$$

2.4 Absorbed microwave energy

The volumetric heat source could be written as:

$$Q_{(x,y)} = \frac{\partial P_{(x)}}{\partial x} + \frac{\partial P_{(y)}}{\partial y} \qquad (10)$$

And the interaction between the food and microwaves is modeled by the Lambert's law.

$$Q_{(x,y)} = 2\alpha \frac{P_o}{A} \left(e^{-2\alpha(L-y)} + e^{-2\alpha(R-x)}\right) \qquad (11)$$

$$\alpha = \frac{2\pi}{\lambda} \sqrt{\frac{\varepsilon'[(1+\tan^2\delta)^{1/2} - 1]}{2}} \qquad (12)$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (13)$$

The dielectric properties of fresh and osmodehydrated fruit could be calculated from the contribution of each individual constituent:

$$\varepsilon'_{eff} = (1-\varepsilon)\varepsilon'_s + \varepsilon S_g \varepsilon'_{w/sol} + \varepsilon S_g \varepsilon'_g \qquad (14)$$

$$\varepsilon''_{eff} = (1-\varepsilon)\varepsilon''_s + \varepsilon S_g \varepsilon''_{w/sol} + \varepsilon S_g \varepsilon''_g \qquad (15)$$

2.4 Initial and Boundary conditions

The model considers uniform initial temperature, liquid-water and water-vapor concentration and pressure. And the following conditions are defined:

Outward liquid flux:

$$n_w\big|_n = h_{mv}\varepsilon S_w(\rho_v - \rho_{v,ext}) + C_w u_w \qquad (16)$$

Outward vapour flux:

$$n_v\big|_n = h_{mv}\varepsilon S_g(\rho_v - \rho_{v,ext}) \qquad (17)$$

Convective and evaporative heat flux in the surface:

$$\begin{aligned} q\big|_n &= h_{conv}(T - T_{ext}) - h_{mv}\varepsilon S_w \rho_v \lambda \\ &- h_{mv}\varepsilon(S_w + S_g)\rho_v Cp_v T - C_w u_w Cp_w T \end{aligned} \qquad (18)$$

Pressure prescripted on the surface:

$$p_s = p_{ext} \qquad (19)$$

3. Numerical Solution

A full 3D geometry was not required since the fruit samples considered were cylindrical in shape. The 2D axisymmetric geometry used for the problem is shown in Fig. 1a. A finer mesh was used in the boundaries, with a total of 836 tetrahedral elements (Fig. 1b).

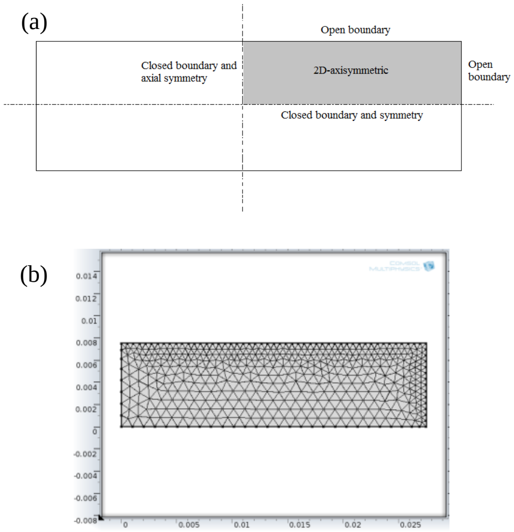

Figure 1. (a) Simplified 2D-geometry of the food (pear) and (b) mesh for the numerical procedure.

A complete 2D-porous media model was developed in COMSOL Multiphysics® 4.4 considering: Transport of Dilute Species for liquid-water concentration (C_w), Maxwell-Stefan Diffusion for concentration of water-vapor (C_v), Darcy's Law for total pressure (p) and Heat Transfer in Fluids for temperature (T). Energy, momentum and mass balance equations were solved using the Direct Segregated Solver (MUMPS) time dependent. The computation time was approximately 76s for 120s of microwave drying time with a time step of 1s (workstation with win7-64bits and processor Intel-i5 3.2GHz, 8GB-Ram).

4. Results and Discussion

The complete microwave drying model was simulated for liquid-water concentration, water-vapour concentration, pressure and temperature. The parameters and physical properties of food (pear) used in the mathematical modeling are summarized in Tables 1.

4.1 Absorbed microwave power

As a result of the applying of the exponential decay function of the electromagnetic energy (Lambert's law) the distribution of the absorbed microwave power inside the food was obtained (Fig. 2). From the sample 2D revolution (Fig. 2), it can be seen that lateral and upper sides of the domain are exposed to the microwaves and generate a resulting distributed absorbed microwave power.

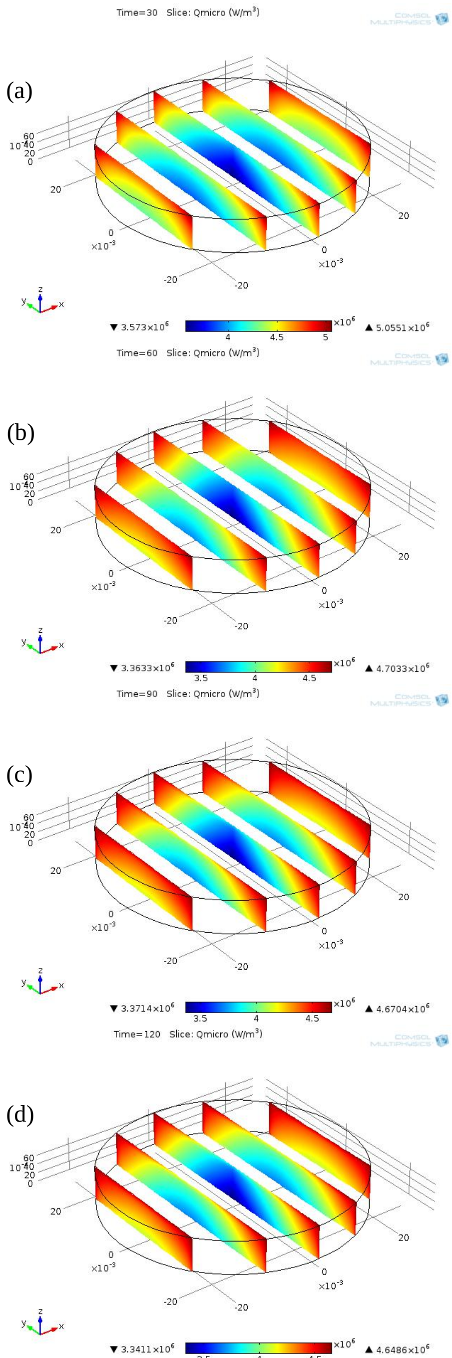

Figure 2. Profiles of the absorbed microwave power at 30, 60, 90 and 120s during the microwave drying of fresh fruit.

Considering that dielectric properties change with temperature and moisture content, the absorbed microwave power will change with process time. Figure 3 shows the evolution of attenuation factor that is function of dielectric properties of food material.

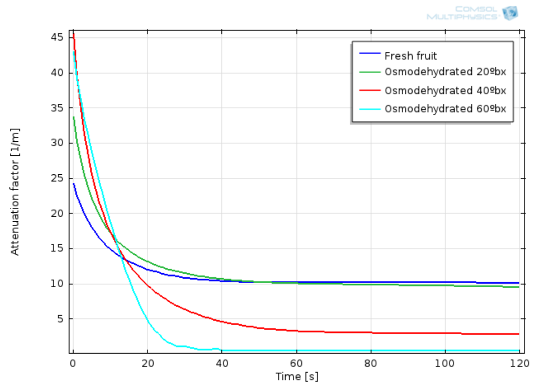

Figure 3. Evolution of attenuation factor of fresh and osmodehydrated food during microwave drying process.

Figures 2a-d shows the evolution of absorbed power profiles at 30, 60, 90 and 120s. With respect to variation of maximum absorbed mw-power with time, from the simulation is possible observe higher variation between 30 and 60s than in the other time intervals. This fact could be due to the important changes in temperature that occurs in the beginning of the process when the sample has the maximum moisture content.

4.2 Temperature, pressure, liquid and vapour concentration profiles

The distribution of the simulated temperature in the 2D computational domain after 10s of processing is shown in Fig. 4a. From the figure it is clear that the maximum value of the temperature is located in the area close to the right upper corner of the domain. This is as expected from the absorbed microwave power profile (Fig. 2). Moreover, the center of the sample presents the lowest temperature (39.8ºC) corresponding to the zone of less absorbed power. Additionally can be appreciated the rapid increase in temperature from 22 to 47ºC in only 10s, despite of the less uniformity of the distribution of absorbed microwave energy.

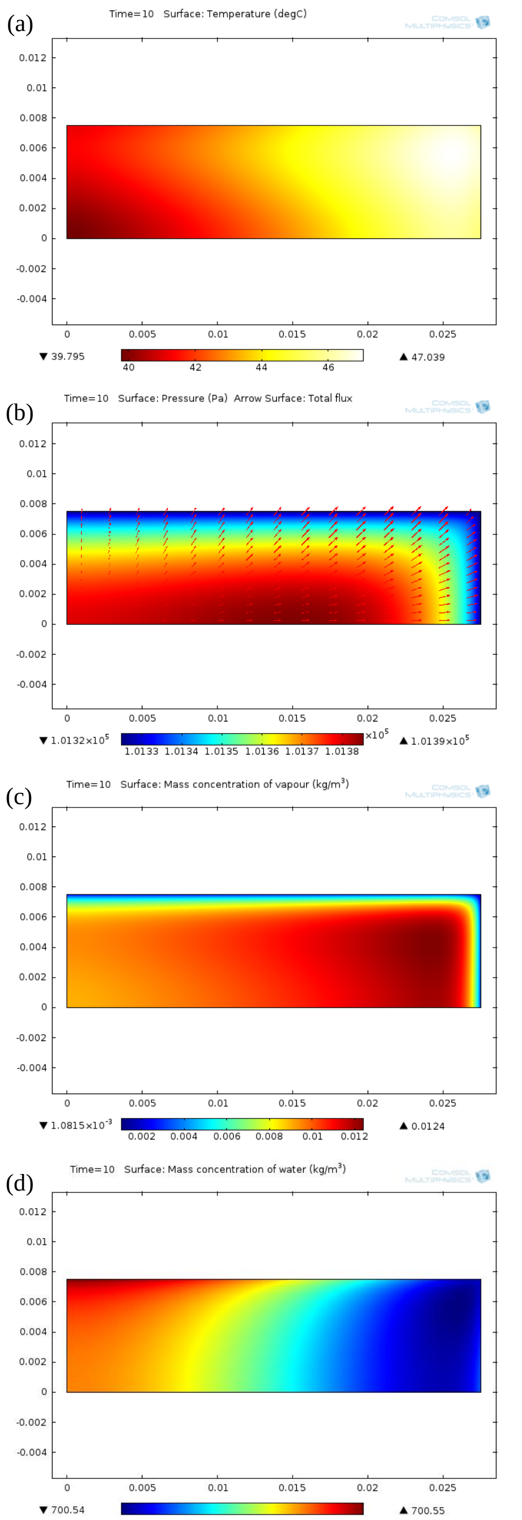

Figure 4. Temperature (a), pressure (b), vapour (c) and liquid-water concentration (d) profiles after 10s of microwave drying of fresh fruit.

With respect to the variation in the inner pressure, Fig. 4b shows its distribution after 10s of processing. The figure demonstrates the zone where the pressure buildup is more important, this zone is located on the right side displaced toward the bottom presenting a maximum value of 1.014e5 Pa.

Considering the mass transfer generated by the heating process and the increasing in the inner pressure, the Figs 4c and 4d show the variation in the concentration of water-vapor and liquid-water after 10 s of microwave processing. As the temperature increases the liquid-water is forced to move toward the surface due to the high values of temperatures in the right side of the domain causing the local phase change of liquid-water. In consequence, the concentration of liquid-water decreases toward the left side. With respect to the profile of water-vapor concentration (Fig. 4c), it is clear that high evaporation rate occurs in the same zone where the maximum temperature takes place, presenting values of 0.012kg/m^3.

4.3 Effect of osmodehydration pretreatment

With regard to the evolution of temperature during microwave drying, two well-defined zones can be observed (Fig. 5). During the first heating stage, the temperature increased rapidly and then a constant equilibrium temperature was reached and the change in temperature became negligible. The slope of each simulated curve represents the rate of temperature increase, which is related to the dielectric properties of the fruit.

It can be seen in Fig. 5 that the treatment in 60ºBrix sucrose solution promoted the highest rate of temperature and the lowest slope is presented by fresh pears. These differences in the slopes can be attributed to the change in dielectric properties due to water loss and solids gain during osmotic pretreatment that affects the capacity of food to transform microwaves into heat (Arballo et al. 2012b, Liao et al. 2003). From the simulated temperatures it is clear that as higher the concentration of osmotic solution in the pretreatment is, higher the increase of temperature rate. With respect to the highest temperature achieved by fresh and osmodehydrated fruits submitted to microwaves, special behavior can be appreciated the ones of 60ºBrix that show the lower value of equilibrium temperature. This behavior could be explained by the rapid decrease in the attenuation factor during the first 20s (Fig. 3).

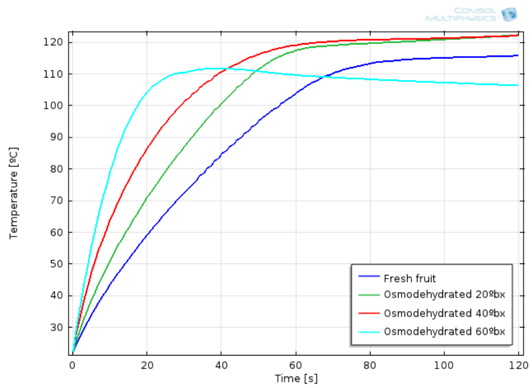

Figure 5. Simulated temperature as function of time during microwave dehydration of fresh and osmodehydrated fruit in sucrose solutions of 20ºBrix, 40ºBrix, and 60ºBrix.

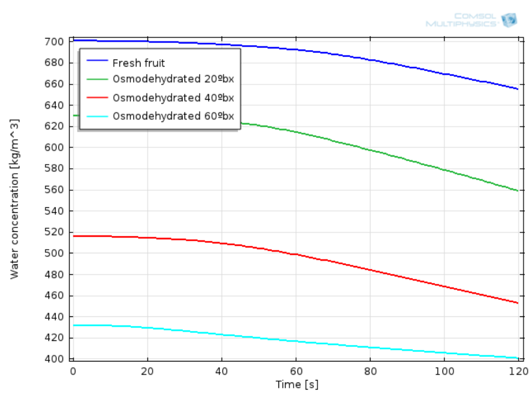

Figure 6. Simulated liquid-water concentration as function of time during microwave dehydration of fresh and osmodehydrated fruit in sucrose solutions of 20ºBrix, 40ºBrix and 60ºBrix.

Fig. 6 and 7 present the simulated liquid-water and vapour concentration as a function of the process time. It can be seen from Fig. 6 the different initial concentration considering the fresh or osmodehydrated samples. A higher dehydration rate was reached during microwave drying when the fruits were pretreated with 20 and 40ºBrix sucrose solutions. This fact could be due to the high temperatures reached that promote the higher vapour production rate than in fresh and osmodehydrated-60ºBrix ones (Fig. 7).

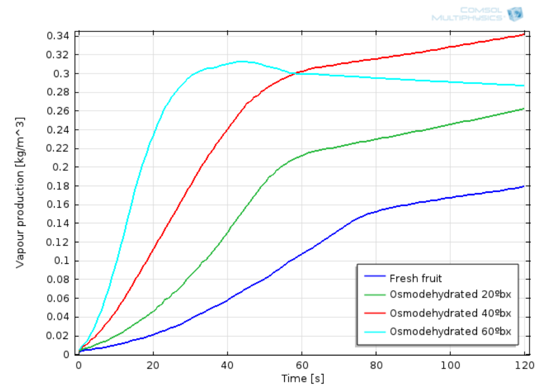

Figure 7. Simulated vapour concentration as function of time during microwave dehydration of fresh and osmodehydrated fruit in sucrose solutions of 20ºBrix, 40ºBrix and 60ºBrix.

5. Conclusions

A complete mathematical model has been developed for simultaneous prediction of temperature, liquid-water concentration, water-vapour concentration and inner pressure profiles during the process of microwave drying of fresh and osmodehydrated food. The obtained porous media model also considers the change in dielectric properties due to the osmotic pre-treatment.

6. References

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7. Acknowledgements

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8. Appendix

Table 1: Parameters used in the computational simulation

Parameter		**Value**
c_{w0}	Initial water concentration of pear (fresh)	38900 [mol/m^3]
ω_{v0}	Initial vapour molar fraction	0.01 [1]
T_{ini}	Initial temperature	295 [K]
P_{ini}	Initial pressure	101325 [Pa]
L_s	Sample thickness	15 [mm]
D_s	Sample diameter	55 [mm]
$k_{i,w}$	Intrinsic permeability (very wet state)	5e-14 [m^2]
$k_{i,g}$	Intrinsic permeability (very dry state)	10e-14 [m^2]
η_w	Water dinamic viscosity	5.468e-4[Pa.s]
η_v	Vapour dinamic viscosity	0.0317[Pa.s]
η_g	Gas dinamic viscosity	1.8e-5[Pa.s]
S_{w0}	Initial saturation of water	0.8
S_{ir}	Intrinsic residual saturation	0.09
ρ_w	Water density	998[kg/m^3]
ρ_s	Solid density (food)	1075[kg/m^3]
h_{mv}	Mass transfer coefficient (vapour)	0.01[m/s]
h_{conv}	Heat transfer coefficient	20[W/(m^2*K)]
ε	Porosity of food (pear)	0.88
P_{surf}	Surface Pressure	101325[Pa]
Cp_s	Solid heat capacity (food)	1650[J/(kg.K)]
Cp_a	Air heat capacity	1006[J/(kg.K)]
Cp_w	Water heat capacity	4180[J/(kg.K)]
Cp_v	Vapour heat capacity	2062[J/(kg.K)]
k_s	Solid thermal conductivity (food)	0.21[W/(m.K)]
k_g	Gas thermal conductivity	0.026[W/(m.K)]
k_w	Water thermal conductivity	0.57[W/(m.K)]
λ	Latent heat of vaporization	2.435e6[J/kg]
P_o	Absorbed microwave power	700 [W]
K_{mv}	Non-equilibrium evaporation constant	1[1/s]
T_{ext}	Environment temperature	295 [K]