Heat and Mass Transfer in Convective Drying Processes

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Abstract: A dynamic mathematical model, based on physical and transport properties and mass and energy balances, was developed for the simulation of unsteady convective drying of agricultural products (fruits and vegetables) in static bed conditions. The local material-averaged drying rate and the heat flux depend on local air humidity and temperature, as well as local mass and heat transfer coefficients in interaction with the moisture and temperature distribution inside the material. The model utilizes water sorption isotherm equations and the change in solid density due to the shrinkage phenomenon. The aim of this article is to describe the modelling and simulation of the dehydration of grapes in a complex drying system processes, using COMSOL Multiphysics Program.

Keywords: **h**eat transfer, mass transfer convective drying processes, numerical model, COMSOL.

1. Introduction

Dehydration involves the simultaneous transfer of heat, mass and momentum in which heat penetrates into the product and moisture is removed by evaporation into an unsaturated gas phase. Owing to the complexity of the process, no generalized theory currently exists to explain the mechanism of internal moisture movement. Although it is now accepted that in most practical situations of air drying of foods the principal rate-determining step is internal mass transfer, there is no agreement on the mechanism of internal moisture movement. In the case of capillary-porous materials such as fruits and vegetables, interstitial spaces, capillaries and gas-filled cavities exist within the food matrix and water transport takes place via several possible mechanisms acting in various combinations. The possible mechanisms proposed by many workers include:

- liquid diffusion caused by concentration gradients,
- liquid transport due to capillary forces,
- vapour diffusion due to shrinkage and partial vapour-pressure gradients (Stefan's law),
- liquid or vapour transport due to the difference in total pressure caused by external pressure and temperature (Poiseuille's law),
- evaporation and condensation effects caused by differences in temperature,
- surface diffusion in liquid layers at the solid interface due to surface concentration gradient,
- liquid transport due to gravity.

Additionally, moisture may also be transported inside a material if a suitable temperature gradient exists (thermo-gradient effect), because of thermodynamic coupling of heat and mass transport processes.

Most foods are classified as capillary porous rigid or capillary porous colloids, (Bruin, 1980). Therefore, it is often proposed that a combination of capillary flow and vapour diffusion mechanisms should be used to describe internal mass transfer.

Water activity, rather than moisture content, influences biological reactions. In the regions of water adsorption on polar sites or when a mono-molecular layer exists, there is little enzyme activity. Enzyme activity begins only above the region of mono-molecular adsorption. When the moisture content of a substrate is reduced below 10 %, micro-organisms are no longer active. It is necessary however to reduce the moisture content to below 5 % in order to preserve nutrition and flavour.

2. Mathematical modelling of drying processes

The simulation of various product drying systems involves solving a set of heat and mass transfer equations which describe:

a) heat and moisture exchange between product and air,

b) adsorption and desorption rates of heat and moisture transfer,

c) equilibrium relations between product and air,

d) psychometrics properties of moist air.

Attempts to describe the manner whereby moisture is dislodged and evaporates from many common materials involve formidable problems and analysis, and are usually tractable only for constant drying conditions. However, process conditions almost always vary from place to place in a dryer and, in case of batch drying, they also change with time. It is thus useful to describe a body of comparatively simple structure, through which the movement of moisture can be analyzed or experimentally modelled in a straightforward way, so that the drying behaviour can be predicted for conditions more representative of those in commercial equipment. This procedure, although very approximate in a quantitative sense, nevertheless provides a number of important clues about drying behaviour in general and strategies for process operation.

For air-drying of root vegetables (e.g. carrots, potatoes, sweet potatoes), the core drying model, which formulates the relation between the changes of the surface areas and moisture content, assumes the formation of a dried layer at the outer side of the sample and the existence of an un-dried core at the centre. This model was found to be in good agreement with the experimental data.

2.1 Simultaneous transport of heat and mass

The most rigorous methods of describing the drying process are derived from the concepts of irreversible thermodynamics in which the various fluxes are taken to be directly proportional to the appropriate "potential", (Ghiaus, 1997). The mass balance inside the product can be written as:

$$\frac{\partial(\rho_b \cdot X)}{\partial t} = \mathrm{div}\left(\rho_b \cdot D_{eff} \cdot \frac{\partial X}{\partial z}\right) \qquad (1)$$

and the heat-energy balance can be set down as:

$$\rho_b \cdot c \cdot \frac{\partial T}{\partial t} = \mathrm{div}\left(\lambda \cdot \frac{\partial T}{\partial z}\right) \qquad (2)$$

Where X - grape moisture content; T -the air temperature; ρ_b - bulk bed density; c - specific heat capacity; λ - thermal conductivity; D_{eff} - effective mass diffusivity.

These considerations lead to complex partial differential equations for the moisture content and temperature fields inside the product. These equations incorporate transport coefficients which must be determined experimentally, and are strong functions of moisture content.

2.2 Modelling of agricultural product properties

Variability in composition and physical characteristics is typical for all food products. For example, the composition of fruits and vegetables depends on variety, location grown, climatic conditions, etc. For most engineering heat transfer calculations performed in commercial food dehydration, accuracy greater than 2-5 % is seldom needed. This is because errors due to varying or inaccurately measured boundary conditions such as air temperature and velocity, would overshadow errors caused by inaccurate thermal properties.

The best sources of thermal property data are prediction equations based on chemical composition, temperature and physical structure (density, porosity, size and configuration of void spaces).

Most thermal property models are empirical rather than theoretical, i.e. they are based on statistical curve fitting rather than theoretical derivations involving heat transfer analysis. In modelling, water is treated as a single, uniform component of the food product. It could be argued that the thermal properties of water in the food depend on how it is configured or "bound" within the product.

Table 1: The parameters used for the Corinthian grapes

Item	Value
Water content W, %	75
Thermal conductivity λ, W/m K	0.5721

Specific heat c, J/kg K	3600
Effective diffusion D_{eff}, m2/s	$3.6 \cdot 10^{-9}$
bulk bed density ρ_b kg/m3	691

3. Results and Discussion

The COMSOL Mutiphysics program is used to simulate the dehydration of grapes in a complex drying system processes which correspond to the numerical solution of these model equations. The above system of non-linear Partial Differential Equations, together with the already described set of initial and boundary conditions, has been solved by Finite Elements Method implemented by Comsol Multiphysics 3.4. We build the geometry of the model, and then we fixed the boundary settings, the mesh parameters and compute the final solution (Figure 1)

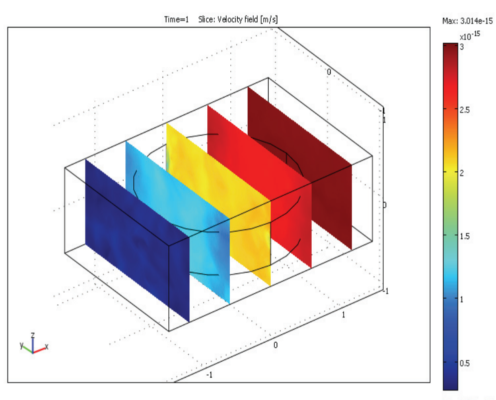

Figure 1. Results from the compute solution in COMSOL Multiphysics.

Figure 2 shows graphically the evolution of grape temperature during the drying process, at the surface and bottom of the bed and as an average. the predicted drying time was calculated to be 38 hours and 21 minutes during which the grapes are dried from 75 % moisture content - wet basis to 15 % moisture content - wet basis.

Differences of temperature between the base and surface of the bed appear only during the first period of drying, approx. the first 5 hours. After this the bed temperature remains uniform until the end of the process. During the first 5 hours the temperature gradient is high and corresponds to the so-called warm-up period of drying. During the next 25 hours the temperature remains practically constant, and during the last period it starts to increase again. At the end of the process, the temperature of the grapes reaches 42.5 °C.

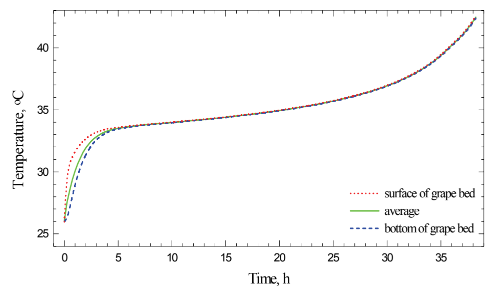

Figure 2. Evolution of grape temperature during the drying process.

Figure 3 presents the evolution of grape moisture content at the surface and bottom of the bed and as an average value. It can be seen that during the whole process the moisture content of the grapes is uniform within the bed thickness. This is due also to the small thickness of the grape bed.

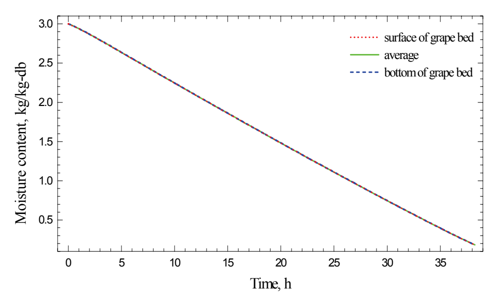

Figure 3. Evolution of grape moisture content during the drying process.

One of the most important drying parameters is the drying rate (Figure 4) which represents the rate of evaporated water from one square meter of drying product. At the beginning of the process the drying rate increases from 0.06 g/s m2 to 0.12 g/s m2 and then has a very small decreasing slope. At the end of the process the drying rate decreases rapidly.

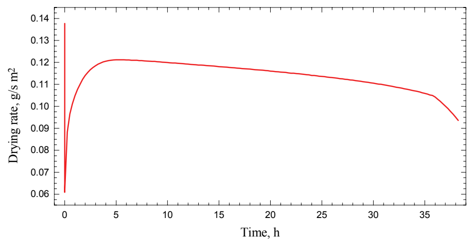

Figure 4. Drying rate vs. drying time for grape dehydration.

As the heat exchangers processes do not involve mass (water vapors) transfer, the absolute humidity values of the preheated air are equal to those of the ambient air, the values of exhaust air are the same as those of the air at the outlet of the drying room and also, the values are identical at the inlet and outlet of the main heat exchanger.

Drying air parameters are predicted at characteristic points of the system: inlet of the fresh air into the economizers (ambient air), outlet of the economizers onto the fresh air path (preheated fresh air), inlet of the main heat exchanger (the mixing between preheated and recycled air), inlet and outlet of the drying room, and the outlet of the economizers onto the exhaust air path. Evolution of drying air temperature is given in Figure 5 and the relative humidity of the drying air in Figure 6.

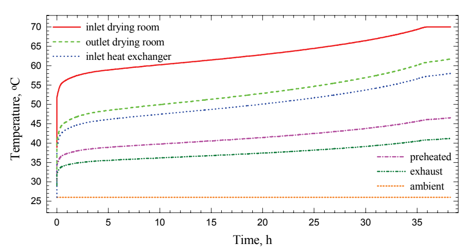

Figure 5. Drying air temperature at different locations vs. drying time.

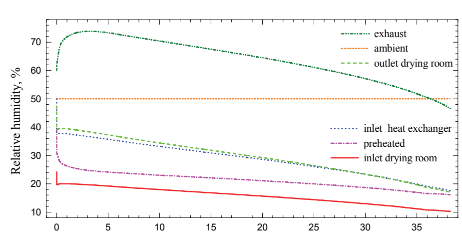

Figure 5. Relative humidity of drying air at different locations vs. drying time.

4. Conclusions

In this paper, we have demonstrated the versatility of COMSOL Multyphisics with regard to the modelling and simulation of the dehydration of grapes in a complex drying system processes. The model was applied to the full scale experimental data with good results.

5. References

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