MODELING OF DRYING PROCESS OF CANDIES OBTAINED WITH STARCH MOLDING TECHNIQUE

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ABSTRACT

Starch molding is a widely used shape forming technique in the confectionery industry. Candies are deposited into cavities imprinted in dry granular starch. A drying stage follows deposition, which largely determines the productivity of the process and the candy quality.

In the present work a finite elements model was developed that quantitatively predicted the moisture diffusion from a single candy piece into the starch bed or air at a given temperature (50°C).

This simulated a simultaneous bidimensional heat and moisture transfer accounting for a variation in the candy physical properties as functions of local moisture content and temperature.

Model validity was attained for candy drying experiments performed both in the laboratory and monitored in the Silagum srl (Lamezia Terme (CZ)), which has contributed to this work. The model is a powerful tool for analyzing the behavior of an industrial drying process.

Keywords: starch molding, finite elements model, heat and moisture transfer, powerful tool

1. INTRODUCTION

Confectionery items such as starch gums and jelly candies have been extensively manufactured using the starch molding technique, which involves a series of operations including deposition of the hot candy syrup into the starch molds and drying by stoving. These operations are very critical in many aspects. The candy suspension (gel) which will be cast into starch molds, must be fluid enough at depositing to get a good shape definition and to prevent tailing. This often requires casting of candy suspension at a moisture content greater than desirable in the final product. For this reason the products need a drying step following depositing, with moisture exchange between the product and both its environment and the starch of the mold. This is a dynamic process involving the candy, molding starch and the air that surrounds them.

The molding starch actually is able to shape the candy and also to adsorb the candy humidity gently; for this reason its moisture content and temperature are very important process parameters. During the period that the product is in contact with the molding starch, moisture content and temperature are constantly changing. The rate at which starch adsorbs moisture is comparatively slow and the dynamic relationship of the product, the starch and the atmosphere has been scarcely investigated (Sudharsan, Ziegler, and Duda 2004). In economic terms, the rate determines I, productivity of the process and the amount of time to spend in making these products.

It is well known that the understanding of the physical processes occurring during the candy production operations and in particular during the drying process, can lead to control the work parameters involved, improving product quality at a lower cost. Then it clearly appears that, unlike in most foods, water is a minor constituent of candies but one that has a major impact on the production process.

In the candy drying stage simultaneous physical phenomena are involved, heat transfer from the air to the product and mass-moisture transfer from the product to the air. This stage is controlled by many parameters: temperature and relative humidity of the air into the oven; initial temperature and moisture content of molding starch; shape of the candies; distance between candies in the mold.

This research proposes a theoretical model describing the transport phenomena involved in candy drying. The aim of the study was to determine the influence of some of the most important operating variables, namely drying air humidity and temperature, on the performance of the drying process of candies.

The main connotation of this study regarded the possibility of increasing the accuracy of the drying process modeling by the use of the finite elements method (FEM). With respect to most of the works published in the literature, the main innovation introduced in this study is represented by the model formulation. In fact, the latter must consider the simultaneous bidimensional heat and moisture transfer accounting for the variation in the candy physical properties as functions of local moisture content and temperature. The resulting system is an unsteady–state partial differential set of equations that has been solved by means of a FEM commercial software, *Comsol Multyphysics* v.3.5 (Comsol, Sweden).

The validation of the model was carried out by comparing simulated and experimental profiles of candy humidity over time during the drying process.

The experimental study was applied before to both model candies and later to industrial ones, prepared with the same recipe and dried in a laboratory and industrial oven respectively. In both cases the drying process was realized by molding starch technique using a cornstarch bed with fixed dimension and distribution of candies. The latter parameters are those employed by Silagum srl (Lamezia Terme (CZ)), a Calabrian candy industry which has contributed to this work, allowing us to monitor and to study its drying process. Industrial operating conditions, such as temperature (50°C) and humidity of candy, starch and air were reproduced in the laboratory to study model systems.

The main objective was to develop an accurate transport model that could be used to simulate the behavior of a real drying process and to define, over a wide range of drying conditions and of different types of candies, the "optimal" set of operating conditions in each specific situation. In this way, it might be possible to minimize expensive pilot test-runs and to have good indications on the characteristics and the quality of final products.

2. THEORICAL BACKGROUND

When a moist food is put in contact with dry and warm air, two different transport mechanisms simultaneously occur: heat transfer from air to the material and transfer of water from food to air. Within the solid material, conductive heat transfer and diffusive water transfer take place.

In this study water and heat transfers are computed through transient mass and energy balances, respectively, whereas the evaporation occurring at air-candy interface was considered by defining proper boundary conditions expressed in terms of heat and mass transfer coefficients estimated by well-known empirical correlations (Perry and Green 1984).

Ellipsoidal geometry was assumed for the candies immersed at the same distance in a starch dry bed. Then, a spherical coordinate system was considered including candy and starch because both the air and the mold starch are able to adsorb product humidity (Figure 1). Dimensions of candies and of starch bed were established with reference to the industrial drying process of candies (Silagum srl, Lamezia Terme (CZ)).

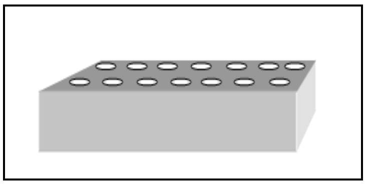

Figure 1: Sketch of mold starch with candies.

The model is based on the following hypothesis:

1. Heat transfer in the product was by conduction.
2. Mass transfer in the product was by diffusion.
3. Transport of water vapor within the dehydrated candy was negligible.
4. No food shrinkage occurred during drying.
5. Azimuth symmetry.
6. Candy and starch densities were constant (Sudharsan, Ziegler, and Duda 2004).
7. Candy and starch heat capacities were constant (Cabras and Martelli 2004).
8. Initial humidity and temperature of candy and starch were uniform within the materials.
9. Candy diffusion coefficients were function of moisture content within the materials.
10. Starch diffusion coefficient was constant in the characteristic humidity range (6-12%) (Sudharsan, Ziegler, and Duda 2004).
11. Immediate achievement of liquid-vapor equilibrium conditions at the interfaces air/candy and air/starch.
12. The drying air was supplied continuously to the product and its flow was parallel to its surface.

2.1. Mathematical model

The energy balance in the solids, candy and starch, based on Fourier's law, leads to:

$$\rho C_p \frac{\partial T}{\partial t} = \underline{\nabla} \cdot \left(k(T,C) \underline{\nabla} T \right) \tag{1}$$

where ρ is density (kg/m^3), *cp* is heat capacity (J/kg K), *T* is the temperature (K), *t* is time (s), and *k* is thermal conductivity (W/m K).

Mass balance, based on Fick's law, leads to

$$\frac{\partial C}{\partial t} = \underline{\nabla} C \cdot \left(D \underline{\nabla} C \right) \tag{2}$$

where *C* is water concentration (mol/m^3), D is the effective diffusion coefficient of water (m^2/s).

The drying model was applied to a central candy in the mold starch for which a symmetrical approach can be applied. Thanks to this approach two domains were considered: the starch and the candy.

Since the considered system is composed of two domains with different physical properties, Eqs. (1) and (2) modeling the drying process must be applied to each one by considering their specific properties.

Supposing that the material parameters c_p, *k* and *D,* are determined by local water concentration and on food temperature, Eqs. (1) and (2) form a system of nonlinear partial differential equations. Initial conditions are straightforward since it is assumed that, at *t*=0, candy and starch concentrations and their temperatures are equal to their initial values, respectively.

Boundary conditions were applied to the border (B) of the system sketched in figure 2.

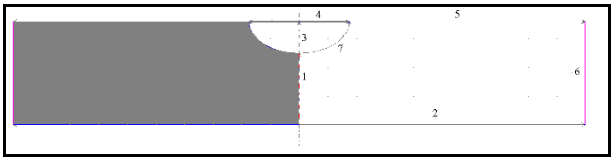

Figure 2: Simulation domain and boundary conditions for the 2-D FEM analysis.

The boundary conditions were applied to the surfaces of the two different domains identified by their normal $\underline{\boldsymbol{n}}$. Room temperature and mass adiabatic conditions were assumed for the starch box (Boundary 2). The physical parameters of candy and starch are indicated with subscripts *c* and *s* respectively.

The boundary conditions relative to eq. (1) were:

- B-1 and B3: $\frac{\partial T}{\partial r} = 0$ (3)
- B-2: $T = T_\infty$ (4)
- B-4: $-\underline{n}\cdot\left(-k_c \underline{\nabla} T\right) - \lambda N_{wc} = h\left(T_\infty - T_c\right)$ (5)
- B-5: $-\underline{n}\cdot\left(-k_s \underline{\nabla} T\right) - \lambda N_{ws} = h\left(T_\infty - T_s\right)$ (6)
- B-6: $-\underline{n}\cdot\left(-k_s \underline{\nabla} T\right) = 0$ (7)
- B-7: $-\underline{n}\cdot\left(-k_c \underline{\nabla} T\right) = -\underline{n}\cdot\left(-k_s \underline{\nabla} T\right)$ (8)

where k is water latent heat of vaporization (J/mol), N_w is water diffusive flux on food surface (mol/m^2 s), h is heat transfer coefficient (W/m^2 K), T_∞ is gas temperature in the bulk, T_s and T_c are starch and candy surface temperatures respectively (all temperatures are measured as °K).

The boundary conditions relative to eq. (2) were:

- B-1 and B3: $\frac{\partial C}{\partial r} = 0$ (9)
- B-2: $\underline{n}\cdot\left(D_s \underline{\nabla} C\right) = 0$ (10)
- B-4: $-\underline{n}\cdot\left(-D_c \underline{\nabla} C\right) = K_c\left(y - y_\infty\right)$ (11)
- B-5: $-n\cdot\left(-D_s \nabla C\right) = K_c\left(y - y_\infty\right)$ (12)
- B-6: $\underline{n}\cdot\left(D_s \underline{\nabla} C\right) = 0$ (13)
- B-7: $-\underline{n}\cdot\left(-D_c \underline{\nabla} C\right) = -\underline{n}\cdot\left(-D_s \underline{\nabla} C\right)$ (14)

where K_c is mass transfer coefficient (mol/m^{2}s), y_∞ is water bulk molar fraction in the air, y_s and y_c are water molar fraction evaluated in gaseous phase at the starch/air and candy/air interfaces respectively

The interfaces candy/air and starch/air were considered to be at the thermodynamic equilibrium. Thanks to this hypothesis it is not necessary to apply the thermodynamic equilibrium at the B-7 surface too. The equality of both temperature and water activity of starch and candies results a consequence of previous boundary conditions.

At the drying air material surface (i.e. B4 and B5) it is possible to calculate y_s and y_c values, from the thermodynamic equilibrium linking between water concentration in the gas phase and water concentration on candy/starch surfaces. If it is assumed that the gas phase behaves as a mixture of ideal gases, the following equation applies:

$$Py = P^0 a_w \tag{15}$$

where P is air pressure (Pa), P^0 vapor pressure (Pa), y the molar water fraction in the gas phase, and a_w is the activity of water of starch or candy respectively.
P^0 was easily calculated with the equation 16 (Perry 2007).

$$P^0 = \exp\left(73.649 - \frac{72582}{T} - 7.3037\cdot\log(T) + 4.1653\, 10^{-6} T^2\right) \tag{16}$$

To compute the equilibrium between drying air and both starch and candies, the same nonideal mixture behavior was assumed by using GAB isotherm that is valid in the 0.1-0.9 activity of water range and links water content to the activity of both materials considered:

$$\frac{U}{U_0} = \frac{CKa_w}{\left(1 - Ka_w\right)\left(1 - Ka_w + CKa_w\right)} \tag{17}$$

Where U is the moisture content in dried material (dry basis- Kg$_{\text{water}}$/Kg $_{\text{dry solid}}$), U_0, C and K are the GAB constants characteristic of dried material. The latter parameters were calculated for candies and mold starch by using their desorption isotherms.

The isotherms were obtained by measuring the moisture content in dried materials with analyzer HB43 (Mettler Toledo, Germany) and the activity water with instrument Sprint TH500 (Novasina, Italy). Desorption isotherms data were fitted by GAB equation by using the software Table Curve 2D.

Fitting results for two types of candies and for mold starch studied were reported in Table 1.

Table 1: GAB constants

Sample	U_0	C	K
Candy_lab	34.60	0.12	1.04
Candy_ind	34.47	0.22	0.93
Mold Starch	12.56	34.53	0.62

Eqs. (3)–(15) were essential to describe properly the complex steps involved during the drying process. Eq. (5), in fact, was expressed in terms of water activity a_w, which is a distinctive parameter of each product being characterized by its own structure. Water activity, then, determines the strength of the bonds between food structure and water. Moreover, U and T through Eq. (15), determine the value of the food water molar fraction, and then the time evolution of the drying process. In particular, if U and T are high enough to have $y > y_\infty$, food drying starts immediately (Eqs. (11) (12)); heat is transferred by convection from air to food whereas latent heat of vaporization is transported from the food to the water thus allowing its evaporation (Eqs. (5) (6)).

The physical properties ρ and c_p of candies and mold starch used in the model with reference Sudharsan, Ziegler, and Duda 2004, Cabras and Martelli 2004 respectively, are reported in Table 2 .

Table 1: Physical properties of candy and mold starch

Sample	ρ (Kg/m^3)	*cp* (J/Kg K)
Candy	748	2300
Mold Starch	700.2	1300

Thermal conductivity values of candies and starch as a function of U and T, are defined by Eq. (18) (Saravacos and Maroulis 2001):

$$K(U,T)=\frac{1}{1+U}\lambda_0\exp\left[-\frac{E_0}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]+\frac{1}{1+U}\lambda_i\exp\left[-\frac{E_i}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right] \quad (18)$$

Where λ_i, λ_0, E_i and E_0 (W/m K) are parameters characteristic of candy and starch and T_{ref} is a reference temperature. The values of them used in the model are that reported in Saravacos and Maroulis 2001.

The diffusivity coefficient of water in starch can be considered constant in the operating range of humidity and temperature, and a value of 10^{-9} m^2/s was used in the model (Vagenas and Karathanos 1991, Sudharsan, Ziegler, and Duda 2004).

A dependence of diffusivity coefficient of water in the candies on the U and T values (equations not reported) was obtained experimentally measuring *D* coefficient of candies having different humidity by using NMR tests (Bruker, USA). These measurements were carried out at three different temperatures (50°C, 60°C, 70°C) on the candies dried in the laboratory oven (Termostabil K3), and on those produced industrially taken from Silagum oven. The trend *D vs* U registered for the latter was reported in figure 3.

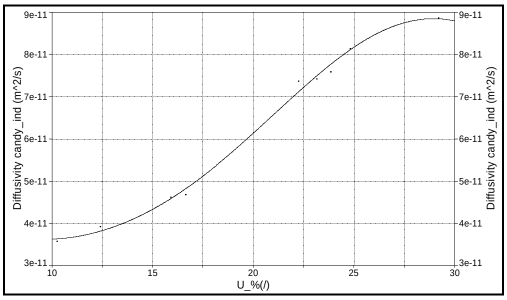

Figure 3: *D vs* U for industrial candies

Heat transfer coefficient *h* was determined as the ratio between the heat flux and the temperature difference among the oven environment and the product surface measured during the drying stage by flux sensor.

Mass transfer coefficients K_c at candy/air and starch/air were calculated with the Chilton-Colburn analogy, for flat slab and air tangential flow (Bird, Steward, Lightfoot 1960).

2.1.1. Numerical solution

The above system of nonlinear partial differential equation has been solved by the finite elements method developed by the commercial package called *Comsol Multyphysics* v.3.5 (Comsol, Sweden).

The control volume concerned was discretised into 23937 and 16888 triangular finite elements for the laboratory system (figure 4) and industrial one respectively, with a thicker mesh close to the candy/starch and candy/air interfaces.

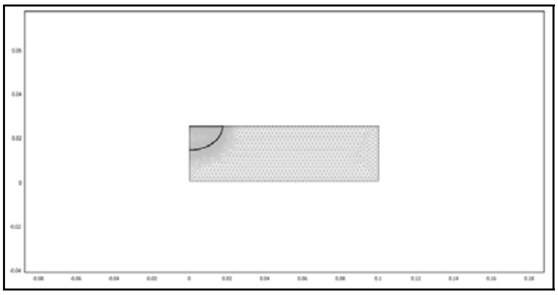

Figure 4: FEM mesh used to model laboratory candies

On 1.67 GHz and Intel Core 2 Duo PC running under Windows 2000, candy drying behavior over a time horizon of 48 h was simulated, on average, in about 15 min, using the time-dependent iterative nonlinear solver already implemented in the Chemical Engineering Module of the software.

It should be remarked that the proposed model does not need any parameters adjustment, but only the specification of a set of input variables that can be varied within a specific range of physical significance to simulate food drying behavior at different operating conditions. The above was tested simulating the humidity profile in the candy over time, varying air temperature in the range 18-50°C, at constant values of air relative humidity and starch humidity. Water activity profile at the candy/air and candy/starch interfaces were also obtained at the same operating conditions.

The water content concentration profile inside the candy was finally obtained from simulation, varying the relative humidity of the drying air in the range 0-100% and maintaining constant values of both air temperature and starch humidity.

3. RESULTS AND DISCUSSION

The simulation results expressed as the time evolution of candy average moisture content (U_b expressed on wet basis- $Kg_{water}/Kg_{wet\ solid}$), calculated as bulk integral, for the laboratory products were presented in figure 5. The candy humidity profile was obtained as a function of air relative humidity (U_r%) at the air temperature T_∞=50°C and starch water activity a_{ws}=0.115. Both temperature and moisture profiles within the candy were also calculated as a function of drying time but were not here reported.

Figure 5 shows the effect of air humidity on the drying process. As expected, with increasing its value, the final candy average moisture content results higher due to a substantial reduction of the concentration gradient, which is the driving force of moisture transfer from the candy to the air.

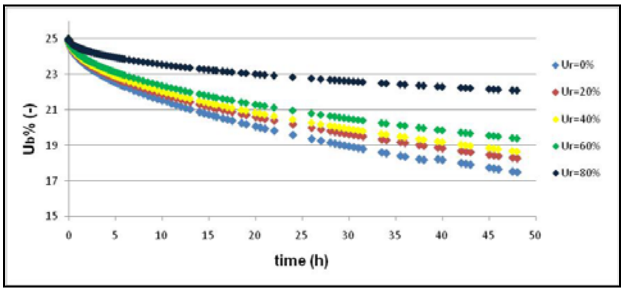

Figure 5: time evolution of laboratory candy U_b at different air relative humidity (U_r%) (T_∞=50°C,a_{ws}=0.115)

To confirm the above the time evolution of laboratory candy water activity (a_{wc}) at the candy/air and candy/starch interfaces were also presented in the figures 6 and 7 respectively.

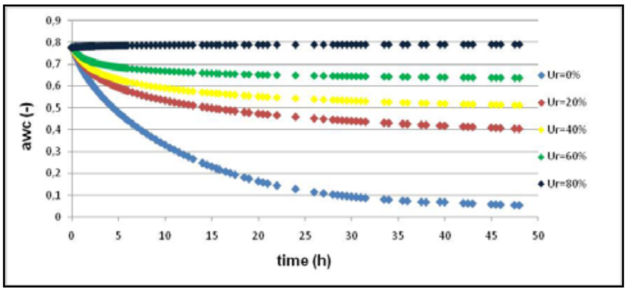

Figure 6: time evolution of laboratory candy a_{wc} at the candy/air interface at different air relative humidity (U_r%) (T_∞=50°C,a_{wc}=0.115)

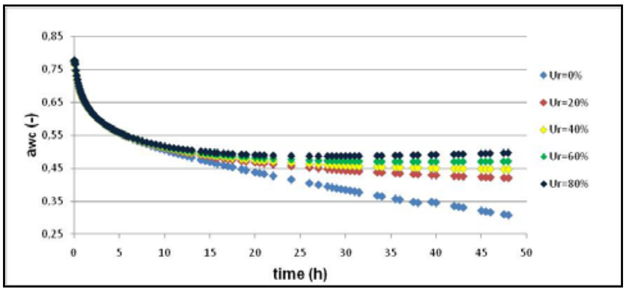

Figure 7: time evolution of laboratory candy a_{wC} at the candy/starch interface at different air relative humidity (U_r%) (T_∞=50°C,a_{ws}=0.115)

At both the interfaces the a_{wc} value after 48 hours of drying decreases with reducing air humidity, and these effects, as expected, result more significant at the candy/air than the candy/starch interface, confirming more and more what was said before.

Moreover, it is important to note that the air humidity also indirectly affects the concentration gradient at the candy/starch interface, confirming the findings of Sudharsan, Ziegler, and Duda 2004.

As expected air relative humidity proved to be the most important operating parameter among those investigated, with which it is possible to modify the candy drying stage. Actually simulations carried out at different air temperature and starch water activity values showed little and negligible effects on the candy humidity profile.

4. MODEL VALIDATION

Candy drying experiments were performed in the laboratory and some data were monitored in industry in order to be compared with the model theoretical predictions so as to verify their validity. Model predictions were obtained respecting the geometrical and operating conditions characteristic of both laboratory and industrial drying experiments.

Model validity was attained in the both cases investigated. Figure 8 shows the comparison between the experimental results and the model predictions for industrial candies only, obtained without any parameter adjustment.

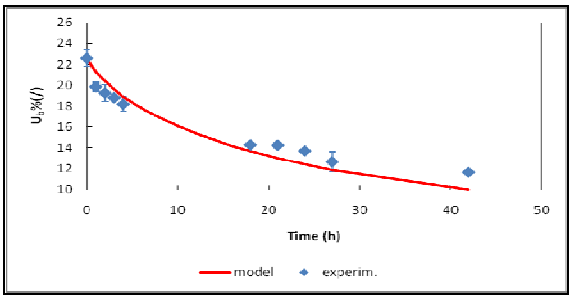

Figure 7: comparison between model prediction and experimental data evolution of industrial candies moisture content

A remarkable agreement is observed especially during the initial drying hours when experimental data and theoretical predictions overlap and relative errors never exceed 5%. Later on, a deviation can be observed, which can be ascribed to the lack of accounting for a formation of candy dry skin in the model. This sort of crust begins to appear typically in the final stage of the candy drying process from a region of low moisture content near the surface and is an additional resistance of moisture transport from the product to the air (Sudharsan, Ziegler, and Duda 2004). For this reason, probably, the model predicted a candy humidity reduction higher than the real one, just over last hours of drying process.

5. CONCLUSION

A theoretical analysis of the drying process of candies, produced with the starch molding technique, was presented. With respect to most works published in the literature, the main innovation introduced by this study lies in the model formulation. This, in fact, simulated the simultaneous bidimensional heat and moisture transfer accounting for the variation of both air and candy physical properties as functions of local values of temperature and moisture content. The numerical solution of unsteady-state heat and mass balance equations, performed by the finite elements method gave a good agreement between experimental results and model predictions, mostly during the initial drying hours. When candy dry skin effects occur a deviation between theoretical predictions and experimental results can be observed. The model that contains no adjustable parameter, is a powerful tool for analyzing the behavior of industrial drying ovens, as it could be used, over a wide range of drying conditions and of different types of candies, to individuate the "optimal" set of operating conditions in each specific situation. In this way, it might be possible to minimize expensive pilot test-runs and to have good indications on the characteristics and the quality of the final products.

The proposed model is general since it is capable of describing both the transport of free and bounded water within the food and the evaporation/condensation phenomena that, as a function of the actual driving forces, may occur at the air/candy and starch/candy interfaces. It is very flexible and can be easily adapted to different geometries with no *a priori* limitation for irregular or complex-shaped systems. Work is, however, in progress for improvement of the model features, in particular by seeking an independent and more reliable determination of heat and mass transfer coefficients and accounting for candy dry skin during the drying process.

AKNOWLEDGEMENT

The University of Calabria and the Food Science and Engineering Interdepartmental Center of University of Calabria and L.I.P.A.C., Calabrian Laboratory of Food Process Engineering (Regione Calabria APQ-Ricerca Scientifica e Innovazione Tecnologica I atto integrativo, Azione 2 laboratori pubblici di ricerca mission oriented interfiliera) are gratefully acknowledged.

The factory Silagum srl (Lamezia Terme (CZ) Italy), is also acknowledged for its kind support in the experiments.

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