A System for Food Drying Using Humidity Control and Low Temperature

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List of symbols

a_w	water activity
A	surface of the product (m^2)
b,c,k_1,k_2	model constants
D	effective moisture diffusivity (m^2/s)
h_m	mass transfer coefficient in the air boundary layer (kg/m^2s)
k_P	product intrinsic permeability to water vapour (m^2)
L	thickness of the product (m)
m_p	mass of the product (kg)
m_s	mass of the solids in the product (kg)
m_w	mass of the water in the product (kg)
$\vec{n}$	normal direction to product surface
p_{in}	water vapour pressure in the product (N/m^2)
p_o	water vapour pressure of the pure water (N/m^2)
p_{out}	vapour pressure outside the product (N/m^2)
$T_{\mathbf{a}}$	air temperature (K)
T_p	Temperature (K)
u_a	air velocity (m/s)
X_s	product moisture content (kg_w/kg_p)
φ_{out} =	p_{out}/p_o
μ	fluid viscosity (kg/ms)
ρ_p	particle density (kg/m^3)

ABSTRACT

Drying and maturation processes are widely used in food production, but a scientific approach has not so widely been applied, so rather empiric rules are often used to set up industrial production, particularly in small-medium firms. Humidity control of food is often achieved by regulation of the R.H. (Relative Humidity) and room temperature, taking into account the water evaporation inside the food matrix according to the air velocity. For each phenomenon a mechanism is ,in general, expressed using a driving force and a transport coefficient. In our model only the dominant mechanisms are considered. For the moisture diffusion in the solid toward its external surface we applied a concentrated parameter model, constant properties and no shrinkage. The system proposed in this paper consists of humidity and temperature control during the food drying process by using a particular dehumidifier equipped with a desiccant rotor containing silica gel. In each experiment we controlled the air humidity, temperature and velocity and we monitored the moisture content and temperature as function of time. Most of researchers worked in conditions tested in laboratory but a few has been done to verify these results under real conditions. Our model validates the experimental results obtained in real conditions and it has, also, been proved that dried products such as sausages treated by this method retain their fresh color, texture and their organoleptic properties to ensure their final quality.

Keywords: Food drying, humidification, relative humidity, temperature.

1. INTRODUCTION

Drying is one of the most diffused food preservation processes which is brought about by a simultaneous heat and mass transfer from/to the drying medium, frequently wet air, to/from the food sample. The process is governed by transient heat and mass transport phenomena. Some authors estimate drying with non-steady heat and mass transfer equations using constant or variable properties, showing that the constant properties assumption has application for engineering purposes and variable properties gives more phenomenological information for further predictions (I.I. Ruiz-Lopez, 2004). A mathematical model to predict the drying kinetics of shrinking bodies was proposed, assuming unidirectional drying and three-dimensional shrinkage. The model was numerically solved by finite differences, taking into account a convective term in the mass balance equation (consequence of non-unidirectional shrinkage (P.E. Viollaz, 2002). A first-order reaction kinetics model was also used, in which the drying constant is function of the process variables, while the equilibrium moisture content of dried products was fitted to GAB equation (M.K. Krokida).Three different mathematical methods were used to determine the diffusivity form the drying data. The first one assumes constant diffusivity, volume and temperature and zero surface resistance to mass transfer. The second one assumes a convective boundary condition. The third one also takes into account the shrinkage of the sample during drying (2003; F.J. Trujillo, 2007; F.J. Trujillo, 2003).In the case of foodstuffs with high initial moisture content and therefore having a high tendency to shrink, the model should incorporate the shrinkage factor for it to reflect the reality in terms of phenomenological prediction model. Using experimental values obtained by a high-speed laser scan micrometers, a critical moisture content, very different from that generally proposed in the literature,was exhibited (B.K. May, 2002). Other models take into account moisture diffusion and convective heat and mass transfer in the air boundary layer. Moisture diffusivity is dependent on material moisture content and temperature, while heat and mass transfer coefficients can be considered as constants (S. Dias 2004; Z.B. Maroulis, 1995). All the authors worked in controlled conditions but a few has been done to verify the results in true conditions as we have done stufying sausages drying processs. The production process for sausages has been investigated with the aim of improving control to obtain a high quality final product. The drying process plays an important role in assuring this because the operational conditions may lead to thermal and mechanical damage that affects the final texture of the sausage. Usually foods such as sausages are commonly dried in naturally ventilated rooms with suitable thermoigrometric conditions or by the use of a traditional refrigerating system (J.L.Roux, 2000; L.Brunetti, 2004). The drying time is affected by temperature and humidity changes due to the weather in the first case, although the method requires theoretically no energy, or to a rough control of temperature and humidity in the second case. In consequence the product may not be of uniform quality. In the present paper a mass transfer model has been analysed in order to determine its validity not only in controlled conditions (laboratory equipment) as done by many researchers but in true operating conditions. The refrigerating system adopted in the present experimentation uses a novel drying system equipped with an absorbing dehumidifier rotor to control the humidity during the drying period of the food. It allows separate control of the humidity and temperature inside the cold store (K.Nogaya, 2006; L.Brunetti, 2004; S.Dias, 2004; C.Salsilmaz, 2000; H.Okano, 1998). This system can be used for other foodstuffs such as cheeses and meat by-products with different humidity requirements. The system can also be used for storing stocks of perspiring food such as fruit and vegetables. The system has been tested under intensive and normal conditions in order to establish its reliability, the conditions under which its performance is highest and to study the potential use of the different elements of the system. The quality of the dried food, related to the system performance, and the dehumidification capacity of the dehumidifier have also been evaluated (K.Nagaya, 2006; H.Okano, 1998; A.Pasini 1999; P.Vega-Mercado, 2001). The cold store works under real conditions at variable temperature and relative humidity. The data recorded during the tests and extrapolation thereof has provided information useful for model validation.

2. MATERIALS AND METHODS

2.1 Physical Formulation

Drying is a complicated process involving simultaneous heat and mass transfer phenomena. Depending on the application, different phenomena are dominant. In convective air drying of solids, the phenomena which must be considered are the moisture diffusion in the solid toward its external surface, the vaporization and convective transfer of the vapour into the air stream, the conductive heat transfer within the solid mass and the convective heat transfer from the air to the solid's surface. For each phenomenon a mechanism is, in general, expressed using a driving force and a transport property (coefficient). Each property is a function of the material and/or the air conditions. In some applications or drying conditions, the contribution of one or two mechanisms can be negligible compared to the overall transport phenomena. In that case, the corresponding coefficient can be eliminated and the model can be simplified by deleting/modifying the corresponding term. In other words, only the dominant mechanisms are considered. Our drying experiments were performed in an experimental cold store, where air passed through the drying product. In each experiment we controlled air humidity, temperature and velocity and we monitored the moisture content and temperature of the product as a function of time. For the moisture diffusion in the solid toward its external surface the Fick's law can be applied (a concentration gradient is the sole driving force: Z.B. Maroulis, 1995):

$$\frac{\partial \rho_p X_p}{\partial t} = \nabla \cdot \left(\rho_p D \nabla X_p \right) \quad (1)$$

where ρ_p is the particle density (considered constant for a given material); X_p is the product moisture content and D is the effective moisture diffusivity (function of material moisture content X_p and the temperature T_p). Is also assumed that the water activity difference between the interface and the bulk mass is the driving force for the mechanism of vapour transfer in the air boundary layer:

$$\left(D \rho_p \nabla X_p \right) \cdot \vec{n} = h_M \left(a_{we} - a_w \right) \quad (2)$$

where h_m is the mass transfer coefficient in the air boundary layer, function of the air water activity a_w, air temperature $T_{\mathbf{a}}$ and velocity u_a, and $\vec{n}$ is the normal direction to product surface.

However this model can be simplified if an easy-to-use model is needed for engineering purposes. In the present paper a concentrated parameter model was chosen. It's known that the water activity is expressed as $a_w = p_{in}/p_o$ where p_{in} is the water vapour pressure in the product and p_o is the water vapour pressure of the pure water at the same temperature T_p of the product (T_p is often varying with time). The water activity at the interface a_{we} is in equilibrium with the solid and it is a function of a product moisture content X_p and the temperature T_p. The rate of moisture loss for a product maintained at a constant temperature and placed in a room of fixed relative humidity can be calculated by the equation:

$$-\frac{dm_p}{dt} = \frac{k_p}{\mu}\cdot\frac{A}{L}\cdot\left(p_{in}(t) - p_{out}(t)\right) = \frac{k_p}{\mu}\cdot\frac{A}{L}\cdot p_o(T(t))\cdot\left(a_w(t) - \varphi_{out}(t)\right) \qquad (3)$$

where $-dm_p/dt$ is the moisture loss for time unit; k_P is the intrinsic permeability (considered constant in most practical cases) of the water vapour; μ is the fluid viscosity; L is the thickness and A is the surface of the product; p_{out} is the vapour pressure outside the product; p_{in} is the vapour pressure inside the product; $\varphi_{out} = p_{out}/p_o$ and time dependence (t) is shown Considering the vapour pressure outside the product as constant, we may calculate the rate of moisture loss $-dm_p/dt$ by the use of 3) and the linear equation (A.L. Brody, 2001; H. Emblem, A. Emblem, 2001):

$$m_p = b\, a_w + c \qquad (4)$$

or, that is the same:

$$m_w/m_{ss} = k_1\, a_w + k_2 \qquad (5)$$

where m_w is the mass of water and m_{ss} the dry bulk mass of the product ($m_p = m_w + m_{ss}$). Then:

$$a_w = (m_p/m_{ss} - 1 - k_2)/k_1 \qquad (6)$$

Equation 3), with the substitution of 6), can be analytically integrated only in particular cases due to the variation of p_o and φ_{out} with time. Therefore numerical integration is performed and a forward difference scheme is used.

2.2 Experimental Equipment

Experimental tests have been carried out on a new drying system (figure 1) consisting of a cold store containing a dehumidifier which controls the humidity of the room air.
Probes connected to a data logger were used to measure main process parameters, in particular:

- a psychrometer to measure the dry temperature, the humid temperature, the dew point temperature and the relative humidity of the air inside the cold store (PasiniA.,1999);
- a hot wire anemometer to measure the absolute velocity of the air inside the cold store. This parameter is used only to verify that the process conditions are the same of those showed in literature (0.1-1 m/s for natural convection Pasini A. 1999).

The controlled period lasted 35 days during which time some sensory evaluations were carried out to verify the organoleptic qualities and appearance of the product (100 kg of meat, from the Large White breed of swine and contained in natural swine gut). The condition of the guts and the meat colour were examined before introduction into the cold store; the colour of the sausage appeared pleasant, with a dark and bright shade of red.
The period of activity of the dehumidifier was changed several times during the process to obtain a loss of weight not higher than 1% and to stop the maturation process before the 35th day from the start of the whole process.

In this system the condensation/drainage stage is omitted since the humid room air is directed out of the cold store (process air) and the dried air is introduced via the dehumidifier inside the cold store. The refrigeration system prevents any rises in temperature. In fact, in this case, the temperature of the cold battery is maintained at a level higher than the dew point to avoid vapour condensation and anomalous behaviours of the relative humidity of the room. In this system the temperature and relative humidity are controlled independently leading to significant benefits: this system positively affects the amount of electrical energy used during the refrigeration process because less power is required and the system is actively working for a shorter period than a traditional refrigeration systems.

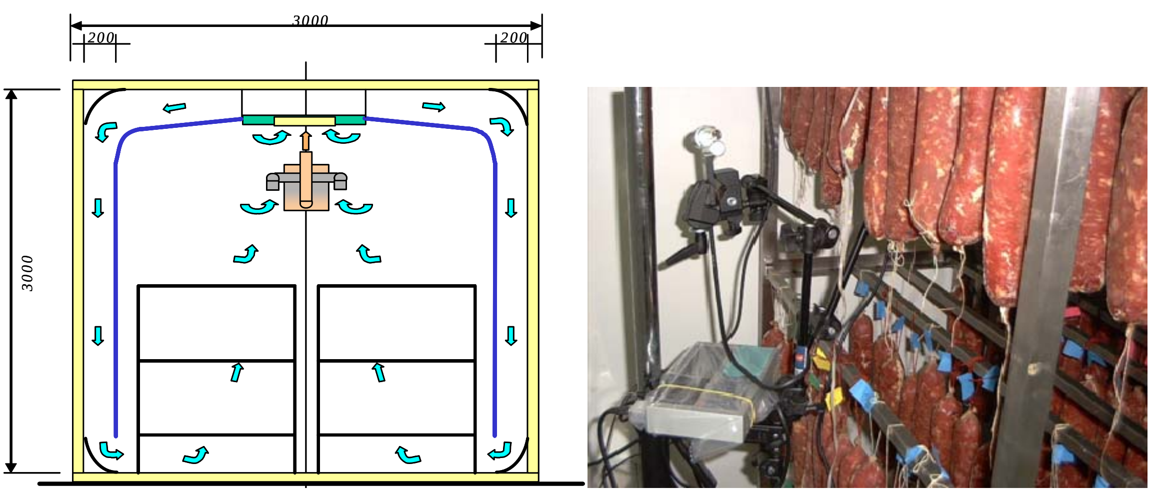

Figure 1. Scheme of the air conditioning and view of the inside of the refrigeration store with probes and products

The dimension of the cold store is 4 m^3. The dehumidifier, equipped with a desiccant rotor containing silica gel, consists of two zones (figure 2)

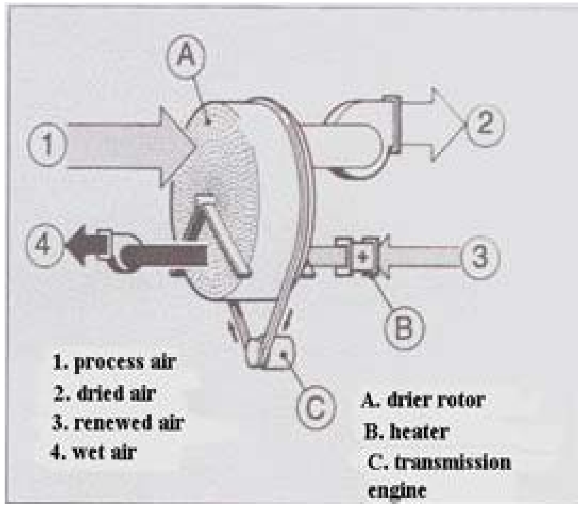

Figure 2. Scheme of the drier rotor and of the in and out air rates

The air which must be dehumidified (process air) is present in the first zone, where the humidity is absorbed by the porous material and the dried air passes through the special exit-grating and is returned to the cold store. Alternatively a split air flow (regenerated air), introduced from outside and properly heated to decrease the relative humidity, is passed to the second zone of the dehumidifier rotor. This airflow which consists of dried process air, is blown out by the same rotor, thus regenerating itself. During this process, the rotor rotates slowly, repeating this cycle and continuously producing dry air. The dehumidifier is installed inside the cold store and a fan blows the dry air up from the bottom, through lateral canals, through the food and out to the upper outlet. This system allows a uniform air distribution inside the cold store and the dehumidifier works as a warming battery following regular stop-and-go cycles for a defined period. The capacity of the heater is 650 W, the blower is capable of a rate of 90 m^3/h and the with total power is 474 W. An optimised process requires that the following process parameters are fixed before starting up the drying system:

1) the daily loss of sausages weight both as a percentage and as the absolute value relative to the intake load of the cold store;
2) the dehumidifier capacity in the time during the pause and process cycles;
3) the daily dehumidification cycles; (a dehumidification cycle is composed of an active period and a pause period of the dehumidifier).

The length of the dehumidification period must be planned for every cycle. The daily loss of weight is related to the number of cycles. Therefore this loss, related to the dehumidification capacity, gives the process-time of the dehumidifier (J.P.Girard, 1999; A.Gac, 1997; C. Fiameni, 2000). These parameters must be fixed in order to obtain optimum quality results for the product under process.
Moreover, other parameters have an influence on the drying process of a sausage:

- the geometry of the product;

- the type of covering material: natural or synthetic. In this case, a natural membrane is utilized as it allows better control of the drying velocity compared to a synthetic membrane;
- the type of mixture (granule size of the mixture, origin of the muscle, amount of fat and fat granule size).

The correct management of these parameters will result in optimal quality (Vega-Mercado, 2001; J.C. Ho, 2002) and a uniform loss of weight in the product.
Aim of the paper is to verify dehumidifier performance during the drying process and to validate the model developed above.

3. RESULTS

Figure 3 shows the trend of different samples of the examined product. The continuous lines represent the theoretical trend calculated using the model described previously; dots represent the values measured experimentally. A good fit is evident among the simulated and the measured values except for the final values; because, theoretically, dehydration should proceed more quickly. In fact, it doesn't occur because the process passed the first stage of drying, being in the second stage. The model used, as linear, has its validity till this time and it could be modified at the start of the non-linear phase. The value of water activity a_w has always been higher than 0.9 and this permitted to decrease the R.H. till the value of 74%.
The desiccant rotor allows the weight loss to be controlled and thus to be uniform and it can be seen that the process is influenced by the relative humidity of the air inside the cold store. When the dehumidifier is active a decrease in R.H. is observed, and when the dehumidifier is not in use the R.H. increases due to water evaporation from the sausages (70% - 85%). Therefore, good control of the humidity inside the cold store can be obtained by adjusting the period of activity of the dehumidifier.

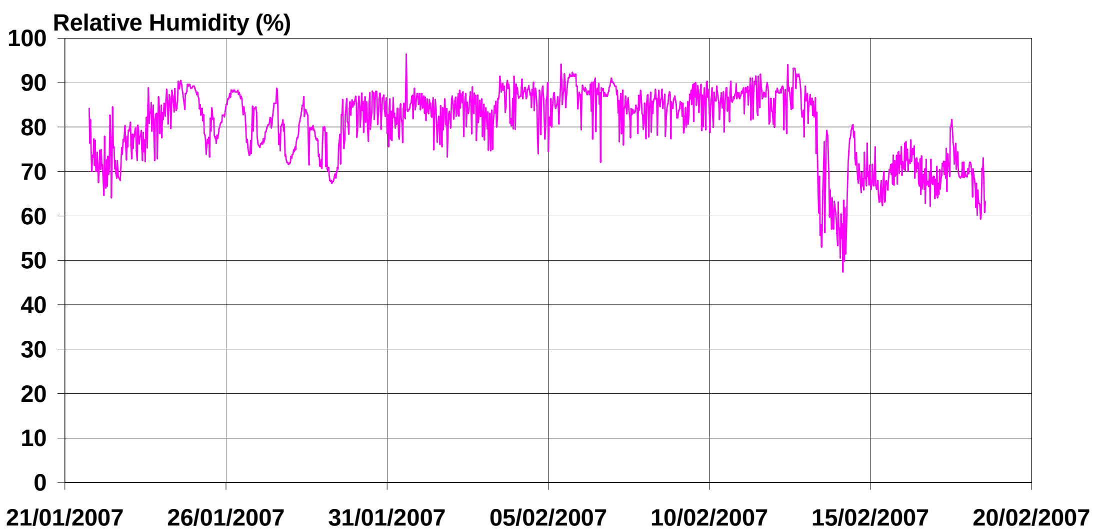

Figure 3a. Trend of Relative Humidity of the air in the cold store.

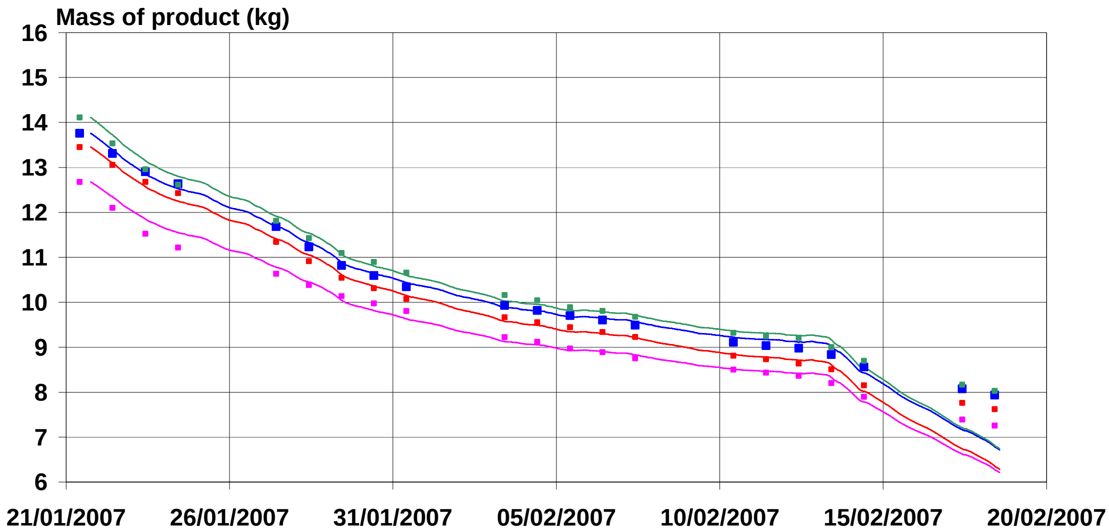

Figure 3b. Trend of product mass during the drying process in the cold store.

4. CONCLUSIONS

This paper is a contribution to the study of the optimization of the project parameters and the set up of a drying system using a dehumidifier equipped with a desiccant rotor containing silica gel.
The good fitting among the simulated and the measured values allows the use of the model in the optimisation of process parameters during food drying in the cold store varying air temperature and relative humidity according the desired weight loss of the product.
In fact the system separately controls the R.H. and the temperature inside the cold store to provide good quality products with regard to the organoleptic, sensory and health characteristics. At the end of the process the food, a typical Italian sausage, had 78% medium humidity with the appropriate loss of weight. The medium temperature of the air inside the cold store was 12 °C. The air velocity was 0.09 m/s with a distribution of the food on the trolleys which permitted a uniform air flow. The dehumidification process was regular and reliable (F.A. Garcia, 2001; G. Taraschi, 2000). The values of the parameters have been tested inside the cold stores. The life of the refrigeration system, one of the critical points of the system, can be assured by the short daily period of activity which may range from 4 to 7 h (instead of the 14–16 h used in a traditional maturing system) (E. Henne, 2000; P. Rapin, P. Jacquard, 1996;A.Y. Cengel, 1997), depending on the activity period of the refrigerator (compressor). This fact increases the reliability and at the same time decreases the costs of maintenance and management of the system.
In conclusion, using a rotating dehumidifier the thermoigrometric parameters inside the cold store can be closely controlled with the consequent beneficial effect on the working cycles.

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