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Drying of durum wheat pasta and enriched pasta: a review of modeling approaches

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Nomenclature

a_w	water activity coefficient, -
c	concentration, kg m^{-3}
C_P	heat capacity, J kg^{-1} K^{-1}
D	diffusion coefficient, m^2 s^{-1}
E_a	activation energy, J mol^{-1}
f	furosine concentration, mg 100 g of protein^{-1}
F	furosine production rate, mg 100 g of protein^{-1} h^{-1}
h	overall heat transfer coefficient, W m^{-2} K^{-1}
H	enthalpy, J kg^{-1}
I	evaporation rate, kg m^{-3} s^{-1}
J	Colburn factor, -
J_n	Bessel function of the first kind and nth order
k	permeability, m^2
k_h	thermal conductivity, W m^{-1} K^{-1}
$K_{m,\Delta c}$	overall mass transfer coefficient described from the gradient $c_{v,R_C,R_{ext}\ or\ X_C} - c_{v,\infty}$, m s^{-1}
$K_{m,\Delta M}$	overall mass transfer coefficient described from the gradient $M_{R_C,R_{ext}\ or\ X_C} - M_E$, kg m^{-2} s^{-1}
$K_{m,\Delta p}$	overall mass transfer coefficient described from a pressure gradient, kg Pa^{-1} m^{-2} s^{-1}
m	mass, kg
M	pasta moisture content on dry basis, kg H_2O kg dry solid^{-1}
MW	molecular weight, Dalton
n	mass flux, kg m^{-2} s^{-1}

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N^{ext}	mass flux at the solid-gas interface, kg m^{-2} s^{-1}
p^0	vapour pressure, Pa
p	partial pressure, Pa
P	pressure, Pa
q	empirical constant in Eq. (72)
r	radial coordinate, m
R	ideal gas constant, J mol^{-1} K^{-1}
R_C	external radius of cylindrical pasta, m
R_{int}	internal radius of tubular pasta, m
R_{ext}	external radius of tubular pasta, m
S	saturation of $V_{app} - V_s$ in water or gas, -
S_i	irreducible saturation, -
S_V	surface/volume ratio, m^2 (m^3)$^{-1}$
t	drying time, s
T	temperature, K
T_g	glass transition temperature, K
U	pasta moisture content on wet basis, kg H_2O kg wet solid^{-1}
V	volume, m^3
x	coordinate for thickness (m)
X_C	thickness of rectangular pasta, m
y	molar fraction, -
Y_n	Bessel function of the second kind and nth order

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z	mass fraction, -
Greek symbol	
α	shrinkage coefficient, -
α_h	thermal diffusivity, m^2 s^{-1}
β_n	roots of the Bessel function of the first kind and zero order, -
γ	first Lame coefficient, Pa
ε	volume fraction, -
κ	mechanical compressibility coefficient, Pa
λ	latent heat of vaporization, J kg^{-1}
η	volumetric fraction of water lost replaced by air, -
ρ	density, kg m^{-3}
ς	radius in Lagrangian coordinates, m
σ	stress, Pa
τ	strain, -
τ_p	pore tortuosity, -
μ	second Lame coefficient, Pa
μ^0	viscosity, kg m^{-1} s^{-1}
χ	shrinkage, -
Dimensionless numbers	
Nu	Nusselt

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Pr	Prandtl
Re	Reynolds
Sc	Schmidt
Sh	Sherwood
Superscripts	
eq	equilibrium
int	internal
ext	external
f	fluid
g	gaseous phase
Subscripts	
0	initial condition
1	first
a	air
app	apparent
eff	effective
E	equilibrium
f	at film conditions
g	gaseous phase
h	heat

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i	intrinsic
lim	limit
m	mass
PPC	pea protein concentrate
r	relative
rr	radial
s	dry solid
sem	semolina
v	water vapour
vol	volume
w	water
θθ	tangential

1. Introduction

Drying is recognized as the step in pasta production that has the greatest impact on the quality of the final product. This operation is generally carried out under relatively severe temperature and moisture conditions which can significantly affect the physical, esthetic, textural, organoleptic and cooking properties of the pasta produced (Andrieu & Stamatopoulos, 1986; Owens, 2001). Consequently, a precise analysis of optimal drying conditions is necessary in order to improve the quality of pasta while at the same time reducing production costs.

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Nowadays, optimal pasta production conditions are usually determined by trial-and-error runs and from the experience acquired by producers over the years (Andrieu & Stamatopoulos, 1986; Migliori et al., 2005a; Veladat et al., 2011). However, this method makes it difficult to completely optimize operating conditions when several interdependent variables must be considered simultaneously, such as the quality of the final products, drying time, energy used and overall production cost. In addition, when a new product is put on the market, many tests may be needed before satisfactory drying conditions are determined. That is why several mathematical models have been developed over the years describing the evolution of certain pasta properties during drying according to the operating conditions. These models make it possible to improve understanding of how the operating conditions impact the properties of dry pasta, to minimize the number of tests required to determine optimal drying conditions, and to develop efficient control strategies for the process (De Temmerman et al., 2007; Veladat et al., 2011).

The models developed to date present varying degrees of complexity depending on the mass and heat transfer mechanisms considered and the hypotheses used. Depending on this degree of complexity, the models can lead to an analytical solution or have to be solved using numerical methods. The analytical solution models are generally preferred for their simplicity. In addition, they provide more direct information in terms of the impact of operating conditions on product properties, since these variables appear directly (explicitly) or indirectly (implicitly) in the equations generated. However, obtaining analytical solutions requires greatly simplifying the phenomena involved or the operating conditions, which can reduce the accuracy of the results. When all the phenomena that occur during drying are considered and described according to first principles equations, numerical solutions are typically generated.

Models can also be classified according to the scope of the parameters they take into consideration. At first, models generally aim to describe the evolution of moisture in pasta during drying according to the operating conditions applied. However, some models have also extended the analysis to mechanical, rheological and chemical properties of pasta, such as the dimensions, porosity, density, rigidity, formation of cracks and furosine production (Andrieu & Stamatopoulos, 1986; Ponsart et al., 2003; Migliori et al., 2005b; Mercier et al., 2011). Incorporating these properties allows to generate a more complete database that can be used to study the relationship between product quality and drying conditions.

Finally, the models can be analyzed according to their ability to adapt to new production realities such as the addition of specific ingredients in the product's final formulation. These ingredients are generally selected for their high content in protein, omega-3, vitamins or other bioactive compounds, and aim to increase the nutritional value of the pasta. However, adding these compounds can have a significant impact on the chemical and physical properties of pasta (Nielsen et al., 1980; Zhao et al., 2005; Alireza Sadeghi & Bhagya, 2008; Gallegos-Infante et al., 2009; Wood, 2009). Consequently, it is relevant to analyze the validity of current models to represent this new reality, because these models were generally developed for pasta consisting of a standard mixture of durum wheat semolina and water.

The purpose of this review is to analyze the models on pasta drying developed up to date and to identify potential advances in the field to help optimize the production process according to product formulation and consumer needs. To achieve this, a description of the main phenomena involved in drying is first presented. The models developed to describe these phenomena are then presented, and the scope of the experimental validation of these models is analyzed. The basic equations for a mechanistic model are then developed and compared with those of current models, and modelling approaches for more accurate description of moisture transport near glass transition are presented. Finally, the ability of models to predict pasta quality as defined by consumers is discussed, along with the validity of the models for describing new production realities such as adding ingredients with high nutritional value in the product formulation.

2. Main phenomena

Pasta production is a process consisting of three main steps: hydration, extrusion and drying (Veladat et al., 2011). In the first step, semolina and water are mixed until they reach a moisture content level of about 50% (db). A gluten network then forms, which represents the main structure for maintaining the physical integrity of the pasta. Additional ingredients that increase the nutritional value of the product can also be added at this stage. The mixture is then extruded using Teflon or bronze matrixes to mould the fresh pasta into the desired size and shape. Drying is the last operation before the final product is packaged.

The purpose of drying is to decrease the water content of the pasta to a value below about 14% (db) in order to reduce the risk of microbial growth, increase the product's shelf life and obtain pasta that is strong enough to be stored and transported easily (Owens, 2001). This operation is generally carried out by placing the pasta in a dryer at temperatures of 40°C–120°C and relative humidities of 40%–95% (Owens, 2001; De Temmerman et al., 2007). Dehydration is then a result of transient mass and heat transfer phenomena occurring until a state of equilibrium between the pasta and dryer environment is reached.

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According to Ogawa et al. (2012), pasta drying can be divided into a constant drying-rate period, where about 20% of water is evaporated, followed by a falling-rate period. It is generally considered that the mass transfer mechanisms involved are the diffusion of the water in liquid form to the surface of the product, followed by evaporation of the water on the surface (Migliori et al., 2005a; De Temmerman et al., 2007). Internal resistance to the transport of water is assumed to be the limiting factor. Consequently, during drying, moisture diffusion develops inside the product, which is commonly described using Fick-type laws (Andrieu & Stamatopoulos, 1986; Migliori et al., 2005a; De Temmerman et al., 2007). However, it is possible that other water transport mechanisms contribute to the dehydration of the product, such as transport of vapour or liquid water by pressure gradient (Litchfield & Okos, 1992; Waananen & Okos, 1996; Veladat et al., 2011). This is particularly true for drying under very high temperatures (> 100°C), which can cause the evaporation front to be displaced deeper into the pasta.

In terms of heat transfer, pasta temperature rises after the pasta is placed in dryers. This increase is caused by convection at the surface and conduction inside the pasta, although internal heat transfer through convection is also possible when there is a hydrodynamic water flow caused by a pressure gradient. When water evaporation is concentrated on the surface and water is supplied rapidly enough to this surface, the pasta acts like a wet bulb thermometer. The heat supplied by the ambient air is then equivalent to the heat absorbed by vaporization, such that the pasta temperature is uniform (wet bulb temperature). When evaporation becomes insufficient, the pasta temperature starts to rise (Bird et al., 1960). According to the relative magnitude of the pasta thermal conductivity and surface heat transfer coefficient, an internal temperature gradient will be established, or the product will be considered as spatially isotherm. The temperature increase is also dependent on the isosteric heat of desorption, defined as the difference between the heat of desorption and the heat of vaporisation. The net isosteric heat of desorption generally increases during drying, such that the energy required to break the attractive forces between the water molecules and the solid phase increases when the pasta is near the equilibrium moisture content (Escobedo-Avellaneda et al., 2011; Noshad et al., 2012). However, given the high thermal conductivity of pasta and its small thickness, the pasta and the environment generally reach equilibrium rapidly compared with the duration of the mass transfer phenomena (Andrieu & Stamatopoulos, 1986; De Temmerman et al., 2007). This is why several models disregard the heat transfer phenomena and consider pasta drying as an isothermal process (Villeneuve & Gelinas, 2007; De Temmerman, 2008; Mercier et al., 2011).

During drying, when the moisture content decreases from about 50% to fewer than 14% (db), pasta usually undergoes glass transition. Glass transition represents the transition of the amorphous components from a supercooled melt to a glassy state, or the opposite (Liu et al., 2006). It is referred as a second-order state transition, which is a transition that occurs without the release or absorption of latent heat (Rahman, 2006). The point at which pasta undergoes glass transition depends both on its water content and drying temperature. Cuq et al. (2003) observed that despite of pasta heterogeneity, for a specific moisture content, it undergoes glass transition at a single apparent glass transition temperature. The glass transition temperature is generally lower for pasta with a high moisture content, which can be explained by the plasticization effect of water on amorphous polymers.

Glass transition is usually associated with significant physical, mechanical, electrical and

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thermal properties changes of the product (Rahman, 1995). As observed by Cuq et al. (2003), pasta behaves as an elastic and rigid product in the glassy state and as a visco-plastic and soft product in the rubbery state, with a transitional state in between. Glass transition can also affect moisture transport during drying. Xing et al. (2007) measured internal moisture profiles of pasta and observed sharper moisture profiles than those predicted from classical Fick-type models. This could be attributed to the formation of a hard, glassy surface which can induce important local changes in the transport properties within the pasta (Hills et al., 1997). The sharp internal moisture profiles could also be explained by the time-dependant viscoelastic relaxation of pasta amorphous components. In the transitional state near the glass transition, the relaxation time of polymers can be of the same order as the diffusion time, thus inducing anomalous diffusion and sharper moisture profiles (Takhar, 2008). These results suggest that changes in the viscoelastic properties taking place during drying should be considered to model accurately the internal moisture profiles of pasta near the glass transition.

Pasta shrinkage also has to be considered for accurate modeling of pasta drying. Shrinkage is caused by the partial replacement of the water lost during drying by air. Mercier et al. (2011) observed shrinkage equivalent to 21% and 30% of initial pasta volume when drying at 40°C and 80°C, respectively. Shrinkage seems to be greater when pasta is dried at high temperatures, which could be explained by the glass transition that occurs at lower water content in high drying temperatures, and the hypothesis that shrinkage is greater in the rubbery state than in the glassy state (Rahman, 2001). This hypothesis is supported by products where shrinkage is greater for convective drying than for freeze drying, such as apples, bananas, potatoes and carrots (Krokida & Maroulis, 1997), soybeans (Qing-guo et al., 2006) and quince (Koç et al., 2008). Pasta shrinkage is an important phenomenon to consider since its intensity has a direct influence on the apparent density and porosity of the product. Although the impact of these properties on pasta quality has not been extensively studied yet, in the case of products such as fresh apples (Vincent, 1989), potatoes (Scanlon et al., 1998) and extruded starch (Bhatnagar & Hanna, 1997), strong dependencies have been observed between these properties and the mechanical behavior of these products. In addition, the results from Waananen & Okos (1996) indicate that pasta porosity has an impact on the effective diffusion coefficients of water, and therefore on the speed at which the product dehydrates during drying. According to these authors, this result could be explained by a more important contribution of water diffusion in vapour form for porous pasta.

The generation of mechanical stress inside the product during dehydration also has to be considered in the modelling of pasta drying. This mechanical stress can cause the formation of cracks inside the product and thereby greatly affect its quality. Generally, crack formation is explained by non-uniform shrinkage of the pasta in the direction of mass transfer (Litchfield & Okos, 1988; Ponsart et al., 2003). This phenomenon is caused by the creation of a moisture gradient inside the pasta, thereby causing non-uniform shrinkage in the direction of water diffusion. This local shrinkage generates radial and tangential stresses inside the product, which can cause cracks to form when these stresses are greater than the maximum tolerance of the gluten network (Musielak, 1996; Ponsart et al., 2003). Glass transition may also play an important role in crack formation and propagation. During drying, the rate of moisture lost at the pasta surface is higher than at the center, such that the surface can be in a glassy state while the core is still in a rubbery state. This non-uniform glass transition induces significant variations of viscoelastic properties in the product, which can contribute to the creation of internal stresses (Cnossen et al., 2001; Takhar et al., 2006; Xing et al., 2007; Hundal & Takhar, 2010).

A more common practice adopted in the industry nowadays consists of drying pasta at high (around 80 ºC) or ultra-high (above 100 ºC) temperatures. The selection of high drying temperatures reduces the time required for the operation and can increase productivity. It is also generally accepted that drying under high temperatures gives less sticky, firmer and better quality pasta (De Noni & Pagani, 2010), which can be explained by the changes in the microstructure of the product during drying. High temperature drying promotes coagulation and aggregation of the gluten proteins, as supported by their lower solubility and the formation of large polymeric proteins at the expense of monomeric proteins (Lamacchia et al., 2007; Wagner et al., 2011). Protein coagulation prior to the cooking step leads to the development of a strong and continuous gluten network surrounding starch granules (Zweifel et al., 2003; De Noni & Pagani, 2010). This gluten network acts as a barrier limiting water penetration, starch swelling and amylose leaching during cooking, resulting in pasta with better overall properties. High drying temperature could also impact starch-proteins interactions, which has been shown to greatly impact the product rheological properties (Edwards et al., 2002).

However, high temperatures favour the development of Maillard reactions, which give the product a brown colour that is generally not appreciated by consumers (Feillet et al., 2000; De Noni & Pagani, 2010). Furthermore, using high temperatures can affect the nutritional properties of pasta because of protein denaturation and reduced digestibility (De Zorzi et al., 2007; Petitot et al., 2010; De Noni & Pagani, 2010). These phenomena have to be considered when selecting drying conditions, especially when heat-sensitive ingredients, such as those with high omega-3 and protein content, are added to the product formulation.

3. Modelling pasta drying

3.1 Mass transfer

As shown in Figure 1, three different shapes are generally considered in pasta modelling: cylindrical (spaghetti, vermicelli, etc.), tubular (macaroni, penne, etc.) and rectangular (lasagna, linguini, etc.). In most models, only the mass transfer in the smallest dimension of the pasta is considered and this transfer is usually described by a Fick-type law:

$$\frac{\partial M}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_{eff}\frac{\partial M}{\partial r}\right) \quad (\text{cylinder or tube}) \quad (1)$$

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D_{eff}\frac{\partial M}{\partial x}\right) \quad (\text{rectangle}) \quad (2)$$

where M represents the total moisture content (i.e., liquid + vapour) of the pasta, D_{eff} is the moisture effective diffusion coefficient, r is the radial coordinate, x is the coordinate for the thickness and t is the time. The effective diffusion coefficient D_{eff} represents a parameter that simultaneously describes the different mass transfer mechanisms involved, including the molecular diffusion of the water that can be in liquid or vapour form, water flow in a liquid form caused by capillarity, and flow caused by pressure gradient (Datta, 2007). The models developed from equations 1 and 2 are therefore semi-empirical and provide a simplified description of product dehydration compared with the more fundamental models based on the first principles for each of the components and phases of the system.

For one-dimensional models, the Fick-type law is usually solved using an initial condition and two boundary conditions. The initial condition refers to the uniformity of the moisture inside the pasta at the start of drying ($t = 0$):

$$M = M_0 \text{ for } 0 < r < R_C \text{ or } R_{int} < r < R_{ext} \; (\text{cylinder or tube}) \quad (3)$$

$$M = M_0 \text{ for } 0 < x < X_C \; (\text{rectangle}) \quad (4)$$

where M_0 represents the moisture content of the pasta at the start of drying, R_C is the radius of cylindrical pasta, R_{int} and R_{ext} are the internal and external radii of tubular pasta and X_C is the thickness of rectangular pasta. The boundary conditions vary according to the shape considered and model studied. These boundary conditions can be divided into three groups: (1) those where the water flux at a surface is specified; (2) those where the water content at a surface is specified; and (3) those where the water flux at a surface is described using a mass transfer coefficient and a surface moisture gradient. The boundary conditions of the first group are generally applied to cylindrical pasta based on their radial symmetry (equation 5), to rectangular pasta with two sides exposed symmetrically to the dryer environment (equation 6) or to rectangular pasta where one side is placed on a plate and is considered to be isolated (equation 7):

$$\frac{\partial M}{\partial r} = 0 \text{ for } r = 0 \text{ and } t > 0 \; (\text{cylinder}) \quad (5)$$

$$\frac{\partial M}{\partial x} = 0 \text{ for } x = \frac{X_c}{2} \text{ and } t > 0 \; (\text{rectangle}) \quad (6)$$

$$\frac{\partial M}{\partial x} = 0 \text{ for } x = 0 \text{ and } t > 0 \; (\text{rectangle}) \quad (7)$$

The boundary conditions of the second group are applied when the external mass transfer resistance is neglected and, consequently, the time required for the pasta to reach an equilibrium moisture value M_E is negligible compared with the total drying time:

$$M = M_E \text{ for } r = R_C, R_{int} \text{ and/or } R_{ext} \text{ and } t > 0 \ (\text{cylinder ou tube}) \quad (8)$$

$$M = M_E \text{ for } x = 0 \text{ and/or } x = X_C \text{ et } t > 0 \text{ (rectangle)} \quad (9)$$

The boundary conditions for the third group are used in the models developed by Ponsart et al. (2003), Migliori et al. (2005a) and De Temmerman et al. (2007). In these models, the moisture flux at the pasta surface is described using a mass transfer coefficient K_m and one of these two driving forces: the difference between the moisture of the pasta at its surface and equilibrium moisture content M_E (equations 10 and 11) or the difference between the concentration of water vapour at the surface of the pasta and inside the dryer (equations 12 and 13):

$$-\rho_{app} D_{eff} \left.\frac{\partial M}{\partial r}\right]_{R_C,\ R_{int}\ or\ R_{ext}} = K_{m,\Delta M}\left(M_{R_C,\ R_{int}\ or\ R_{ext}} - M_E\right) \ (\text{cylinder or tube}) \quad (10)$$

$$-\rho_{app} D_{eff} \left.\frac{\partial M}{\partial x}\right]_{X_C} = K_{m,\Delta M}\left(M_{X_C} - M_E\right) \text{ (rectangle)} \quad (11)$$

$$-\rho_{app} D_{eff} \left.\frac{\partial M}{\partial r}\right]_{R_C,\ R_{int}\ or\ R_{ext}} = K_{m,\Delta c}\left(c_{v,R_C,\ R_{int}\ or\ R_{ext}} - c_{v,\infty}\right) \ (\text{cylinder or tube}) \quad (12)$$

$$-\rho_{app} D_{eff} \left.\frac{\partial M}{\partial x}\right]_{X_C} = K_{m,\Delta c}\left(c_{v,X_C} - c_{v,\infty}\right) \text{ (rectangle)} \quad (13)$$

where M_{R_c}, $M_{R_{ext}}$ and M_{X_c} represent pasta moisture (solid side) at the pasta-air interface, c_{v,R_c}, $c_{v,R_{ext}}$ and c_{v,X_c} are water vapour concentration (air side) at the pasta-air interface and ρ_{app} is the apparent density of the pasta. The water vapour concentration inside the dryer $c_{v,\infty}$ is calculated using an equation of state (such as the ideal gas law) and an activity coefficient a_w assuming a state of equilibrium at the interface (i.e., $y_v^{eq} = y_{v,R_C\ ,R_{ext} or\ X_C}$):

$$Py_v^{eq} = p_w^0 a_w, \tag{14}$$

where P represents the pressure inside the dryer, y_v is the mole fraction of water vapour and p_w^0 is the water vapour pressure. The water activity coefficient is assumed to be dependent on the temperature T and the moisture content of the pasta. Many equations have been developed to relate these variables, and their accuracy for describing pasta dehydration isotherms has been studied by De Temmerman et al. (2008). The best results were obtained with an Oswin equation:

$$\bar{M} = \left(A_1 - A_2 T\right)\left[\frac{a_w}{1-a_w}\right]^{\left(B_1+B_2 T\right)}, \tag{15}$$

where $A_1 = 0.138$, $A_2 = 10.4 \times 10^{-4}$, $B_1 = 0.396$, $B_2 = 11.6 \times 10^{-4}$, $\bar{M}$ is the pasta average moisture content (according to r or x) and T is in ºC.

The choice of the boundary conditions is a determining factor in the ability to solve the Fick-type law and obtain an analytical solution. Table 1 shows the analytical solutions obtained for several pairs of boundary conditions. These solutions were developed by the separation of variables method and are valid under the following assumptions: (1) the initial moisture profile of the pasta is uniform or analytical; (2) pasta shrinkage is negligible and (3) the effective diffusion coefficient is constant for the considered moisture range.

3.1.1 Mass transfer coefficients

The use of boundary conditions (10)-(13) requires the value of the mass transfer coefficient K_m to be known. In the models developed by Migliori et al. (2005a) and De Temmerman et al. (2007), the value of the mass transfer coefficients $K_{m,\Delta c}$ is estimated using Colburn factors for the mass (J_m) and heat (J_h) transfer. These factors are related to the Nu, Sh, Sc

and *Pr* numbers of the system according to the following definitions:

$$J_m = \frac{Sh}{ReSc^{1/3}} \tag{16}$$

$$J_h = \frac{Nu}{RePr^{1/3}} \tag{17}$$

The mass transfer coefficient can then be determined using the Chilton-Colburn analogy according to which, for the system being considered, $J_m = J_h$. The following equation is thus obtained:

$$\frac{h}{K_{m,\Delta c}} = \rho_a C_{p,a} \left(\frac{\alpha_{h,a}}{D_{v-a}} \right)^{2/3} \tag{18}$$

In equation (18), the density (ρ_a), heat capacity ($C_{p,a}$) and thermal diffusivity of the air ($\alpha_{h,a}$), as well as the diffusion coefficient of water in the air (D_{v-a}), are dependent on the temperature. As a function of the temperature inside the dryer T_∞, equation (18) becomes (De Temmerman et al., 2007):

$$\frac{h}{K_{m,\Delta c}} = -208.09 \ln\left(T_\infty\right) + 1795.4 \tag{19}$$

Equation (19) makes it possible to determine the value of the mass transfer coefficient when the heat transfer coefficient h is known. In the model developed by De Temmerman et al. (2007), the value of coefficient h is determined experimentally. In the model by Migliori et al. (2005a), the following two-parameter equation is used:

$$J_h = aRe^b, \tag{20}$$

where, for the conditions and geometry (tubular) considered, a = 0.4096 and b = -0.4485.

However, the model developed by Migliori et al. (2005a) initially led to lower moisture results compared with the experimental data. It was assumed that this difference was caused by an overestimate of the mass transfer coefficient. New optimized transfer coefficients were then calculated in order to minimize the squared error between the experimental data and the data derived from the model. A ratio between the optimized coefficients and the initial coefficients of 0.0085 was obtained. However, the hypothesis that the divergence between the theoretical and experimental results was caused solely by a poor initial estimate of the mass transfer coefficient was not verified.

In the case of pasta, few data are available to estimate the value of the mass transfer coefficient when the difference between the moisture of pasta (solid side) at the surface and the equilibrium moisture content is used as the driving force (equations 10 and 11). It does not seem possible to relate this coefficient to the value for the mass transfer coefficients $K_{m,\Delta c}$ because of the non-linearity between the moisture content of the pasta and the relative humidity of the dryer (equations 14 and 15). However, some values for these coefficients are available for the drying of different products with a similar shape. For instance, a ratio $K_{m,\Delta \mathrm{M}} / \rho_{app}$ of 3.798 x 10^{-7} m s^{-1} has been calculated for the drying of rice (modelled as cylinders with a diameter of 2.34 mm and an infinite length) at 60°C and under an air velocity of 1.5 m s^{-1} (Silva et al., 2010).

3.1.2 Effective moisture diffusion coefficients

Solving the Fick-type law using its initial condition and its two boundary conditions also requires knowledge of the value of the effective diffusion coefficient D_{eff} of water in the pasta. In the model developed by Migliori et al. (2005a), the value of this coefficient is determined

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experimentally for pasta with a moisture content greater than 0.2 (wb) using nuclear magnetic resonance (NMR). In the absence of experimental measurements, the value of this coefficient can still be estimated using correlations listed in the literature. Table 2 presents the correlations that have been developed specifically for pasta, along with the extrusion and experimental drying conditions used to develop these equations. In addition, Table 3 presents the values of the effective diffusion coefficients obtained from these correlations for drying under typical conditions (T_∞ = 80°C, RH = 65%, P_∞ = 101 kPa, M = 0.30 and ε = 0.10). This table also presents the effective diffusion coefficients obtained when more extreme values of these five parameters are applied one by one compared with the reference scenario.

Basically, the equations in Table 2 have a similar structure by the description of the dependence of the effective diffusion coefficient for the temperature based on an Arrhenius equation of the form $D_{eff} = Aexp(-E_a / RT_\infty)$. An increase in the drying temperature is therefore related to an increase in the effective diffusion coefficients of a magnitude determined by the value of the activation energy E_a. According to the data presented in Table 3, rising the drying temperature from 40°C to 120°C would result in an increase in the effective diffusion coefficient in the order of 10^{-10} m^2 s^{-1}. For illustration purposes, according to the analytical solution of the Fick-type law for cylindrical pasta under boundary conditions (5) and (8) (see Table 1), the time required to reduce the moisture from 0.5 to 0.14 (db) in pasta 2.5 mm in diameter with an equilibrium moisture content of 0.1 would be about 370 minutes at 40°C and 80 minutes at 120°C.

Depending on the correlation considered, terms are added to the Arrhenius equation to describe the impact of additional parameters on D_{eff}, including the relative humidity maintained inside the dryer. In general, an increase in relative humidity is associated with a decrease in the value of the effective diffusion coefficients. In the correlation developed by Villeneuve & Gelinas (2007), this effect is taken into account by introducing an additional term inside the exponential. According to their sensitivity analysis using this equation, the effect of relative humidity on the effective diffusion coefficient value would be greater than the effect of temperature. However, this result contradicts those of Andrieu & Stamatopoulos (1986) and Litchfield & Okos (1992), whose experimental data suggest that the impact of this parameter tends to be negligible. According to Villeneuve & Gelinas (2007), these differences could be attributed to their drying system that consists of an environmental chamber in which moisture is controlled using an electric steam generator and a cooling circuit. This system could allow more precise, stable and efficient control of relative humidity compared with systems where this parameter is measured using dry-bulb and wet-bulb thermometers and controlled with salt solutions or generators located in separate compartments.

In the equations developed by Litchfield & Okos (1992) and De Temmerman et al. (2007), terms are also added to the Arrhenius equation to describe the dependence of the effective diffusion coefficient for pasta moisture. In general, studies suggest that the value of the effective diffusion coefficients decreases during drying as the amount of free water (i.e., $M - M_E$) diminishes. Nevertheless, these variations can sometimes be neglected within certain water content ranges (Datta, 2007). In the model developed by Villeneuve & Gelinas (2007), the value of the effective diffusion coefficient is considered to be constant throughout drying. This hypothesis seems to be supported by the correlation from De Temmerman et al. (2007) according to which a negligible difference in the value of the effective diffusion coefficients is obtained

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within the moisture range of 0.1 to 0.5 (db) at the drying conditions considered. The results of Andrieu & Stamatopoulos (1986) suggest that the variation of diffusion coefficients is negligible for the following three moisture ranges (db): $M > 0.27$; $0.27 > M > 0.18$ and $0.18 > M > M_E$. According to their experimental data of pasta Young's modulus as a function of its water content, these three ranges match the transition of pasta from a rubbery state to a transient state and then to a glassy state. Consequently, it is possible that the variation in effective diffusion coefficients during drying could be partially attributed to changes in the rheological properties of the pasta. As shown in Table 3, a difference of about 40 x 10^{-12} m^2 s^{-1} can be observed between the value of the effective diffusion coefficient at the start and end of drying for a temperature of 80°C. This difference is an order of magnitude similar to the one calculated using the Litchfield & Okos (1992) correlation for moisture contents between 0.5 and 0.1 (db) at this same temperature.

Waananen & Okos (1996) studied the effect of porosity and pressure on the effective diffusion coefficient. Their results indicate that the value of the effective diffusion coefficients is proportional to the porosity of the pasta and inversely proportional to the pressure maintained inside the dryer. This effect could be attributed to a larger contribution of water diffusion in the form of vapour for pasta with a high porosity and dried at low pressures. However, according to the data in Table 2, the sensitivity of the effective diffusion coefficients for these two parameters seems to be lower than their sensitivity for temperature, relative humidity and water content of the pasta.

Overall, according to the results presented in Table 3, a difference of a little more than one order of magnitude in the value of D_{eff} is observed depending on the equation used. Many reasons could contribute to explaining this degree of variability, including:

(1) The type of experimental drying system used in developing the equations. This parameter can influence the precision with which the operating conditions are controlled, and can have an impact on the parameters that are not considered in the models such as air velocity at the surface of the pasta.

(2) The experimental drying conditions used in developing the equations. These parameters can influence the precision of the value obtained for the effective diffusion coefficients, particularly when the equations are used to estimate the effective diffusion coefficient in drying conditions that are different from those considered experimentally.

(3) The method used to calculate D_{eff} from experimental data. In the studies considered, the main variable measured during drying is the evolution of the water content of the pasta. The value of the effective diffusion coefficients is then determined by minimizing the error between the experimental water content data and the water content predicted from a model. Consequently, the value of D_{eff} is directly dependant on the model used. For example, the correlations from Litchfield & Okos (1992), Waananen & Okos (1996) and Villeneuve & Gelinas (2007) were developed using D_{eff} values obtained from the analytical solutions of the Fick-type law (Table 1), while the experimental values of D_{eff} from the De Temmerman et al. (2007) correlation were determined using a model where the external mass transfer resistance, heat transfer and pasta shrinkage were considered.

3.2 Heat transfer

Heat transfer is treated differently according to the model studied. In the models developed by Migliori et al. (2005a) and De Temmerman et al. (2007), heat transfer is treated according to a unidirectional energy balance equation:

$$\rho_{app} C_{p,app} \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r}\left(r k_h \frac{\partial T}{\partial r} \right) \text{ (cylinder or tube)} \qquad (21)$$

$$\rho_{app} C_{p,app} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_h \frac{\partial T}{\partial x} \right), \text{ (rectangle)} \qquad (22)$$

where $C_{p,app}$ is the specific heat capacity of pasta and k_h is its thermal conductivity. This equation is valid for products that have negligible internal water evaporation, since the evaporation term is included in the boundary condition (equation 27), and not in the energy balance itself. Similarly to the mass transfer modelling, the initial condition required to solve the heat balance equation is deduced from the hypothesis of a uniform initial temperature T_0. For cylindrical or rectangular pasta, a first boundary condition generally results from the symmetry of the product (equations 23 and 24) or when there is an isolated surface (equation 25):

$$\frac{\partial T}{\partial r} = 0 \text{ for } r = 0 \text{ and } t > 0 \text{ (cylinder)} \qquad (23)$$

$$\frac{\partial T}{\partial x} = 0 \text{ for } x = \frac{X_c}{2} \text{ and } t > 0 \text{ (rectangle)} \qquad (24)$$

$$\frac{\partial T}{\partial x} = 0 \text{ for } x = 0 \text{ and } t > 0 \text{ (rectangle)} \qquad (25)$$

The boundary condition at the surface of the product is described based on a heat transfer coefficient:

$$-k_h \frac{\partial T}{\partial r}\bigg]_{R_C,\ R_{int}\ or\ R_{ext}} = h\left(T_{R_C,\ R_{int}\ or\ R_{ext}} - T_\infty \right) - \lambda N_w^{ext} \text{ (cylinder or tube)} \qquad (26)$$

$$-k_h \frac{\partial T}{\partial r}\bigg]_{X_C} = h\left(T_{X_C} - T_\infty \right) - \lambda N_w^{ext} \text{ (rectangle)} \qquad (27)$$

where λ represents water latent heat of vaporization and N_w^{ext} is the water flow at the solid-air interface. Depending on the type of dryer, a term for the radiation (proportional to $T^4_{R_C\ ,R_{ext} or X_C} - T_\infty^{\ 4}$) can also be incorporated in the boundary condition (De Temmerman et al., 2007).

Modelling the temperature based on equations (21)-(27) requires the knowledge of the specific heat capacity and thermal conductivity of pasta. For the specific heat capacity, Migliori et al. (2005a) and De Temmerman et al. (2007) assume that it is equivalent to that of the main components (water, starch and proteins) weighted according to their mass fraction (z_i):

$$C_{p,app} = \sum z_i C_{p,i}, \tag{28}$$

where $C_{p,w} = 4184$, $C_{p,amidon} = 5.737T + 1328$ and $C_{p,protéines} = 6.329T + 1465$.

Thermal conductivity is determined by the following equation (Saravacos & Maroulis, 2001):

$$k_h = \frac{0.273}{1+M} + \frac{0.8M}{1+M} exp\left[\frac{-2700}{R}\left(\frac{1}{T} - \frac{1}{60}\right)\right], \tag{29}$$

where R is the ideal gas constant (J mol^{-1} K^{-1}) and T is the temperature in ºC.

In the model developed by Ponsart et al. (2003), the internal heat transfer resistance is neglected and the internal temperature of pasta is therefore assumed to be uniform. The temperature variation is then determined from an energy balance that quantifies the difference between the heat lost by water vaporisation and the heat absorbed by convection at the surface of the pasta:

$$\frac{dT}{dt} = \frac{S_v \lambda K_{m,\Delta p}}{\rho_s \left(C_{p,s} + C_{p,s}\bar{M}\right)}\left[65\left(T_\infty - T\right) - \left(p_w^0 - p_{v,\infty}\right)\right], \tag{30}$$

where S_v represents the surface/volume ratio of the product, p_w^0 is the vapour pressure of pasta at its surface, $K_{m,\Delta p}$ is the mass transfer coefficient and $p_{v,\infty}$ is the partial pressure of the water vapour inside the dryer.

Finally, in the models developed by Andrieu & Stamatopoulos (1986), Litchfield & Okos (1992), Villeneuve & Gelinas (2007) and De Temmerman (2008), heat transfer is considered to be substantially faster than mass transfer and pasta temperature is thus assumed to be equivalent to the dryer temperature.

3.3 Other properties considered

3.3.1 Shrinkage

In the models developed by Ponsart et al. (2003) and De Temmerman et al. (2007), shrinkage is considered by solving the Fick-type law in Lagrangian coordinates (ζ):

$$\frac{\partial M}{\partial t} = \frac{1}{\xi}\frac{\partial}{\partial \xi}\left[\left(\frac{D_{eff}}{\left(1+\alpha_{vol}M\right)}\xi\right)\frac{\partial M}{\partial \xi}\right] \text{ (cylinder or tube)} \qquad (31)$$

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial \xi}\left[\left(\frac{D_{eff}}{\left(1+\alpha_{vol}M\right)^2}\right)\frac{\partial M}{\partial \xi}\right] \text{ (rectangle)} \qquad (32)$$

where α_{vol} represents the volumetric shrinkage coefficient. This coefficient is defined by the following equation:

$$\frac{\rho_{app}}{\rho_s} = \frac{1+\bar{M}}{1+\alpha_{vol}\bar{M}} \qquad (33)$$

The apparent density ρ_{app} and the density of the dry matter ρ_s can be linked to the apparent volume of the pasta (V_{app}), to the mass (m_s) of the dry matter and to the volume (V_s) of the dry matter using the following definitions:

$$\rho_{app} = \frac{m_s\left(1+\bar{M}\right)}{V_{app}} \tag{34}$$

$$\rho_s = \frac{m_s}{V_s} \tag{35}$$

Substituting these two definitions in equation (33) makes it possible to link the apparent volume of the pasta to its moisture content:

$$V_{app} = V_s\left(1+\alpha_{vol}\bar{M}\right) \tag{36}$$

Consequently, the description of the mass transfer in Lagrangian coordinates based on this definition of the volumetric shrinkage coefficient is valid only under the hypothesis of a linear relation between pasta shrinkage and water content. This hypothesis is supported by experimental results from Andrieu et al. (1989). However, these results were obtained after fresh pasta was placed in different desiccators at room temperature, which diverges significantly from the drying process used in the industry. Linear relations between shrinkage and water content were also observed in the drying of potatoes (Wang & Brennan, 1995), carrots (Krokida & Maroulis, 1997) and Japanese noodles (Inazu et al., 2005), among others.

In the model developed by De Temmerman et al. (2007), the volumetric shrinkage coefficient is considered to be equivalent to the ratio between the density of the pasta dry matter and the density of the water (ρ_w):

$$\alpha_{vol} = \frac{\rho_s}{\rho_w} \tag{37}$$

The density of the water can be linked to the moisture and mass of pasta dry matter using the following equation:

$$\rho_w = \frac{m_s \bar{M}}{V_w}, \tag{38}$$

where V_w represents the volume occupied by the water. Substituting equations (37) and (38) in equation (36) gives the following:

$$V_{app} = V_s + V_w \tag{39}$$

Consequently, the hypothesis in which the volumetric shrinkage coefficient is equivalent to the ratio between the dry matter and water densities is valid only for non-porous pasta, since the volume occupied by air (V_{air}) is not included in equation (39). Shrinkage is also considered to be ideal, i.e., the volume of water lost is assumed to be directly equivalent to the shrinkage.

In the model developed by Mercier et al. (2011), shrinkage is considered using a dimensionless coefficient (η) describing the fraction of water lost during drying that is replaced by air inside the gluten network:

$$\eta = 1 - \frac{V_{app,0} - V_{app}}{V_{w,0} - V_w} \text{ (for } t > 0\text{)} \tag{40}$$

Substituting equations (34) and (38) in equation (40) makes it possible to develop a relation between the evolution of the apparent volume and water content of the pasta during drying:

$$V_{app} = V_{app,0}\left[1 - \beta\left(M_0 - \bar{M}\right)\right], \tag{41}$$

where: $\beta = \dfrac{1-\eta}{\rho_w / \rho_{app,0}\left(1 + M_0\right)}$

Thus, Mercier et al. (2011) also assume a linear relation between the evolution of the apparent volume of pasta and its water content. However, shrinkage is not assumed as ideal since the dimensionless coefficient is calculated from experimental measurements of the apparent density of the pasta at the start and end of drying. Values of 0.28 ± 0.03 and 0.15 ± 0.01 of coefficient η for pasta dried at 40°C and 80°C were obtained, respectively.

In the model developed by Migliori et al. (2005a), evolution of the pasta radius during drying is described using the following equation:

$$R_C = R_{C,0}\left[1+\alpha_{rr}\left(\bar{U}-U_0\right)\right], \tag{42}$$

where α_{rr} represents the radial shrinkage coefficient and U is the moisture content on a wet basis. In this model, a constant value of 0.42 is calculated for this parameter based on experimental data from Andrieu et al. (1989). However, the value of this parameter is expected to change with temperature. Furthermore, no experimental data is available to validate the assumption that the shrinkage is a linear function of the water loss for the entire range of moisture content usually encountered during pasta drying.

For cylindrical pasta ($V_{app} = \pi R_C{}^2 L$), equation (42) can be rewritten to express the evolution of pasta volume as a function of its moisture content on a dry basis:

$$V_{app} = \frac{L}{L_0} V_{app0}\left[1+\alpha_{rr}\left(\frac{\bar{M}}{1+\bar{M}}-\frac{M_0}{1+M_0}\right)\right]^2 \tag{43}$$

Consequently, the evolution of pasta radius based on equation (42) is valid for a non-linear relation between pasta volume and water content. Under most conditions, using equation (42) would indicate that pasta shrinkage is less important at the end of drying than at the beginning for an equivalent loss of water. Using this equation to estimate the variation of pasta volume during drying also requires the knowledge of longitudinal shrinkage. According to experimental data from Mercier et al. (2011) compiled for drying at 40°C and 80°C, longitudinal shrinkage contributes to about 30% of the volumetric shrinkage of pasta.

3.3.2 Porosity and density

Mercier et al. (2011) studied the evolution of the density and gas phase porosity (ε^g) of pasta fortified with pea protein concentrate during drying. The following porosity definition was used:

$$\varepsilon^g = 1 - \frac{V_{sem} + V_{PPC} + V_w}{V_{app}}, \tag{44}$$

where V_{sem} and V_{PPC} represent the volumes occupied by the semolina and pea protein concentrate, respectively. Using the definitions for the shrinkage coefficient η (equation 40), water density (equation 38) and apparent density of pasta (equation 34), the following equations were developed for cylindrical pasta:

$$\rho_{app}(t) = \frac{\rho_w\left(1 + \Delta M\delta + M_E\right)}{\Delta M\left(\eta - 1\right)\left(1 - \delta\right) + \nu\left(1 + M_0\right)} \tag{45}$$

$$\varepsilon^g(t) = 1 - \frac{\rho_w}{\Delta M\left(\eta - 1\right)\left(1 - \delta\right) + \nu\left(1 + M_0\right)}\left[\left(\frac{1}{\left(1 + 1/\psi\right)\rho_{sem}} + \frac{1}{\left(1 + \psi\right)\rho_{PPC}}\right) + \frac{\Delta M\delta + M_E}{\rho_w}\right], \tag{46}$$

where $\delta = \dfrac{\bar{M} - M_E}{M_0 - M_E} = \sum_{n=1}^{\infty}\dfrac{4}{\beta_n^2} exp\left(-\dfrac{\beta_n^2 D_{eff} t}{R_C^2}\right)$, $\psi = \dfrac{m_{sem}}{m_{PPC}}$, m_{sem} is the mass of the semolina, m_{PPC} is the mass of the pea protein concentrate and β_n are the roots of the Bessel function of the first kind and zero order. These equations make it possible to predict the evolution of the density and porosity of pasta during drying using the effective diffusion coefficient. They were developed for cylindrical pasta, but they can also be used for tubular or rectangular pasta by substituting the δ with the term equivalent to $\frac{\bar{M}-M_E}{M_0-M_E}$ in the analytical solutions of Table 1. For standard white pasta, equation (46) can be used considering the value of ψ as equivalent to $+\infty$.

3.3.3 Mechanical stress

Some drying conditions can promote the development of cracks inside pasta, which can greatly affect the quality of the final product. To determine the risks of crack formation based on drying conditions, Ponsart et al. (2003) developed a model to estimate the mechanical stress generated inside cylindrical pasta. In this model, it is assumed that the mechanical stress is a consequence of the pasta differential shrinkage. This shrinkage is described using the volumetric shrinkage coefficient α_{Vol} according to the following differential equation (equation 47) and initial and boundary conditions (equations 48 and 49):

$$r\frac{\partial r}{\partial t}=\alpha_{Vol}D_{eff}\left(\frac{r}{\xi\left(1+\alpha_{vol}M\right)}\right)^{2}\xi\frac{\partial M}{\partial \xi} \quad (47)$$

$$r=\xi \text{ for } t=0 \quad (48)$$

$$\xi=0 \text{ for } r=0 \quad (49)$$

Numerical resolution of this partial differential equation makes it possible to quantify the local strain of pasta from radial position. Two local strains are calculated, radial (τ_{rr}) and tangential ($\tau_{\theta\theta}$):

$$\Delta\tau_{rr}=\frac{\partial\Delta\Gamma}{\partial r} \quad (50)$$

$$\Delta\tau_{\theta\theta} = \frac{\Delta\Gamma}{r} \tag{51}$$

where : $\Gamma = r_t - r_0$ and $\Delta\Gamma = r_{t+\Delta t} - r_t$

The radial (σ_{rr}) and tangential ($\sigma_{\theta\theta}$) stresses are then calculated from the strains:

$$\Delta\sigma_{rr} = \gamma\Delta tr\tau + 2\mu\Delta\tau_{rr} - \kappa\Phi\Delta M \tag{52}$$

$$\Delta\sigma_{\theta\theta} = \gamma\Delta tr\tau + 2\mu\Delta\tau_{\theta\theta} - \kappa\Phi\Delta M, \tag{53}$$

where : $\Phi = \frac{1}{\alpha_{vol} + M}$

In equations (52) and (53), γ and μ represent the Lame coefficients derived from pasta effective Young's modulus and Poisson's coefficient (measured experimentally) and κ is the mechanical compressibility coefficient. The model therefore makes it possible to estimate the compressive and tensile stresses in pasta as a function of radial position during drying. It is then assumed that cracks will form when the generated stresses exceed a tolerance limit σ_{lim}. However, the model was not validated using experimental data, and no consideration was given to the potential impact of glass transition on the formation and the propagation of cracks.

4. Experimental validation

4.1 Moisture profile

Litchfield & Okos (1992), Migliori et al. (2005), De Temmerman et al. (2007), De Temmerman et al. (2008) and Mercier et al. (2011) experimentally validated the capacity of their model to predict the evolution of water content in pasta during drying. Table 4 summarizes the structure of these models with respect to the shape of the pasta, diffusion law, boundary conditions, heat transfer description, shrinkage description and method for calculating the effective diffusion coefficients. Table 5 reports the experimental extrusion and drying conditions used in validating the models, and the goodness of fit between the model predictions and experimental data.

The results of most studies therefore suggest that the evolution in average water content of pasta $\overline{M}$ during drying is Fickian and can be described using the equations presented in section 3. Furthermore, the results from Mercier et al. (2011) indicate that the evolution in average moisture content of pasta can be described using a simplified model where the heat transfer, shrinkage and external resistance to mass transfer can be neglected. These hypotheses make it possible to describe the evolution in average water content of pasta using the analytical solutions of Table 1.

Nevertheless, some observations can be made about the extent of experimental validation conducted to date. Few studies have been conducted on validating the models to describe drying at temperatures above 100°C. At such temperatures, phenomena such as water vaporization within the pasta can occur and have an impact on the mass transfer mechanisms, on the relative contribution of the water transfer in liquid form and vapour form, and on pasta structure. It would therefore be relevant to verify the validity of current models to describe the drying of pasta under such conditions, especially since this practice is becoming increasingly common in the industry because it allows for a significant reduction in the time required to produce pasta.

Litchfield & Okos (1992) studied the evolution of the moisture profile that developed inside pasta during drying. To achieve this, the pasta was taken out of the dryer at different moisture stages, frozen in liquid nitrogen and cut into sections 0.1 mm thick. The moisture of each section was then measured. Their results show that the moisture profile generated inside the pasta can be adequately estimated using a Fickian diffusion model for drying at 40°C. However, for temperatures of 60°C and 80°C, the moisture profile measured was flatter that the one predicted by the model and moisture near the surface of the pasta was higher than expected. The authors propose three hypotheses to explain these results:

(1) Water diffusion by concentration gradient is not the mechanism by which the mass transfer occurs, or other mechanisms are also present in addition to the concentration gradient diffusion.

(2) The surface of the pasta does not dry to the equilibrium moisture value M_E, or the surface of the pasta was remoistened before it was placed in the liquid nitrogen or while the frozen samples were being cut.

(3) The mass transfer resistance of the pasta at the surface could be considerable, which could be explained by the smooth texture of the pasta after extrusion.

Xing et al. (2007) also studied the moisture profile inside pasta during drying. To do this, the moisture profile was measured by NMR, a non-destructive technique that limits the risk of changing pasta moisture when the pasta is cut. Pasta with an initial moisture content level of about 0.20 (db) was used and dried at two temperatures (22°C and 40°C) that were selected based on the operational constraints of the NMR unit. The results suggest that for drying at 40°C, the moisture profile inside the pasta according to r is relatively flat for moisture content between 0.20 and 0.15, and more curved for lower moisture content. Similar results were also obtained by Hills et al. (1997). The change in moisture profile is consistent with the glass transition of pasta which occurs at a moisture content of 0.15 (db) at this temperature (Kulkarni, 2005). The authors thus explain this result with the hypothesis that, as observed for other biopolymers, moisture transport cannot be described from previous Fick-type models near the glass transition (Singh et al., 2003). As noted previously, this could be explained by the local changes in pasta transport properties, or by the time-dependant conformational changes in food biopolymers, which adds an additional stress term to fluid flow near the glass transition (Hills et al., 1997; Takhar, 2008). At 22°C, a relatively curved moisture profile was observed for the entire duration of drying. Given that at this temperature the glass transition of pasta occurs at a moisture content of about 0.24 (db), which is higher than the initial moisture of the pasta during the experiment, this result suggests that water diffusion is Fickian for pasta in the glassy state (Liu et al., 1997).

Furthermore, it is important to note that these experiments were conducted by drying commercial pasta with a moisture content level of about 0.09 (db). To achieve this, the pasta had to first be pre-moistened in an environmental chamber at a temperature of 30ºC and under controlled relative humidity. It could therefore be relevant to measure the moisture profile generated inside pasta when it is dried by a method more representative of the industrial process, i.e., using fresh pasta extruded from hydrated semolina. It would also be relevant to study the moisture profile generated inside pasta during drying using a non-destructive method such as NMR imaging for temperatures that are more representative of those used in the industry (40°C-120°C). The knowledge of the moisture profiles under these conditions could provide a better understanding of the mass transfer mechanisms involved in pasta drying, as well as promoting more accurate prediction of crack formation within the product.

4.2 Pasta properties

Using the models presented in section 3 requires the knowledge of pasta properties such as heat capacity, thermal conductivity, effective diffusion coefficients, and mass and heat transfer coefficients. The value of most of these parameters can be estimated from data found in literature, which are often available as correlations or semi-empirical models. However, many of these correlations and models were developed by extrapolating experimental measurements taken on products other than pasta, or under different operating conditions than those considered, which can cause considerable variability in the results obtained. Consequently, the value of some of these parameters must be revised in many studies using estimation methods based on experimental moisture content data. For example, the model developed by Migliori et al. (2005a) initially overestimated the average moisture content in pasta during drying when the external mass transfer coefficient value was calculated using equations (16), (17) and (20). To correct the data from the model, a new value for this parameter was calculated using the non-linear least squares method. A value of about two orders of magnitude higher than the one initially calculated was obtained, but it was not confirmed that the lack of goodness of fit between experimental and predicted moisture content was entirely caused by a poor initial estimate of this parameter.

4.3 Drying systems

Few studies were conducted regarding the reproducibility of the drying curves between the different types of experimental drying systems. The drying system has an impact on important parameters such as the air velocity or the air humidity at the pasta surface. According to the results of Inazu et al. (2003) for the drying of Japanese noodles, an increase in air velocity to about 2 m s^{-1} cause an increase in the value of the effective diffusion coefficients. Beyond this velocity, the impact of this parameter becomes negligible. However, this value could also depend on the angle at which the air comes into contact with the pasta. The drying system can also influence the accuracy with which drying conditions, like air humidity, are controlled. For instance, Villeneuve & Gelinas (2007) suggest that the value of the effective diffusion coefficients is more sensitive to variations in air relative humidity than air temperature in contrast with the results of Andrieu & Stamatopoulos (1986) and Litchfield & Okos (1992). This could be explained by the drying system used where air humidity is controlled using an electric steam generator and a cooling circuit. Such a system could permit more precise, rapid control of air humidity compared with systems where this parameter is controlled using salt solutions or an external steam generator.

Another aspect of drying systems concerns the orientation in which pasta is dried. Depending on the system used, pasta can be placed horizontally on plates or hung vertically on racks. If pasta sags in the amorphous state because of its weight, the consequences are likely to be different depending on the drying system. For pasta hung vertically, sagging could result in a larger radius or thickness at the bottom of the pasta rather than near the rack, thereby affecting the uniformity of the moisture profile in the longitudinal direction. For cylindrical pasta placed horizontally on plates, sagging could affect the radial symmetry of pasta that is generally assumed when models are developed. Pasta orientation could also affect the mechanical stresses generated inside the product and the crack formation process.

5. Development of mechanistic models

The models of pasta drying developed to date are semi-empirical models where the description of the mass transfer mechanisms is lumped in a single coefficient, the effective diffusion coefficient. In these models, no distinction is made between the transport of water in liquid or in vapour form, or between diffusion, flow by capillary action and flow by pressure gradient. In contrast, mechanistic models are more fundamental and are developed from the mass, heat and momentum balances for each of the phases and substances of the system. These models are mathematically more complex, but the physical considerations behind the equations are generally better understood, the hypotheses are clearer and the parameters are better defined (Datta, 2007). Therefore, the development of mechanistic models should improve our understanding of the mass and heat transfer mechanisms involved in pasta drying.

Since no mechanistic model on pasta drying has been developed so far, this section describes an approach derived from model on the drying or baking of other porous media that could lead to such models. For the drying rectangular pasta, assuming a unidirectional mass transfer, models could be developed from equations (54)-(56) (Bird, 1960; Whitaker, 1977; Datta, 2007). These equations describe the conservation of the three main components of the system considered, which are water in a liquid state, water in a vapour state and air.

$$\frac{\partial c_w}{\partial t} = \frac{\partial c_w}{\partial x} - I \tag{54}$$

$$\frac{\partial c_v}{\partial t} = \frac{\partial n_v}{\partial x} + I \tag{55}$$

$$\frac{\partial c_a}{\partial t} = \frac{\partial n_a}{\partial x}, \tag{56}$$

Where c_w, c_v, and c_a represent the liquid water, water vapour and air concentration, I is the evaporation rate and n_w, n_v and n_a are the mass fluxes of water in a liquid state, water in a vapour

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state and air. Taking the concentration and pressure gradients as the two main driving forces of the mass transfer, the mass fluxes n_w, n_v and n_a can be described using equations (57)-(59):

$$n_w = \rho_w \frac{k_w}{\mu_w^0} \frac{\partial P}{\partial x} + D_w \frac{\partial c_w}{\partial x} \qquad (57)$$

$$n_v = \rho_v \frac{k_g}{\mu_g^0} \frac{\partial P}{\partial x} + D_{g,eff} \frac{\partial c_v}{\partial x} \qquad (58)$$

$$n_a = \rho_a \frac{k_g}{\mu_g^0} \frac{\partial P}{\partial x} + D_{g,eff} \frac{\partial c_a}{\partial x}, \qquad (59)$$

where k_w and k_g represent the permeability of the liquid and gas phases, μ_w^0 and μ_g^0 are the viscosity of the water and the gas phase, D_w is the diffusivity of the water in the pasta and $D_{g,eff}$ is the effective diffusivity of the water vapour or the air in the gaseous phase. When the temperature profile developed inside the pasta during drying is to be studied as well, the equations above (54)-(59) can be linked with an energy balance:

$$\rho_{app} C_{p,app} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(n_w H_w + n_v H_v + n_a H_a\right) + \frac{\partial}{\partial x}\left(k_h \frac{\partial T}{\partial x}\right) - \lambda I, \qquad (60)$$

where $H_w = C_{p,w}T$, $H_v = C_{p,v}T$ and $H_a = C_{p,a}T$ represent the enthalpy of the components. In the previous equation, the first term on the right-hand side represents the convective heat transfer, the second term is the conductive transfer and the third is the latent heat of vaporization. Solving the system composed of equations (54)-(60) requires an additional equation to describe the evaporation rate I. It is generally developed by assuming a liquid-vapour equilibrium at all points in the medium that is described using an activity coefficient. However, no experimental data obtained to date make it possible to validate this hypothesis. To avoid using this hypothesis, it would be possible to describe the evaporation rate using a kinetic law, which could be particularly suitable for the drying of pasta with a low moisture content or in high drying temperature (Ousegui et al., 2010; Rakesh & Datta, 2011).

One of the main difficulties in using mechanistic models involves estimating the value of diffusivities and permeabilities. In the following paragraphs, typical parameter values are mainly given for products that have a porosity in the range of 0-30%, in agreement with the results of Waananen & Okos (1996) and Mercier et al. (2011). These parameter values can be used as a first approximation of the order of magnitude of the transport properties of durum wheat pasta. However, it should be expected that these properties are highly dependent on the product being dried, such that experimental measurements on pasta would be required to develop more accurate models.

Few data are available to estimate the liquid water diffusion coefficient in pasta D_w since the data are usually collected as effective diffusivities D_{eff}. For potatoes, a product with a similar porosity as pasta (Wang & Brennan, 1995), Ni (1997) describes the liquid water diffusivity with the following equation:

$$D_w = 1.0 * 10^{-8} exp\left(-2.8 + 2.0M\right) \quad (61)$$

This relation was developed primarily from the following two hypotheses: (1) for high moisture content, the diffusion coefficient value should be similar to the effective diffusion coefficient value, because the contribution from the transfer of water in vapour form is negligible and (2) for low moisture content levels, the diffusion coefficient value should be such that an internal moisture profile matching those generally observed in the falling-rate period is obtained, meaning a sigmoidal profile where the fall in moisture in the centre of the product is slow.

The effective diffusion value of water vapour and air inside a porous medium $D_{g,effff}$ could be estimated using the following equation (Geankoplis, 2003):

$$D_{g,eff} = D_{a-v} \frac{\epsilon}{\tau_p}, \tag{62}$$

where ϵ represents the volumetric fraction of pasta occupied by the gaseous phase, D_{a-v} is the diffusivity of the binary system of water vapour–air and τ_p is pore tortuosity. For inert solids, tortuosity generally varies from 1.5 to 6 (Aguilera & Stanley, 1999; Geankoplis, 2003). To estimate the value of the diffusion coefficient of the binary system of water vapour–air inside tubular pasta, Migliori et al. (2005a) use the Fuller-Schettler-Giddings correlation (Fuller et al., 1966):

$$D_{a-v} = \frac{10^{-3} T_f^{1.75} \left(\frac{MW_w + MW_a}{MW_w MW_a} \right)^{0.5}}{P\left[\left(\sum \nu \right)_v^{1/3} + \left(\sum \nu \right)_a^{1/3} \right]^2}, \tag{63}$$

where T_f represents the film temperature (which can be estimated by calculating the arithmetic average between T_∞ and $T_{R_C, R_{ext} or X_c}$), MW_w and MW_a are the molecular weight of water and air, $\left(\sum \nu\right)_v$ and $\left(\sum \nu\right)_a$ are the atomic diffusion volume of the components (cm^3 mol^{-1}) and P is the pressure (atm). For water vapour and air, values of the atomic diffusion volume of 12.7 and 20.1 cm^3 mol^{-1} were suggested, respectively (Perry & Green, 1984).

Finally, studying the presence of flow caused by pressure gradient inside pasta also requires estimating the value of the pasta's liquid and gaseous permeability. According to Darcy's law, zero permeability would indicate that no flow caused by pressure gradient can be observed, whereas high permeability would suggest a more significant contribution from the product's dehydration mechanism caused by pressure gradient. Permeability can be broken down into intrinsic k_i and relative k_r permeabilities using the following relations (Datta, 2006):

$$k_w = k_{i,w} k_{r,w} \quad (64)$$

$$k_g = k_{i,g} k_{r,g} \quad (65)$$

These two types of permeability are generally related to the saturation levels in liquid (S_w) and in gas (S_g) defined using the following equations:

$$S_w = \frac{V_w}{V_{app} - V_s} \quad (66)$$

$$S_g = \frac{V_v + V_a}{V_{app} - V_s} \quad (67)$$

Intrinsic permeability represents the permeability for the liquid or gas when the product is saturated, i.e., when the entire volume of apparent pores of the product is occupied by liquid water (S_w = 1) or gas (S_g = 1), respectively. Datta (2006) measured an intrinsic liquid permeability in the order of 10^{-17} to 10^{-19} m^2 for potatoes and beef slices. For gas permeability, Zhang & Datta (2006) and Chaunier et al. (2008) obtained results in the order of 10^{-10} to 10^{-12} m^2 for bread.

Equations (68) and (69) are commonly used to describe the relative permeability of porous media (Datta, 2006):

$$k_{r,w} = \left(\frac{S_w - S_i}{1 - S_i} \right)^3 \text{for } S_w > S_i$$

$$k_{r,w} = 0 \text{ for } S_w \le S_i \quad (68)$$

$k_{r,g} = 1 - 1.1 S_w$ for $S_w \le 0.9$

$$k_{r,g} = 0 \text{ for } S_w > 0.9 \tag{69}$$

These equations were developed primarily from experimental measurements of the permeability of a system consisting of a porous medium, a non-wetting phase, oil, and a wetting phase, water (Scheidegger, 1960). S_i represents the irreducible permeability, i.e., a critical water saturation value below which the liquid phase is not continuous and the permeability of the product for this phase is zero. In the model describing transport phenomena inside porous media by Nasrallah & Perre (1988), a value for S_i of 0.09 is assumed. However, this value is not based directly on experimental measurements and mostly represents an initial estimate used to carry out a sensitivity analysis of the model parameters. The value of S_i is sometimes assumed to be zero, such as in the model describing the dehydration of apples from Feng et al. (2004), which assumes that flow caused by pressure gradient can be observed even when the water phase is non-continuous.

6. Modelling pasta drying near glass transition

Current experimental data suggest that the evolution of the average moisture content during drying can be predicted adequately with the semi-empirical models described in section 3 for the operating conditions investigated to date (Migliori et al., 2005a; De Temmerman et al., 2007; De Temmerman et al., 2008; Mercier et al., 2011). However, significant differences exist between the models estimates and experimental results for the internal moisture profiles (Litchfield & Okos, 1992; Xing et al., 2007).

NMR imaging showed that the lack-of-fit between model estimates and experimental moisture profiles is particularly significant near glass transition. Sharper moisture profiles were observed compared to the profiles estimated from current semi-empirical models, which suggests that the stress resulting from the time-dependant conformational changes has a significant impact on the moisture transport, or that local changes in pasta transport properties should be considered to model accurately moisture transfer (Hills et al., 1997; Xing et al., 2007).

A number of modeling approaches have been proposed to improve the description of moisture transport near glass transition for biopolymers. Hills et al. (1997) developed a model in which moisture transport is Fickian, but where the formation of a hard, glassy layer at the surface of the pasta is considered by adjusting the diffusion coefficient according to the local moisture content of the product. While the estimated moisture profiles were more representative of experimental results compared to previous models, there was no quantitative validation of this model.

Xing et al. (2007) suggested that non-Fickian models, which consider the stress induced by polymers relaxation, can provide a good representation of experimental results. One such non-Fickian model was developed for biopolymers by Singh et al. (2003) using the hybrid mixture theory. This multi-scale model showed good agreement with the experimental drying curves for soybeans. It takes into account the relaxation time using the following equation:

$$\dot{\varepsilon}^f + \left(\varepsilon^f - 1\right)\nabla\left(D\nabla\varepsilon^f\right) - \left(\varepsilon^f - 1\right)\nabla\left[\int_0^t B_C G\left(t - t^*\right)\nabla\dot{\varepsilon}^f\left(t^*\right)dt^*\right] = 0, \qquad (70)$$

where ε^f is the volume fraction of the fluid, $\dot{\varepsilon}^f$ is the material time derivative of ε^f with respect to the motion of the solid phase, ∇ is the gradient operator in spatial dimensions, G is the stress relaxation function (which can be described with an equation as the generalized Maxwell model) and B_C is a parameter that links the effect of polymer relaxation with the fluid movement. Overall, the first two terms of Eq. (70) are similar to typical Fick-type models, while the integral term accounts for the additional stress related to the time-dependant conformational changes within the product.

The resolution of such models for pasta requires the knowledge of the viscoelastic properties of pasta. Takhar et al. (2006) measured the pasta storage modulus and tanδ (i.e. the ratio of the loss modulus to the storage modulus) at different temperatures and moisture contents using a mechanical thermal analyzer. Cuq et al. (2003) measured the apparent strength of pasta (here defined as the force at 0.3 mm deformation) and apparent relaxation coefficient (defined as the relative change between the force measured at a 0.3 mm deformation and the force recorded 30 s after relaxation). The following equation showed good agreement with their experimental results (Cuq et al., 2003):

$$Z(W,T)=\frac{Z_H(T)-Z_L(T)}{\left(1+exp\left(\frac{M-M_i(T)}{A(T)}\right)\right)}+Z_L(T), \qquad (71)$$

where $Z(W,T)$ is the mechanical property considered, $Z_H(T)$ is the maximum value of the property, $Z_L(T)$ is the minimum value, $M_i(T)$ is the moisture content (d.b.) at the inflection point, $A(T)$ is the transition spread and T is in ºC. The values of these parameters are related to temperature using the exponential functions presented in table 6. Eq. (71) can be used to show that the pasta behaves as a soft and visco-plastic product at high moisture content, but as a more rigid and elastic product at moisture contents under glass transition.

The range of conditions for which classical Fick-type models cannot describe accurately moisture transport without considering the glass transition remains to be identified. Cuq & Icard-Verniere (2001) measured the glass transition of pasta at different moisture contents using modulated differential scanning calorimetry. Good agreement was found between their experimental results and the Kwei model:

$$T_g = \frac{\frac{1}{1+M} T_{g,1} + q_1 \frac{M}{1+M} T_{g,2}}{\frac{1}{1+M} + q_1 \frac{M}{1+M}} + q_2 \frac{M}{\left(1+M\right)^2}, \qquad (72)$$

where $T_{g,1}$ and $T_{g,2}$ are the glass transition temperature of semolina and water (ºC), and q_1 and q_2 are two empirical constants. For drying, these parameters take the following values: $T_{g,1}$ = 273 ºC, $T_{g,2}$ = -135 ºC, q_1 = 9.5 and q_2 = 346. Moreover, results of Cuq et al. (2003) show that the sharp changes in apparent strength and apparent relaxation coefficient of pasta during drying occur within a moisture range of about 2 – 5 kg water kg dry matter^{-1}. As a first approximation, this range could also be assumed to correspond to the spread near the glass transition where moisture transport cannot be describe accurately with classical Fick-type models. However, measurement of internal moisture profiles for a wider range of conditions is needed before an accurate assessment of the impact of glass transition on moisture transport can be made.

7. Modelling the evolution in pasta quality

The main objective of pasta drying models is generally to describe the evolution of pasta water content as a function of drying conditions. Several models have also expanded the analysis to additional properties, such as the porosity, shrinkage, density and mechanical properties of pasta. However, for consumers and pasta producers, pasta quality is determined by its cooking characteristics and its organoleptic, esthetic and nutritional properties, and not by the physical and thermodynamic properties that are described by current models. Consequently, there seems to be a need to develop models that allow predicting pasta quality as defined by consumers.

This approach was used by Migliori et al. (2005b) in order to quantify the evolution of furosine production. Since furosine is an early product in Maillard reactions, monitoring it provides information on the browning of a product and its digestibility, among other things (Feillet et al., 2000; De Zorzi et al., 2007). In this model, a zero-order kinetic production is assumed:

$$\frac{df}{dt} = F\left(a_w, T\right), \qquad (73)$$

where f is the furosine content of pasta and F is its production rate. In addition, an Arrhenius equation is established between the kinetic coefficient F and the two dependent variables:

$$F = F_0 exp\left(-\frac{E_a a_w}{RT}\right) \qquad (74)$$

Since equations (73) and (74) ultimately depend on the temperature and water content of pasta, inserting them into current models makes it possible to directly predict the furosine content according to the drying conditions. Other pasta properties could also be suitable for developing similar models, such as firmness, adhesiveness, rheological properties and cooking loss, because many studies have demonstrated that these properties are highly dependent on the drying conditions applied (Güler et al., 2002; Zweifel et al., 2003; Lamacchia et al., 2007).

8. Adding ingredients high in nutritional value

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Pasta is a relatively affordable product that is consumed frequently in many regions of the world. Moreover, the matrix of pasta generally has the capacity to be partially substituted (up to about 10-15%) with other ingredients without an apparent loss of quality in the final product (Torres et al., 2007; Petitot et al., 2010). These properties have led to a new practice in the pasta industry that involves introducing ingredients high in nutritional value into the formulation of the product. Most of the studies on this subject focus on the addition of compounds with a high protein content, such as plant protein flours, concentrates or isolates (Nielsen et al., 1980; Bahnassey et al., 1986; Yanez-Farias et al., 1999; Zhao et al., 2005; Sabanis et al., 2006; Shogren et al., 2006; Torres et al., 2007; Gallegos-Infante et al., 2009; Wood, 2009; Petitot et al., 2010; Martinez-Villaluenga et al., 2010). Adding these proteins makes it possible to compensate for pasta deficiencies in lysine and threonine, two essential amino acids (Kies & Fox, 1970; Abdel-Aal & Hucl, 2002). Supplementation with ingredients rich in animal proteins or in fibre and with certain oils has also been considered (Fuad & Prabhasankar, 2010; Krishnan & Prabhasankar, 2012).

Studies on the enrichment of semolina with ingredients high in nutritional value show that this practice can affect pasta properties related to texture (Nielson et al., 1980), colour (Gallegos-Infante et al., 2009), cooking properties (Zhao et al., 2005) and organoleptic properties (Alireza Sadeghi & Bhagya, 2008). In general, these changes are attributed to the properties of the ingredient added, the weakening of the gluten network associated with its dilution and the chemical bonds formed between the new ingredients and the starch or gluten of the semolina (Ribotta et al., 2005; Roccia et al., 2009; Petitot et al., 2010; Mercier et al., 2012).

However, few studies have been conducted on the impact of enrichment on the drying process. Mercier et al. (2011) observed that fortifying pasta with 5% or 10% of pea protein isolate causes an increase in the effective diffusion coefficients at 80°C, which could be attributed to the impact of fortification on the fundamental mass and heat transfer mechanisms involved. Current pasta drying models are therefore not necessarily adapted to this new reality, since these models are semi-empirical and group all the mass transfer mechanisms within a single parameter, the effective diffusion coefficient. More fundamental models based on continuity, heat and momentum equations could thus be better adapted to this reality and could be used to increase the understanding of how enrichment impacts the mass and heat transfer mechanisms involved in the drying of fortified pasta.

9. Conclusion

Drying is a step in pasta production that can greatly influence the properties of the final product. In the last few years, many models have been developed to describe the transport phenomena that occur during this step of production. Most of these models are semi-empirical and combine mass transfer mechanisms within a single parameter, the effective diffusion coefficient. The main differences between the models are the hypotheses related to the mass transfer at the interface, the treatment of shrinkage and the consideration of heat exchanges. In general, the models considered in this study allows an adequate description of the evolution in average water content of pasta during drying based on the temperature and relative humidity applied. However, major differences can be observed between experimental and modelled data regarding the moisture profile generated inside the product during drying, particularly around the glass transition. In the light of these observations, different recommendations can be made regarding future work on modelling the drying of pasta, including:

(1) Expand the experimental validation of the models. On the one hand, there seems to be a need to study the validity of the models for drying in temperatures higher than 100°C, because phenomena such as water vaporization can be more important and affect pasta structure and mass transfer mechanisms. On the other hand, applying the models currently requires data extrapolated from experimental measurements obtained with other products than pasta or under different operating conditions than those considered. Consequently, it also seems relevant to continue collecting experimental data for the value of some physico-chemical and thermodynamic properties of pasta, including the effective diffusion coefficient and the mass and heat transfer coefficients.

(2) Develop mechanistic models. These models, which are more fundamental than the current ones, would improve our understanding of the mass and heat transfer mechanisms involved in the dehydration of pasta.

(3) Measure internal moisture profiles of pasta for industrially relevant drying conditions. As of now, internal moisture profiles were obtained with low-precision destructive techniques, or for temperature conditions rarely used in the pasta making industry. The knowledge of internal moisture profiles would be particularly relevant near the glass transition of pasta, in order determine the range of moisture content where current Fick-type models are inadequate for modeling pasta drying.

(4) Develop models describing the evolution of pasta quality during drying as defined by the consumers and the industry. These properties, such as colour, texture, taste and presence of cracks are generally not taken directly into account by current models, but represent critical

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factors in the choice of optimal operating conditions.

(5) Adapt the models to pasta enriched with ingredients high in nutritional value. Adding these ingredients can modify the physico-chemical properties of pasta and add additional constraints to production, such as using low temperatures for drying products containing heat sensitive ingredients. These models could promote better understanding of interactions between the new ingredients and the pasta matrix, and answer questions such as the maximum amount of exogenous ingredients that the gluten network can support without affecting the physical integrity of the product.

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Table 1. Fick-type law analytical solutions (Eq. 1-2) for different shapes and boundary conditions (Crank, 1975)

Shape	First Boundary Condition	Second Boundary Condition	Analytical Solution
Cylinder	For $r = 0$ and $t > 0$: $\frac{\partial M}{\partial r} = 0$	For $r = R_C$ and $t > 0$: $M = M_E$	$\frac{\bar{M} - M_E}{M_0 - M_E} = \sum_{n=1}^{\infty} \frac{4}{\beta_n^2} exp\left(-\frac{\beta_n^2 D_{eff} t}{R_C^2}\right)$
	For $r = 0$ and $t > 0$: $\frac{\partial M}{\partial r} = 0$	For $r = R_C$ and $t > 0$: $-\rho_{app} D_{eff} \frac{\partial M}{\partial r}\Big]_{R_C} = K_{m,\Delta M}\left(M_{R_C} - M_E\right)$	$\frac{\bar{M} - M_E}{M_0 - M_E} = \sum_{n=1}^{\infty} \frac{4Bi^2}{\Upsilon_n^2\left(\Upsilon_n^2 + Bi^2\right)} exp\left(-\frac{\Upsilon_n^2 D_{eff} t}{R_C^2}\right)$, where B_i is the Biot number: $Bi = \frac{R_C k_{m,\Delta M}}{D_{eff}}$ and Υ the roots of the equation: $\Upsilon J_1(\Upsilon) - Bi J_0(\Upsilon) = 0$, with J_0 et J_1 the Bessel functions of the first kind and orders zero and one, respectively.
Tube	For $r = R_{int}$ and $t > 0$: $M = M_E$	For $r = R_{ext}$ and $t > 0$: $M = M_E$	$\frac{\bar{M} - M_E}{M_0 - M_E} = \frac{4}{R_{ext}^{\ 2} - R_{int}^{\ 2}} \sum_{n=1}^{\infty} \frac{J_0(R_{int}\phi_n) - J_0(R_{ext}\phi_n)}{\phi_n^2\left[J_0(R_{int}\phi_n) + J_0(R_{ext}\phi_n)\right]} exp($, where ϕ_n are the positive roots of the equation : $H_0(R_{int}\phi_n) = J_0(R_{int}\phi_n) Y_0(R_{ext}\phi_n) - J_0(R_{ext}\phi_n) Y_0(R_{int}\phi_n)$, with J_0 et Y_0 the Bessel functions of the first and second

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			kind.
Rectangle	For $x = \frac{X_c}{2}$ and $t > 0$: $\frac{\partial M}{\partial x} = 0$	For $x = X_C$ and $t > 0$: $M = M_E$	$\frac{\bar{M} - M_E}{M_0 - M_E} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left[-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4\left(\frac{X_c}{2}\right)^2} \right]$.
	For $x = 0$ and $t > 0$: $\frac{\partial M}{\partial x} = 0$	For $x = X_C$ and $t > 0$: $M = M_E$	$\frac{\bar{M} - M_E}{M_0 - M_E} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left[-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4(X_c)^2} \right]$.

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Table 2. Empirical correlations developed to determine the value of the effective diffusion coefficient and experimental conditions validated

Equation	Parameters	Extrusion Conditions	Drying Conditions			Reference
			T (°C)	*RH* (%)	*P* (kPa)	
$D_{eff}=\left[A exp\left(\frac{-E_a}{RT_\infty}\right)\left[1-exp\left(-BM^C\right)+M^D\right]\right]*10^{-12}$	$E_a=26.0\frac{kJ}{mol}$ $A=2.9320\ x\ 10^5$ $B=7.9082\ x\ 10^{14}$ $C=1.5706\ x\ 10^1$ $D=6.8589\ x\ 10^1$	Adjustable ribbon die of 2-3 mm thickness	40-85	1-94	101	Litchfield & Okos, 1992
$D_{eff}=\left(C'_{10}+\varepsilon\frac{C'_{20}}{P_\infty}\right)exp\left[-\frac{E_a+E_b}{RT_\infty}\right]$	$E_a=22.6\frac{kJ}{mol}$ $E_b=\left[6.0exp\left(-20M\right)\right]\frac{kJ}{mol}$ $C'_{10}=1.2x10^{-7}\frac{m^2}{s}$ $C'_{20}=8x10^{-5}\frac{m^2}{s}$	Circular Teflon die of 3.18, 4.76 and 5.56 mm	40-122	1-94	77-202	Waananen & Okos, 1996
$D_{eff}=\left[exp\left(\frac{-E_a}{RT_\infty}-ARH-B\right)\right]*10^{-4}$	$E_a=11.4\frac{kJ}{mol}$ $A=0.0221$ $B=8.635$	Circular die of 2.5 mm	40-80	65-85	101	Villeneuve & Gelinas, 2007

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$D_{eff} = Aexp\left[-B\left(\frac{1}{T_\infty} - \frac{1}{T_{Ref}}\right)\right]exp(CM)$	$T_{Ref} = 293\ K$ $A = 1.2\ x\ 10^{-11}$ $B = 3036.95$ $C = 6.46\ \ x\ 10^{3}$	Laminated pasta of 1.3 mm thickness	40-90	3-12	101	De Temmerman et al., 2007

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Table 3. Effective moisture diffusion coefficients (x 10^{-12}) from the correlations presented in Table 2 and for the following reference scenario: T_{∞} = 80°C, RH = 65%, P_{∞} = 101 kPa, M = 0.30 and ε = 0.10

Parameter		Equation				Average ± SD
		Litchfield & Okos, 1992	Waananen & Okos, 1996	Villeneuve & Gelinas, 2007	De Temmerman et al., 2007	
Base Case		45	57	87	70	65 ± 18
Drying temperature (°C)	**40**	14	21	53	23	28 ± 17
	120	112	125	129	168	133 ± 24
	$\lvert \Delta \boldsymbol{D_{eff}} \rvert$	98	104	76	145	105 ± 29
Relative humidity (%)	**0**	-	-	365	-	365
	100	-	-	40	-	40
	$\lvert \Delta \boldsymbol{D_{eff}} \rvert$	-	-	325	-	325
Pressure (Pa)	**77 000**	-	58	-	-	58
	222 000	-	55	-	-	55
	$\lvert \Delta \boldsymbol{D_{eff}} \rvert$	-	3	-	-	3
Pasta moisture (kg H_2O kg dry solid^{-1})	**0.1**	11	-	-	70	41
	0.5	51	-	-	70	31
	$\lvert \Delta \boldsymbol{D_{eff}} \rvert$	39	-	-	0	20
Pasta porosity (%)	**0**	-	54	-	-	54

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	25	-	62	-	-	62
	$\lvert \Delta \boldsymbol{D}_{eff} \rvert$	-	8	-	-	8

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Table 4. Structure of models describing pasta drying where experimental validation has been done

Model	Shape	Mass Transfer				Heat Transfer		Shrinkage
		Equation	**Boundary Conditions**	**D_{eff}**	**K_m**	**Equation**	**h**	
Litchfield & Okos, 1992	Rectangular	Eq. (2)	Eq. (6) and (9)	Table 1: correlation by Litchfield & Okos (1992)	-	Neglected	-	Neglected
Migliori et al., 2005a	Tubular	Eq. (1)	Eq. (12) for the interior and exterior surface of tubular pasta	Value determined by NMR for pasta with $U > 0.2$; Table 1, correlation by Waananen & Okos (1996) for $U \leq 0.2$	K_m^{ext}: Optimization by the non-linear least squares method; K_m^{int}: Eq. (16)-(17), assuming that the air velocity inside tubular pasta is 3 times lower than the external velocity	Eq (21)	Eq. (20)	Eq. (42), with $\alpha_{rr} = 0.42$
De Temmerman et al., 2007	Rectangular	Eq. (32)	Eq. (7) and (13)	Table 1: correlation by De Temmerman et al. (2007)	Eq. (19)	Eq (22) in Lagrangian coordinates	Measured using a heat flux sensor	Eq. (32) and (33), with $\alpha_{vol} = \frac{\rho_S}{\rho_w}$
De Temmerman et al., 2008	Cylindrical	Eq. (31)	Eq. (5) and (12)	Table 1: correlation by De Temmerman et al. (2007)	Eq. (19)	Neglected	Measured using a heat flux sensor	Eq. (31) and (33), with $\alpha_{vol} = \frac{\rho_S}{\rho_w}$

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Mercier et al., 2011	Cylindrical	Eq. (1)	Eq. (5) and (8)	Optimization by the non-linear least squares method	-	Neglected	-	Neglected in mass transfer description

Table 5. Experimental conditions validated for the models of Table 4 and goodness of fit between experimental and predicted data

Model	**Extrusion Conditions**	**Drying System**	**Drying Conditions**			**Experimental Data Measured**	**Goodness of fit**
			***T* (°C)**	***RH* (%)**	**P (*kPa*)**		
Litchfield & Okos, 1992	Adjustable ribbon die of 2-3 mm thickness; fresh pasta equilibrated 24h at 4°C	Convection dryer in which pasta is hung vertically on poles	40-85	1-94	101	Evolution of pasta moisture content M at different positions according to x during drying	Overestimation of the moisture gradient inside pasta
Migliori et al., 2005a	Circular die of 5 mm	Static oven in which pasta is placed horizontally on plates	70-80	58-68	101	Evolution of pasta average moisture content $\overline{U}$ during drying	Good estimate of the evolution of average pasta moisture content
De Temmerman et al., 2007	Laminated pasta of 1.3 mm thickness; fresh pasta equilibrated 24h at 4°C and 80% RH	Convection oven with laminar air flow in which pasta is placed horizontally on aluminum sheets	40-100	0-80	101	Evolution of pasta average moisture content $\overline{M}$ during drying	Good estimate of the evolution of average pasta moisture content
De Temmerman et al., 2008	Circular die of 4.0 mm thickness; fresh pasta	Low-temperature oven	10-90	0.1-15	101	Evolution of pasta average moisture content $\overline{M}$	Good estimate of the evolution of average pasta moisture content

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	equilibrated 24h at 4°C and 80% RH					during drying	
Mercier et al., 2011	Circular die of 2.5 mm	Environmental chamber in which pasta is hung vertically on poles	40-80	65	101	Evolution of pasta average moisture content $\overline{M}$ during drying	Good estimate of the evolution of average pasta moisture content

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Table 6. Model parameters of Eq. (71)

Apparent strength (N)	Apparent relaxation coefficient
$Z_L = 4.3exp\left(1.1*10^{-3}T\right)$	$Z_L = 2.09exp\left(0.1*10^{-3}T\right)$
$Z_H = 70.4exp\left(1.1*10^{-3}T\right)$	$Z_H = 56.5exp\left(0.1*10^{-3}T\right)$
$M_i = 37.9exp\left(-1.24*10^{-3}T\right)$	$M_i = 32.7exp\left(-1.2*10^{-3}T\right)$
$A = 4.55exp\left(-7.1*10^{-3}T\right)$	$A = 3.13exp\left(-1.45*10^{-3}T\right)$

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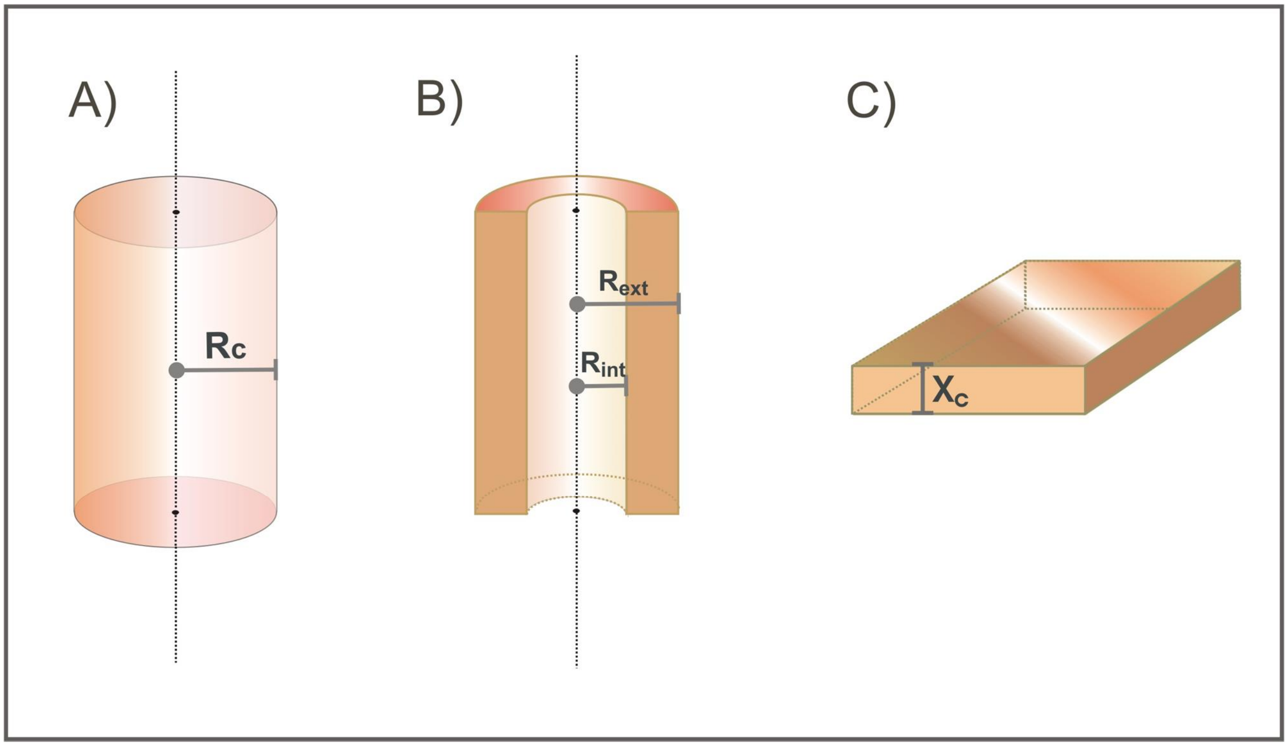

Fig. 1. Schematic diagram of the three main shapes considered in modelling the drying of pasta (A-cylindrical; B- tubular and C- rectangular).

