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Food freezing with simultaneous surface dehydration: approximate prediction of weight loss during freezing and storage

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Abstract

Weight loss of unpackaged foods during freezing and later storage is an important quality and economic issue. It is originated on surface ice sublimation due to differences in water activity between food surface and the refrigerating air. Weight loss rate is determined by refrigerating conditions and product characteristics. The modelling of this phenomenon has merited very little attention; at present there are no simplified methods to predict weight losses during the freezing and the storage of unpackaged foods. In previous studies we developed a detailed model for the simultaneous heat and mass transfer during food freezing and storage with ice sublimation. Based on the information of this numerical model, simplified analytical methods for the prediction of weight loss during the freezing and the storage of unpackaged frozen foods were developed. The methods account for product characteristics and storage conditions. The prediction equations are very simple and results of their use—simulating usual freezing and storage conditions for different products—give very good accuracy when tested against the previously cited numerical model and experimental data.

1. Introduction

Freezing is a widespread preservation method in food industry. Using actual technologies foods can be frozen and stored during relatively long periods at reasonable costs and maintaining most of their original quality attributes. A very significant characteristic is the fact that freezing avoids the use of additives or chemical preservatives; also nutrient losses are minimized when exposing foods to low temperatures.

A high proportion of foods are frozen—and many times also stored—unpackaged or within a loose packaging. When unpackaged or loose packaged foods are frozen, stored and/or transported they lose water due to interactions with the surrounding media. The difference between the water vapour pressure on food surface and that in the surrounding atmosphere is the driving force for dehydration.

In both situations (freezing and storage), surface ice sublimes forming a porous dehydrated layer, whose thickness increases as time elapses [1]. This leads not

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Nomenclature

A	area of the food, m^2
Bi	Biot number ($=h_tL/k_0$)
C	molar concentration of water, mole/m^3
C_p	specific heat, J/(kg °C)
D	effective diffusion coefficient of water, m^2/s
e	relative error, %
f	parameter in Eq. (6)
f_{ads}	adsorbed ice fraction, (kg of ice)/(kg of dried solid)
fr	freezing rate, cm/h
g	parameter in Eq. (6)
GI	geometric index (0 for slabs, 1 for cylinders, 2 for spheres)
h	parameter in Eq. (6)
h_t	heat transfer coefficient, W/(m^2 °C)
i	parameter in Eq. (6)
j	parameter in Eq. (6)
k	parameter in Eq. (6)
k_m	mass transfer coefficient (referred to vapour water driving force), m/s
k'_m	mass transfer coefficient (referred to liquid water driving force), m/s
k_0	thermal conductivity of unfrozen food, W/(m °C)
k_t	thermal conductivity of food, W/(m °C)
l	parameter in Eq. (6)
L	half-thickness or radius, m
m	parameter in Eq. (6)
m_0	initial mass of food, kg
m_s	sublimated mass by unit volume, kg/m^3
n	parameter in Eq. (7)
o	parameter in Eq. (7)
p	parameter in Eq. (7)
q	parameter in Eq. (7)
r	parameter in Eq. (7)
Re	Reynolds number ($=\rho_a v_a L/\mu_a$)
RH	relative humidity, %
s	parameter in Eq. (7)
st	storage time, day
t	time, s (or min)
T	temperature, °C
u	parameter in Eq. (7)
v	velocity, m/s
Vol	volume, m^3
w	ice content, (kg of ice)/(kg of food)
WL	weight loss, 100 (kg of water)/(kg of food)
x	spatial coordinate, m
x_1	moving sublimation front position, m
Y_0	initial water content (kg of water)/(kg of food)

Greek symbols

ρ	density, kg/m^3
μ	viscosity, Pa s

Subscripts

a	air
f	freezing
i	ice
if	initial freezing
L	surface
0	initial
st	storage
t	accumulated
v	water vapour
w	liquid water
1	of unfrozen surface
2	of frozen surface

only to weight losses, but mainly to quality decay owing to a general appearance spoilage and to changes in taste, texture and colour [2,3].

It is clear that if not properly managed, surface drying may produce important quality and economic losses in frozen products, so its prediction and control are of the highest practical interest [4–6]. That is why, it is essential to count on adequate prediction methods to quantify the influence of process conditions and food characteristics on weight loss.

In a companion paper [7], the existing numerical and approximate methods for the prediction of heat and mass transfer during food freezing and storage were reviewed. In brief, there are some useful specific numerical methods but there is no simplified approximate equation for the prediction of weight loss during freezing and storage. Most of the existing literature is devoted to quantify weight loss during frozen storage. There are some experimental researches on pieces of potato [8], tylose and ice [9] and samples of meat products [10]. Besides there are some reports on average data of weight loss during frozen storage of beef quarters and pork and mutton sides [11,12]. On the other hand there are few papers on the development of simplified prediction models. In this sense, Pham and Willix [12,13] have developed simple prediction equations based on drying theory and the psychrometric chart.

Based on the previous considerations, the objective of this work is to develop and verify simplified methods for the evaluation of weight loss during freezing and frozen storage. The methods are obtained by regression of the results provided by a previously developed numerical model. They consist of simple analytical equations that allow the calculation of the percent weight loss of high water content foods during freezing and frozen storage as a function of food characteristics and operating conditions.

2. Theory

During freezing and frozen storage of unwrapped foods, they lose weight due to the environmental interaction. When frozen water sublimates a porous dehydrated layer is formed on the food surface, which alters the food physical and sensory characteristics.

During freezing, two phase-changes take place simultaneously: the free liquid water is frozen and the superficial frozen water sublimates. In the case of frozen storage, only one phase change takes place, the sublimation of superficial ice.

From a physical point of view, food can be considered as a combination of a solid matrix, an aqueous phase and a gaseous phase (air and water vapour). For the freezing process, the food can be divided into three zones: unfrozen, frozen and dehydrated. During the storage, there are only two zones: frozen and dehydrated. From the mathematical point of view the storage stage can be considered as a special case of the most general formulation (freezing stage) and needs no special mathematical development.

A complete mathematical model has to solve the heat transfer (freezing) and the mass transfer (weight loss) simultaneously. As the industrial freezing process begins with the food at temperatures higher than $T_{\rm if}$ the model must also consider the weight loss by liquid water evaporation during the initial refrigeration step.

In previous works [5,14,15] a complete numerical modelling was performed for regular unidimensional geometries (plane plate, infinite cylinder, sphere). A general formulation could be developed which accounts for each of these three geometries by means of the use of the geometric index GI. In brief, the microscopic heat and mass balances lead to Eqs. (1) and (2) that are valid for all the food ($0 \leqslant x < L$), where x is the axial or radial coordinate. Adequate initial and boundary conditions are considered:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial k_{\rm t}}{\partial x}\frac{\partial T}{\partial x} + k_{\rm t}\frac{\partial^2 T}{\partial x^2} + {\rm GI}\frac{k_{\rm t}}{x}\frac{\partial T}{\partial x} \tag{1}$$

$$\frac{\partial C}{\partial t} = \frac{\partial D}{\partial x}\frac{\partial C}{\partial x} + D\frac{\partial^2 C}{\partial x^2} + {\rm GI}\frac{D}{x}\frac{\partial C}{\partial x} \tag{2}$$

In each region (unfrozen/frozen/dehydrated) specific values for the thermal properties are needed. Besides, in the unfrozen and frozen regions the values of water concentration and diffusion coefficient considered are those of liquid water: $C_{\rm w}$ and $D_{\rm w}$. Meanwhile in the dehydrated zone they are $C_{\rm v}$ and $D_{\rm v}$ those of water vapour.

When the surface is already frozen and sublimation begins an additional balance is needed to evaluate the position of the sublimation front x_1 (and the thickness of the dehydrated layer $L - x_1$). In this sense, the model establishes that, at $x = x_1$:

$$-m_{\rm s}\frac{{\rm d}x_1}{{\rm d}t} = -D_{\rm v}\frac{\partial C_{\rm v}}{\partial x} \quad \text{where } m_{\rm s} = \rho(w - f_{\rm ads}(1 - Y_0)) \tag{3}$$

That is to say: the mass of ice sublimated (left term in Eq. (3)) equals the amount of water vapour that diffuses through the dehydrated layer (right side of Eq. (3)).

The weight loss in function of time is evaluated accumulating the instant surface loss calculated for each time step. Eq. (4) corresponds to unfrozen surface and Eq. (5) to frozen surface.

$${\rm WL}_1 = \frac{k'_{\rm m}A\int_0^{t_{\rm if}}(C_{w_{\rm L}} - C_{v_{\rm a}})\,{\rm d}t}{m_0} \tag{4}$$

$${\rm WL}_2 = \frac{k_{\rm m}A\int_{t_{\rm if}}^{t}(C_{v_{\rm L}} - C_{v_{\rm a}})\,{\rm d}t}{m_0} \tag{5}$$

Integrals (4) and (5) are numerically evaluated based on the values of water concentration in the surface ($C_{w_{\rm L}}$ or $C_{v_{\rm L}}$) provided by the numerical method at each time step. In these equations $t_{\rm if}$ is the time at which food surface begins to freeze (it reaches the initial freezing temperature $T_{\rm if}$).

3. Simplified prediction methods

3.1. Freezing stage

So as to count with a high number of accurate values of weight loss during freezing, the prediction software was run covering a wide range of operating conditions possible to be found in industrial freezing conditions. In all the runs of the numeric model thermal properties for minced meat, representative of high water-content foods, were used [5,15]. Table 1 presents the range for the different parameters tested in the modelling. These predicted values—together with the related operating conditions—were taken as the basis for the deduction of the approximate methods.

In a first instance, the parametric analysis of the predicted results allows us to observe similarities in the behaviour of freezing time $t_{\rm f}$ and weight loss WL during freezing: They show that both $t_{\rm f}$ and WL strongly depend on L (they increase with L), $T_{\rm a}$ (they increase with $T_{\rm a}$), $v_{\rm a}$ (they decrease with $v_{\rm a}$) and T_0 (they increase with T_0). The only important difference is related to air relative humidity RH that strongly influences weight loss (WL decreases strongly with higher RH), but has a

Table 1
Range of operating conditions used for the fitting of Eqs. (6) and (7)

Parameter	Plane plate	Infinite cylinder	Sphere
L	0.02–0.04	0.02–0.04	0.02–0.04
Y_0	0.72–0.80	0.74–0.80	0.70–0.80
T_0	0–10	0–10	0–10
v_a			
Freezing	1–5	1–5	1–5
Frozen storage	0.5–1.5	0.5–1.5	0.5–1.5
T_a			
Freezing	−20 to 40	−20 to −40	−20 to −40
Frozen storage	−20 to 30	−20 to −30	−20 to −30
RH			
Freezing	0.5–0.9	0.5–0.9	0.5–0.9
Frozen storage	0.6–0.8	0.6–0.8	0.6–0.8

negligible influence on freezing time [5,7]. Based on these considerations, for each simple regular geometry (plane plate, infinite cylinder and sphere), a non-linear regression model is proposed of the type:

$$\mathrm{WL_f}(\%) = f(L)^g \mathrm{Re}^h (1 + iT_0)(1/Bi + j) \times (-1 - T_a)^k (1 - \mathrm{RH})^l Y_0^m \qquad (6)$$

where Re is Reynolds number, Bi is Biot number, while f, g, h, i, j, k, l and m are regression parameters.

3.2. Frozen storage

In a first instance, heat and mass transfer conditions are completely different during frozen storage, respect to those of the previous freezing stage. Heat transfer has only a minor influence and weight loss rate is mainly determined by mass transfer parameters. That is why, a relation similar to Eq. (6) is not adequate under these circumstances.

In this respect, an exhaustive parametric analysis of the system has been done taking advantage of the ability of the numerical software to predict water loss as a function of storage time. So, the software was used to analyse the influence of the storage conditions (air rate, humidity and temperature) and food characteristics on the weight loss [5].

Freezing influences the later weight loss during the storage stage, because different freezing conditions lead to different thickness of the dehydrated layers, determining that the "initial" conditions for the storage stage vary according to weight loss during freezing. A lower weight loss during freezing produces a thinner dehydrated layer and thus, less resistance to water vapour diffusion during the storage than for the case of higher weight loss during freezing. These differences could counterbalance the weight loss results of the freezing stage and must be properly considered. That is why, the analysis through the numerical model was performed considering two very different initial stages—determined by the final state of the freezing period: after a slow freezing (air at −20 °C and 1 m/s) and after a quick freezing (−40 °C, 5 m/s). In both cases RH during freezing was supposed to be 75%. The range of operating conditions tested with the simulation software is also included in Table 1.

Based on the previous considerations, and after a parametric study of the predicted values, the accumulated amount of weight loss at the end of storage is proposed to vary according:

$$\mathrm{WL_t}(\%) = \mathrm{WL_f} + \mathrm{WL_{st}} = \mathrm{WL_f} + n(L)^o Re^p \mathrm{st}^q (-T_a)^r (s - \mathrm{RH})^u \qquad (7)$$

where $\mathrm{WL_t}$ is the total (accumulated) weight loss, $\mathrm{WL_{st}}$ is weight loss during storage, st (days) is the storage time, T_a is the ambient temperature (°C) and $\mathrm{WL_f}$ is weight loss during freezing, (given by Eq. (6)). Constants n, o, p, q, r, s and u are the regression parameters.

4. Results and discussion

4.1. Freezing

Table 2 presents the results obtained for the three geometries. As can be seen, parameter j has negligible influence and can be omitted. The accuracy of the approximate equation is very high (R^2 higher than 0.999 for the three shapes).

4.1.1. Validation against numerical results

An additional test proof of the accuracy of Eq. (6) over all the range of operating conditions given in Table 1 is presented in Fig. 1 and Table 3.

Fig. 1 presents the comparison of predicted $\mathrm{WL_f}$ (by Eq. (6)) against numerical results for the three shapes. As can be seen, predicted values lie on a narrow band centered on the 45° line, without any bias. Meanwhile,

Table 2
Parameters for Eq. (6) for the three geometries tested

Parameter	Plane plate	Cylinder	Sphere
f	18.146	0.396	0.448
g	0.489	0.003	0.003
h	0.350	0.512	0.497
i	0.029	0.038	0.049
j	0.000	0.000	0.000
k	−1.033	−0.831	−0.848
l	0.058	0.045	0.048
m	1.991	2.122	1.927
R^2	0.999	0.999	0.999

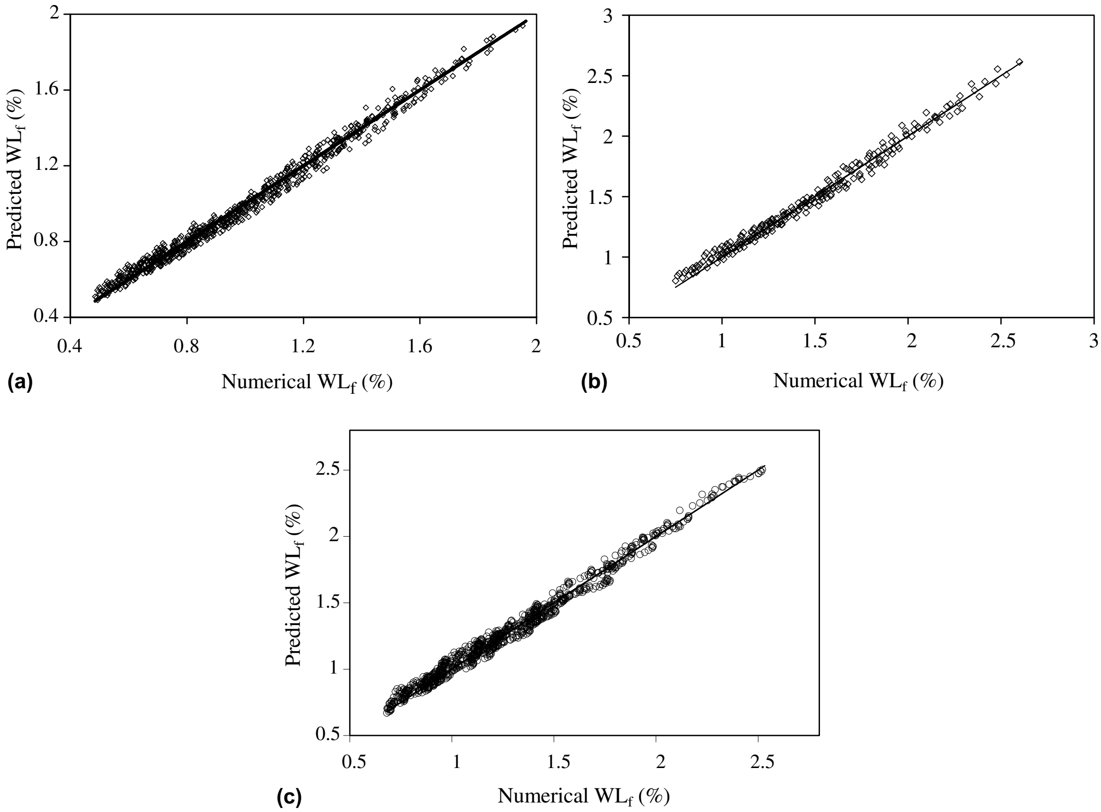

Fig. 1. (a) Predicted (◇) vs. numerical WL_f for plane plates, (b) predicted (◇) vs. numerical WL_f for infinite cylinders and (c) predicted (○) vs. numerical WL_f for spheres.

Table 3
Average percent errors of WL_f predicted using Eq. (6) for the three regular shapes

Geometry	Average e_{WL_f} (%)
Plate	−0.033
Cylinder	0.601
Sphere	0.102

Table 3 presents the average values for e_{WL_f}, the relative percent errors of predicted WL_f, defined as:

$$e_{WL_f}(\%) = 100 * \frac{WL_{f_{pred}} - WL_{f_{num}}}{WL_{f_{num}}} \quad (8)$$

The results show the very good agreement between predicted and numerical values.

4.1.2. Validation against experimental data

To our knowledge, the only set of experimental data of WL_f, whose range of experimental conditions lays within that covered in the deduction of Eq. (6), belongs to a previous work by the authors [10]. In this work, the t_f and the WL during the freezing and storage of hamburgers, chicken slabs, beef cylinders and meat balls were determined experimentally in a prototype tunnel, under different operating conditions. The total number of samples was 58: 13 for hamburgers and beef cylinders and 16 for meat balls and chicken slabs. Further details of the experimental arrangement and results can be found elsewhere [5,10].

Fig. 2 presents the comparison of the predicted values of WL_f—given by Eq. (6)—against the whole set of experimental data. As can be seen, despite the dispersion of the experimental data [10], the results are uniformly distributed at both sides of the 45° line. The average error of predicted WL_f is 9.83%, a low value, considering all the assumptions and approximations incurred in the experimental and calculation procedures. Besides, the comparison of experimental values against the predictions of the numerical method presents the same dispersion pattern and a higher average error of 12.96% [10].

In the validation of both prediction equations, Eqs. (6) and (7), specific values for the thermal properties of each food were used. In the same sense the values needed for the heat and mass transfer coefficients were taken

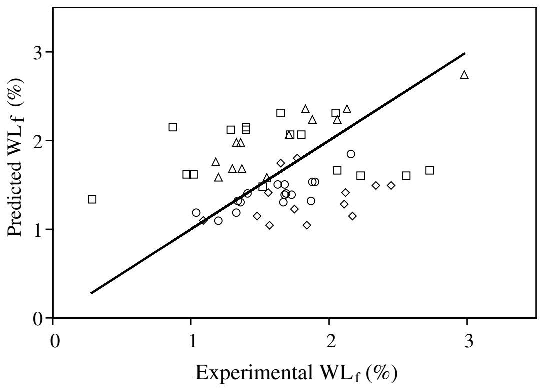

Fig. 2. Predicted vs. experimental WL_f for different foods: (◇) hamburgers, (○) chicken slabs, (△) beef cylinders, (□) meat balls.

from own data or calculated using equations from literature. Table 6 presents a list of these values and the references to the literature sources.

4.2. Frozen storage

As previously stated, two freezing conditions were used as a base for the different storage conditions, as defined by the International Institute of Refrigeration IIR [20]. They define freezing rate fr as the ratio between food half width (for plane plate) or radius (for cylinder and sphere) and the freezing time. A fr of 0.2 cm/h is considered as "slow freezing" SF, meanwhile a fr in the range of 0.5–3.0 cm/h is defined as "quick freezing" QF.

For each of both freezing conditions, in each run of the numerical model 90 days of frozen storage of a meat product were simulated with a limitation of weight loss of 25%. These high levels of losses are completely unusual in commercial frozen storage and, besides, for these conditions the numerical method would lead to biased results as the physical structure on which it is based would not be valid. The range of operating conditions studied were detailed in Table 1.

In Table 4 the values of the regression parameters and the correlation coefficient are shown for each geometry, for both the cases of previous slow (SF) and quick (QF) freezing. They were obtained by means of a software for nonlinear regressions [21]. As can be seen, high correlation coefficients ($R^2 > 0.999$) were obtained.

These results show a similar dependence of WL_{st} on storage conditions for previous QF and SF, but both the numerical model and the values of constants given in Table 4 determine a higher weight loss rate for QF foods as depicted in Fig. 3. This figure shows the predicted accumulated weight loss WL_t of two equal meat balls frozen under the two conditions and then maintained in the same storage situation. QF foods lose weight at a higher rate during storage and the accumulated WL for both QF and SF tend to equal at long storage times (normally not reached in practical storage situations).

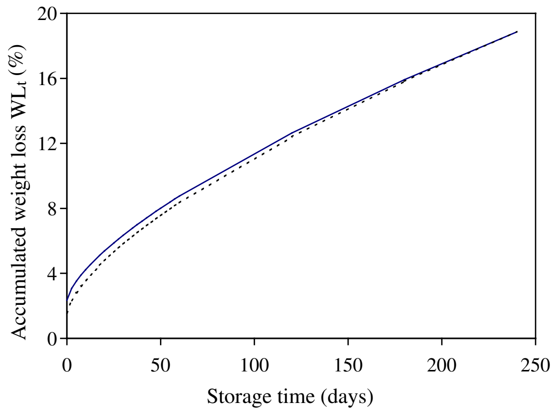

Fig. 3. Accumulated WL of a meat ball during storage: (—) after slow freezing, (- - -) after quick freezing.

Table 4
Parameters of Eq. (7) for the three geometries and two freezing conditions studied

Parameter	Plane plate		Cylinder		Sphere	
	SF[a]	QF[a]	SF	QF	SF	QF
n	0.021	0.027	0.018	0.019	0.028	0.028
o	−1.171	−1.130	−1.320	−1.305	−1.338	−1.327
p	0.078	0.080	0.1120	0.133	0.122	0.135
q	0.662	0.640	0.687	0.672	0.682	0.675
r	−1.543	−1.486	−1.618	−1.589	−1.651	−1.632
s	1.000	1.000	1.002	1.009	1.018	1.012
u	0.654	0.631	0.694	0.700	0.731	0.711
R^2	0.999	0.999	0.999	0.999	0.999	0.999

[a] SF: slow freezing, QF: quick freezing.

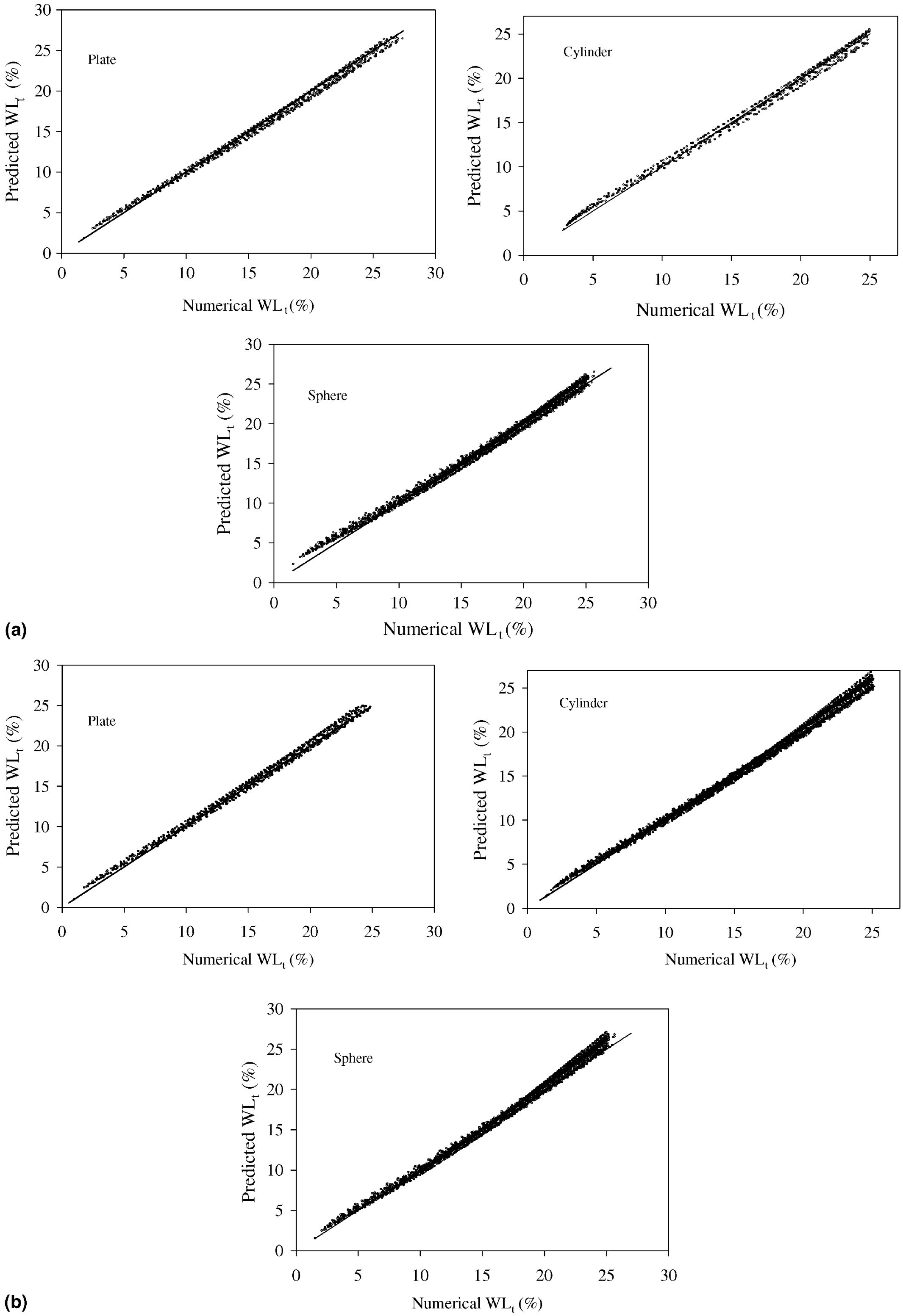

Fig. 4. (a) Predicted (○) vs. numerical WL_t after slow freezing, for plates, cylinders and spheres and (b) predicted (○) vs. numerical WL_t after quick freezing, for plates, cylinders and spheres.

4.2.1. Validation against numerical results

An additional test proof of the accuracy of Eq. (7) over all the range of operating conditions tested is presented in Fig. 4a and b and in Table 5.

Fig. 4 presents the comparison of predicted WL_t (by Eq. (7)) against numerical results for the three shapes during a storage period of 90 days—or up to 25% WL_t—, after a SF (Fig. 4a) or a QF (Fig. 4b). As can be seen, in both cases predicted values lie on a narrow band centered on the 45° line, without any bias. Meanwhile, Table 5 presents the average values for e_{WL_t} of predicted data. The results show the very good agreement between predicted and numerical values.

Table 5
Average percent errors of WL_t during frozen storage predicted using Eq. (7) for the three regular shapes

Geometry	Average e_{WL_t} (%)	
	Slow freezing	Quick freezing
Plate	2.377	7.018
Cylinder	3.228	6.870
Sphere	5.233	7.147

4.2.2. Validation against experimental results

As previously stated, the only comprehensive sets of experimental data of weight loss during freezing and frozen storage of simple-shaped foods belong to a previous work by these authors [10]. The different experimental freezing runs for each type of food (hamburgers, chicken slabs, beef cylinders and meat balls) were continued under storage conditions and weight loss during this period was registered at established time intervals. These data of WL during storage were used for comparison purposes.

Fig. 5a–d present the predicted accumulated weight loss during freezing and storage WL_t against the experimental WL_t. Predicted WL_t was calculated assuming the possibility of previous quick freezing (QF) or previous slow freezing (SF). For this purpose the experimental fr for each test was calculated based on experimental t_f and sample size [10]. When doing this, it was verified that the whole set of experimental data belonged to the QF type with fr ranging between 0.52 and 3.19 cm/h. So, Eq. (7) with the coefficients for the QF case was used for predictions. Fig. 5 also includes—for comparison purposes—the WL_t predicted using the numerical method [10]. Evaluation of these results shows an overall accurate prediction over all the range of products,

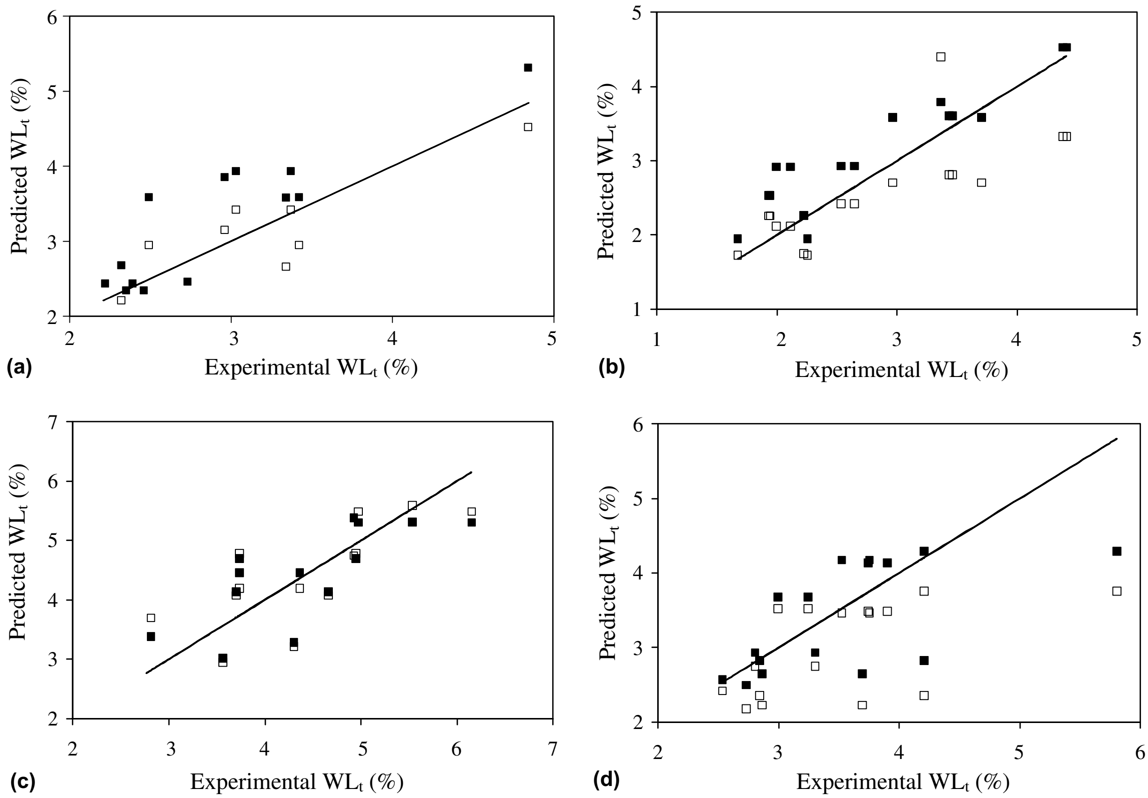

Fig. 5. Predicted ((■) Eq. (7), (□) numerical method) vs. experimental WL_t of (a) hamburgers, (b) chicken slabs, (c) beef cylinders and (d) meat balls.

Table 6
Values for the thermal properties used and references from where they were taken, for the testing of Eqs. (6) and (7)

Product	Reference for the values of h	Value for k_0 [W/(m K)] and reference for that value	Value for α_0 [m^2/s] and reference for that value
Lean beef	[5,16,17]	0.48 [18]	1.31×10^{-7} [18]
Chicken slab	[5,16,17]	0.48 [18]	1.31×10^{-7} [18]
Minced beef (balls and hamburgers)	[5,16,17]	$0.0866 + 0.501\,Y_0 + 5.0521 \times 10^{-4}\,Y_0 T$ [19]	$k_0/(1053 * 3474.86)$ [5]

Table 7
Average percent errors of predicted WL_t during frozen storage for the four sets of experimental data

Product	Average e_{WL_t} (%)	
	Eq. (7)	Numerical
Hamburger	11.917	−7.759
Chicken slab	14.147	−6.397
Beef cylinder	1.889	1.433
Meat ball	−1.361	−13.164

shapes and storage conditions, despite the dispersion of experimental data. The average error e_{WL_t} (%) of predicted WL_t is low as shown in Table 7. The same table presents the e_{WL_t} (%) of calculated WL_t using the numerical method. As can be seen both prediction methods have the same order of accuracy.

5. Conclusions

- Simple and accurate prediction equations could be developed for the calculation of weight loss during freezing and frozen storage of unpackaged foods. These equations cover a wide range of possible operating conditions accounting for cooling air properties and food characteristics.
- The developed equations were validated against numerical and experimental data of weight loss of four types of foods (beef hamburgers, balls and cylinders and chicken slabs).
- The average errors of predicted values by the approximated method—when comparing against experimental data—were in the same range that those of the numerical method.

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