Monitoring of Weight Losses in Meat Products during Freezing and Frozen Storage

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During freezing and frozen storage, the surface of unpackaged food is exposed to mass transfer exchange with the environment. Ice sublimes forming a dry, porous layer altering the sensory characteristics of the foods. This work describes the design and use of an experimental equipment with controlled operating conditions to quantify weight losses during refrigeration, freezing and frozen storage. Experiments were carried out with several meat products (hamburgers, meat balls, beef cylinders and chicken slabs) under different air conditions: temperature (−40 to −20 °C), relative humidity (50–95%) and air velocity (1–5 m/s). Weight loss occurred during freezing ranged between 0.28 and 2.98%, meanwhile the global values corresponding to both stages (freezing plus storage up to reach 1200 min of refrigeration) ranged between 1.67 and 6.15%. Good agreement was found between experimental data for the different products tested and data from a numerical model developed in previous work. The results demonstrated that surface dehydration degree should be regarded as an important quality parameter to take into account and to quantify.

Key Words: meat, freezing, storage, ice sublimation, weight loss

INTRODUCTION

One of the main purposes of food industry is to optimise preservation technologies of perishable foods, so as to reach a final product with optimal quality. Among the various methods currently used, the most important are those based on the action of low temperatures, both refrigeration and freezing. Freezing is particularly widespread because it does not require either chemical agents or irradiation as preservation methods; besides, nutrients losses are minimised when exposing the food to low temperatures.

During freezing of unpackaged products, dehydration degree should be regarded as an important quality parameter to take into account and to quantify. Foods loose moisture during the freezing process because their surface is exposed to heat and mass transfer exchange with the environment. The difference between the water vapour pressure on food surface and that in the air bulk is the driving force for dehydration.

Temperature fluctuations in the environment during the storage of frozen products are frequent and unavoidably affect the stored products. Therefore, periods where the surface food temperature is higher than that of the environment alternate with periods where the opposite occurs that additionally favours dehydration or weight losses. In both situations (freezing and storage) surface ice sublimes thus forming a dry porous layer altering the sensory characteristics of products. This leads mainly to quality losses due to general appearance spoilage and to changes in colour, taste and texture.

Weight losses by ice sublimation related to the freeze-drying process have been widely studied. In such process, food is first frozen and then dehydrated under vacuum in a second stage, where ice crystals are allowed to sublime. Studies conducted in this field are aimed at gaining knowledge of the ice sublimation process at low pressures. In contrast, in the freezing field more attention has been paid to develop methods for heat transfer prediction than at evaluating weight losses.

Besides, the results obtained during the freeze-drying process cannot be transferred directly to the freezing process because lyophilisation is conducted at very low pressures, whereas freezing and frozen storage are carried out at atmospheric pressure, under which the mechanisms of sublimation and vapour diffusion inside the product are different.

The literature related to food preservation offers very few works aimed at quantifying weight losses during frozen storage. Aström (1972) reported overall weight loss data in food freezing, where a minimum value of about 1% is found, that could be higher depending on the type of equipment and freezing method used. Lambrinos and Aguirre Puente (1983) built a freezing

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tunnel to measure weight loss during potato freezing and frozen storage. The equipment was also used to record weight losses in tylose and pure ice (Aguirre Puente and Sukhwal, 1984). Pham and Willix (1984, 1985) developed simple prediction equations based on drying theory and the psychrometric chart to evaluate the weight losses during frozen storage of foods. The authors also measured the resistance of frozen lamb pieces (carcass quarters) to drying under different environmental conditions. Méndez Bustabad (1999) recorded experimental data on weight loss during long term frozen storage (six months) of beef quarters and pork sides. The results reported for freezing in tunnels were between 0.05% (beef wrapped with polyethylene, and in cardboard boxes) and 1.20% (unwrapped forward quarters). During frozen storage, the maximum value of weight loss was 7.36% (pork sides) and the minimum was 1.30% (pork sides in polyethylene).

Mathematical simulation of freezing and frozen storage processes described by Sukhwal and Aguirre-Puente (1983) outlined the energy and mass balances that describe these phenomena, without reaching a quantitative (approximate or numerical) solution. Recently, Campañone et al. (2001) developed a mathematical model that resolved differential equations arising from the statement of the coupled microscopic energy and mass balances during freezing and frozen storage. The model paid special attention to the generation and growth of a porous, dehydrated surface layer and to the specific characteristics of the heat and mass transfer phenomena in it. The implemented numerical solution accurately predicted freezing times and weight losses during freezing and frozen storage, growth of the dried porous layer and the behaviour of products exposed to fluctuating operating conditions. As there was not enough experimental information to validate the mathematical model, it was decided upon the construction of an experimental equipment. This would provide controlled operating conditions to quantify weight losses during refrigeration, freezing and frozen storage.

The main objective of this work was to obtain a fair set of experimental data on weight losses during freezing and frozen storage of various food products: meat hamburgers, meat balls, beef cylinders and chicken slabs, under different temperature and air velocity conditions. These sets of experimental data were compared with the numerical ones calculated through the model developed previously by the authors (Campañone et al., 2001).

MATERIALS AND METHODS

Samples

Minced Beef

Refrigerated minced beef was utilised which was moulded as hamburgers (10 cm diameter, 1.5–2 cm thick) and meat balls (5 cm diameter).

Beef Cylinders

Cylindrical samples from semitendinosus muscle (called *peceto* in Argentina), 2.75 cm in diameter and 10 cm long were taken with a punch. Cylinder bases were insulated with polystyrene discs (5 mm thick) to avoid axial energy and mass losses, so only the lateral cylinder surface remains exposed to transfer with the air (Figure 1).

Chicken Slabs

Parallelepiped samples 1.5–2.25 cm thick, 6 cm wide and 10 cm long were taken from chicken breasts. Slabs laterals were insulated with expanded polystyrene, 5 mm thick, to ensure one-dimensional mass and energy transfer through the faces having greater surface (Figure 1).

Methods

Equipment

The assays were carried out in a prototype tunnel purpose-built to reproduce those operating conditions

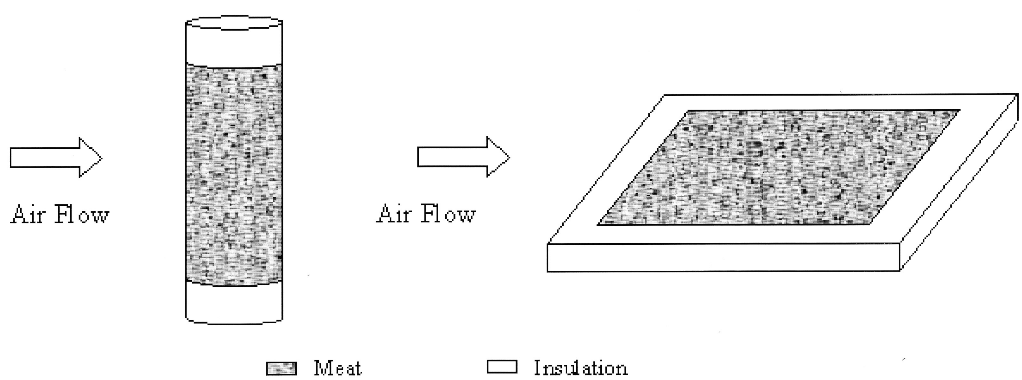

Figure 1. Scheme of samples arrangement (beef cylinders and chicken breasts).

typical of the industrial practice. This equipment was placed inside a standard modular cold store with a rated refrigerating capacity of 4254 kJ/h. The air circulation path and other details of the tunnel are shown in Figure 2.

The refrigeration source of the tunnel was the evaporator of the cold store. The air circulating inside the tunnel is refrigerated on flowing through the evaporator, then forced by two axial fans. To straighten the flow, a honeycomb-type arrangement was devised and was placed past the fans in the direction of airflow, upstream the measuring section. Downstream this sector, the air completes the circuit by returning to the evaporator. This equipment can work at temperatures above the freezing point so it may also be used to carry out weight loss experiments in refrigeration, as well as to determine heat or mass transfer coefficients (Campañone et al., 2000). All tunnel operating variables were measured and controlled as follows.

Air temperature inside the tunnel, T_{air}: Air temperature was measured by Cu–Ct thermocouples connected to a Series 500 (Keithley KDAC 500) data acquisition and control equipment. The system allows this temperature to be controlled within an accuracy of $\pm 0.5\,^{\circ}$C. This software-based control is of proportional plus integral type ($P + I$), the acquisition interval was 1 s while that for taking control actions being of 10 s. The control acts on a source of cold (the store refrigerating system) and on two heat sources (four electrical resistances, 1 kW each and an injection current of hot gas flowing past the compressor, obtained from a by-pass to the condenser of the store refrigerating system). The acquisition and control software was programmed in Quick Basic language which incorporates KDAC 500 acquisition routines. The programme allowed to choose between a step, a sine wave or a sine-exponential function for constant or time-varying air temperature experiments.

Air velocity v_{air}: It was measured by means of a Solomat anemometer using two different sensors (hot wire and vane). The hot wire operates between 1 and 5 m/s while the vane sensor does it in a wider range (1–10 m/s).

A variable speed device was connected to the axial fans that operated by a manual control placed on an instrument panel outside the cold store to allow the air circulation velocity to be adjusted and kept to a constant value over the entire experiment or, else, to vary it as a function of time.

Air relative humidity RH: An OMEGA HX48 capacitive hygrometer is employed whose sensor operates between -40 and $140\,^{\circ}$C.

Sample Size

The characteristic dimensions were measured with calipers, diameter (D) for spheres and cylinders, and thickness (E) for plates.

Sample Initial Water Content

It was determined by the AOAC (1980) method. An initial sample of about 5 g is weighed before being placed for a week in the oven set at $60\,^{\circ}$C. The initial water content was calculated based on the difference between initial and final weights.

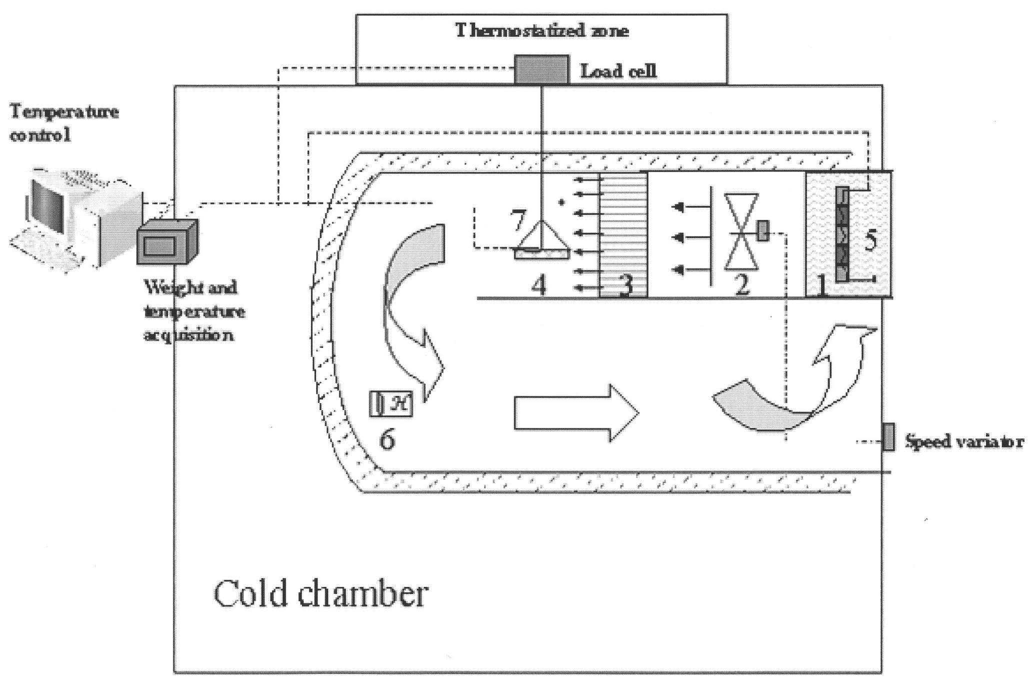

Figure 2. Scheme of freezing tunnel: 1 evaporator, 2 blowers, 3 flow straightener, 4 measuring sector, 5 heaters, 6 humidity sensor, 7 sample.

Sample Weight

It was measured by using strain gauges. These allowed weight variations to be sensed without removing the samples from the tunnel. The equipment possesses two different strain gauges:

Load cell 1 (Flexar): It works under compression with the maximum allowable weight of 2 kg and an accuracy of 0.5 g in process conditions.

Load cell 2 (Tedea): It works under tension with a maximum weighing capacity of 3 kg and an accuracy of 0.09%.

The response of these strain gauges is very sensitive to temperature, therefore both were placed outside the tunnel in an insulated and thermostated zone (within ± 1.5 °C). The control of this external temperature does not interfere at all with the value inside the tunnel.

Both gauges were connected to the KDAC 500 data acquisition system to monitor the weight evolution almost continually.

Sample Temperature

Rigid Cu–Ct thermocouples were used to record the internal thermal history of samples. They were placed and connected to the data acquisition and control system mentioned above.

Experimental Procedure

Each experiment involved the continuous measuring of weight loss and internal temperature of the various products during freezing and the further frozen storage. Three samples were utilised in each experimental series, two of them to measure weight variations while the remaining one to record the thermal history. The first two were placed in a tray each, connected to the strain gauges. A thermocouple was inserted in the thermal centre of the remaining sample deposited in a perforated support also placed in the tunnel measuring zone.

The experiments were carried out according to the following procedure:

1. The cold store was switched on.
2. The operating temperature T_{air} was selected by the data acquisition and control system.
3. The operating air velocity v_{air} was manually selected.
4. Once the tunnel reached the operating temperature, the relative humidity RH was measured.
5. Samples were weighed outside the store using an analytical balance (W_o) and a rigid thermocouple was carefully inserted in the corresponding sample so that the sensing head is placed in the sample centre.
6. Initial sample temperature T_{initial}, outside the cold store, was recorded.
7. Samples were placed inside the freezing tunnel.
8. The data acquisition and control system recorded the internal temperature and the weight provided by the strain gauges (stopping air circulation for 10 s during each measure) along the course of the experiment. Each value of weight and temperature are the average of ten values (sampling interval: 1 s). The total duration of each experimental run is of 24 h.

The following variables were evaluated for each test:

- Freezing time (t_f) defined as the period required for the thermal centre of the product to reach − 18 °C.
- Percentage weight loss during freezing (WL_f): it is given by the following expression:

$$WL_f = \frac{W_o - W_{\mathrm{eof}}}{W_o} \times 100 \quad (1)$$

where W_o is the initial sample weight and W_{eof} the value at the end of freezing.

- Percentage global weight loss: this is computed using the following ratio:

$$WL_g = \frac{W_o - W_e}{W_o} \times 100 \quad (2)$$

where W_o is the initial sample weight, W_e being the weight at the end of the experiment (in all cases, total duration was 1200 min).

As far as weighing is concerned, values were recorded in two different samples for each experimental series though, in some cases, results were based on only one sample because the load cell 2 was very sensitive to external noise and in some runs the signal was received with considerable fluctuations that masked weight variation.

In order to study various usual situations of industrial practice, experimental determinations were carried out at constant (Tables 1–4) and time-varying operating conditions (Table 5) . At constant conditions three air

Table 1. Experimental determination of weight losses in hamburgers at different operating conditions and sample characteristics.

	Tunnel			Sample	
Condition	T_{air} (°C)	v_{air} (m/s)	RH (%)	T_{initial} (°C)	Thickness E (cm)
HA1	− 20.2	5.0	80.0	4.5	1.5
HA2	− 20.1	2.7	80.0	14.2	1.5
HA3	− 20.2	1.1	49.8	15.4	1.5
HA4	− 25.0	5.0	80.0	2.8	1.5
HA5	− 25.0	2.7	57.4	14.6	1.5
HA6	− 25.0	1.1	57.7	9.8	1.5
HA7	− 29.2	5.0	65.0	6.3	2.0
HA8	− 29.1	2.7	63.6	11.1	2.0
HA9	− 28.8	1.1	64.0	15.5	2.0

Table 2. Experimental determination of weight losses in meat balls at different operating conditions and sample characteristics.

	Tunnel			Sample	
Condition	T_{air} (°C)	v_{air} (m/s)	RH (%)	$T_{initial}$ (°C)	Diameter (cm)
MB1	– 20.0	5.0	66.0	10.0	5.0
MB2	– 20.1	2.7	64.0	9.5	5.0
MB3	– 19.8	1.1	64.6	13.1	5.0
MB4	– 24.9	5.0	66.0	16.2	5.0
MB5	– 24.9	2.7	70.7	8.5	5.0
MB6	– 23.9	1.1	70.0	7.0	5.0
MB7	– 29.8	5.0	61.9	5.8	5.0
MB8	– 29.9	2.7	67.3	9.0	5.0
MB9	– 28.4	1.1	65.3	10.9	5.0

Table 3. Experimental determination of weight losses in beef cylinders at different operating conditions and sample characteristics.

	Tunnel			Sample	
Condition	T_{air} (°C)	v_{air} (m/s)	HR (%)	$T_{initial}$ (°C)	Diameter (cm)
BC1	– 20.2	5.0	63.3	9.6	2.7
BC2	– 19.9	2.7	63.3	9.7	2.7
BC3	– 20.1	1.1	64.6	14.1	2.7
BC4	– 25.6	5.0	57.9	8.9	2.7
BC5	– 24.2	2.7	57.9	10.7	2.7
BC6	– 23.6	1.1	57.2	12.9	2.7
BC7	– 29.8	5.0	62.3	11.1	2.7
BC8	– 29.7	2.7	70.0	9.1	2.7
BC9	– 29.2	1.1	62.6	8.6	2.7

Table 4. Experimental determination of weight losses in chicken breasts at different operating conditions and sample characteristics.

	Tunnel			Sample	
Condition	T_{air} (°C)	v_{air} (m/s)	RH (%)	$T_{initial}$ (°C)	Thickness E (cm)
CH1	– 19.8	5.0	68.7	15.7	2.2
CH2	– 20.1	2.7	80.0	7.8	1.5
CH3	– 19.7	1.1	63.3	8.1	1.5
CH4	– 24.8	5.0	95.0	12.3	1.5
CH5	– 24.7	2.7	80.0	12.7	1.5
CH6	– 24.0	1.1	64.6	12.4	1.5
CH7	– 29.5	5.0	80.0	16.6	1.5
CH8	– 29.7	2.7	80.0	9.8	1.5
CH9	– 28.9	1.1	61.9	12.4	1.5

temperature levels (– 20, – 25 and – 30 °C) and three air velocities (1, 2.5 and 5 m/s) were selected to cover a wide operating range. As the experimental equipment did not control relative humidity, reported values corresponded to the value measured when air temperature stabilised around its set point.

Table 5. Experimental determination of weight losses in beef cylinders under variable operating conditions and sample characteristics.

	Tunnel			Sample	
Condition	T_{air} (°C)	v_{air} (m/s)	RH (%)	$T_{initial}$ (°C)	Diameter (cm)
VA1	variable[a]	5.0	50.0	10.6	3.0
VA2	– 20.0	variable[b]	50.0	7.5	3.0

[a]T_{air}: a square-type wave signal; minimum value: – 22.5 °C; amplitude: 4 °C; period: 1 h.
[b]v_{air}: a square-type wave signal; minimum value: 1 m/s; amplitude: 4 m/s;period: 1 h.

Table 5 presents the characteristics of two experimental series conducted in time-varying conditions to test cylindrically-shaped beef samples. In the first of them, air temperature was programmed to follow a square-type wave signal, by means of the acquisition and control software. The wave had a minimum of – 22.5 °C, an amplitude of 4 °C and a period of 1 h. In the second series, air velocity was manually adjusted again to obey a square wave function with a minimum at 1 m/s and a maximum at 5 m/s, the period also being of 1 h.

RESULTS AND DISCUSSION

A preliminary analysis of the results showed that sample temperature and weight followed a similar behaviour with time (Figure 3). The internal product temperature curve presented three slope changes. The first coincided with the beginning of surface freezing, the second occurred at the end of the change of state whereas the last took place when the internal product temperature approaches the air temperature. The weight loss curve displayed only one pronounced slope change when the temperature of the sample reached the air temperature. This behaviour is explained based on the phenomena involved in freezing and frozen storage; at the beginning, moisture loss is caused by liquid water evaporation during refrigeration. Then, as the surface becomes frozen, weight losses are due to ice sublimation. At both stages, the driving forces are the vapour pressure and temperature differences between food surface and the bulk air. As the sample approaches the external temperature, the temperature driving force disappears, so only the vapour pressure difference remains and the weight loss rate decreases.

According to the previous model (Campañone et al., 2001) predicted and experimental weight variations showed good agreement for freezing and during later frozen storage (Figures 3–7, Tables 6–9). In the case of replicated samples we find that, even when an important difference of WL_g could exist between samples, they presented positive and negative differences respect to the

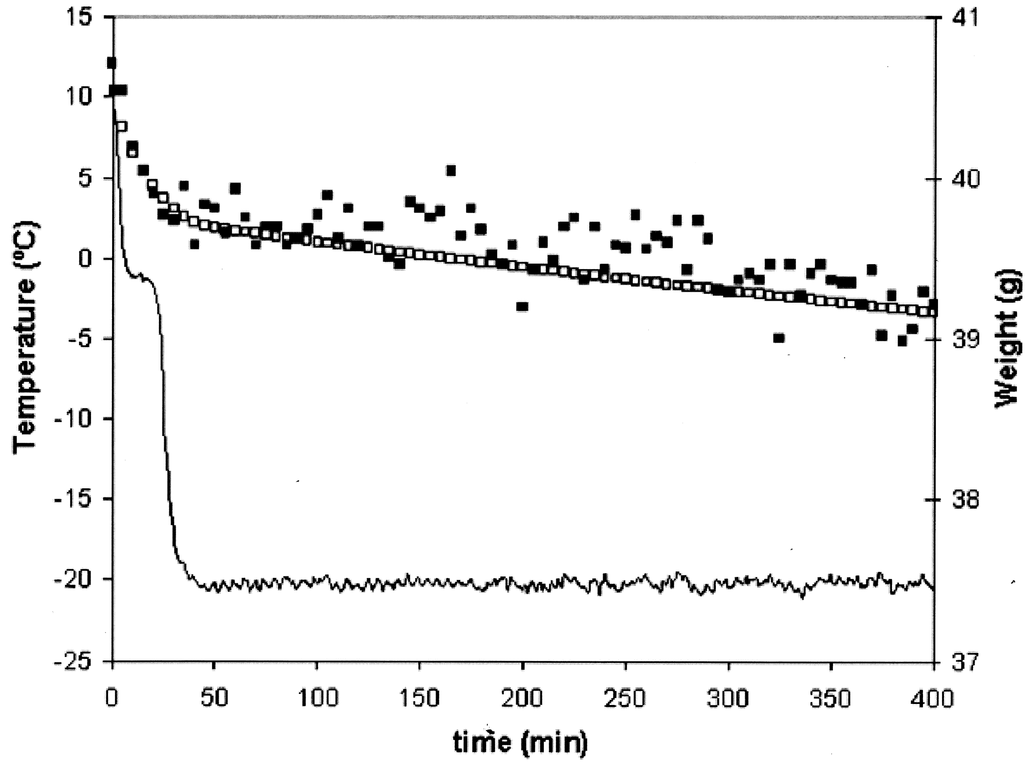

Figure 3. Experimental (■) and predicted (□) weight and sample temperature (—) during freezing and storage of a beef cylinder (Sample BC1).

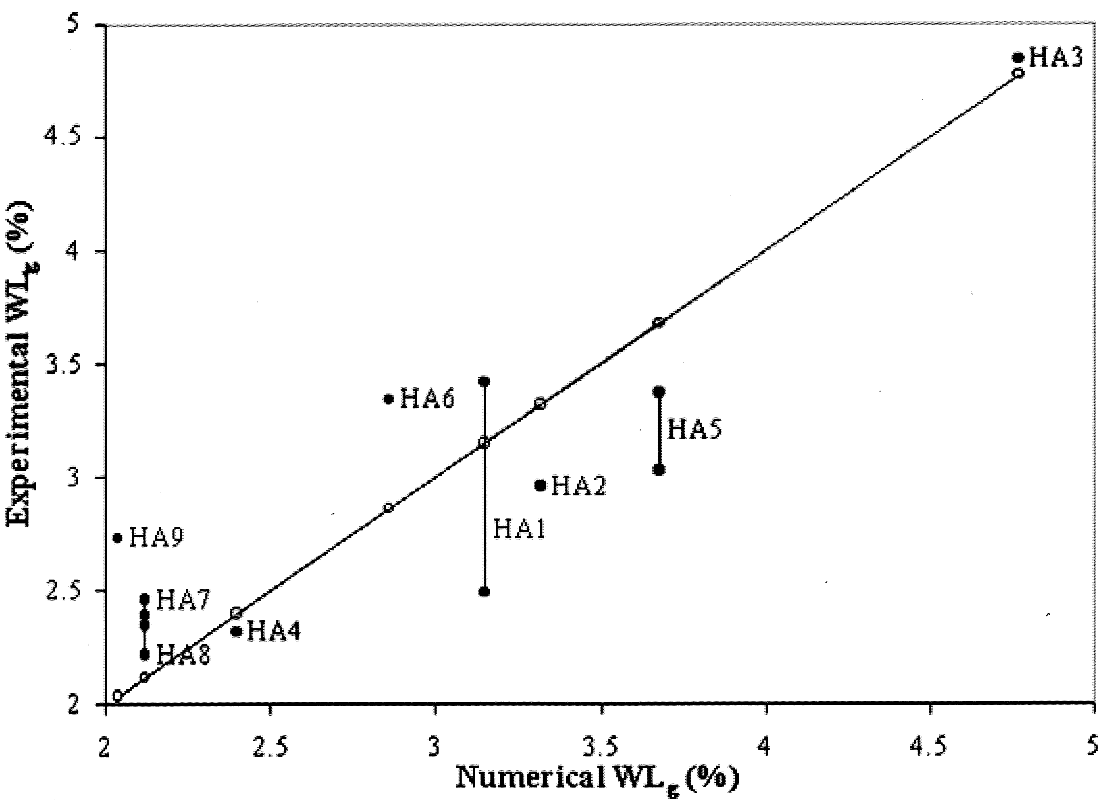

Figure 4. Global experimental (●) and predicted (○) weight loss of hamburgers. Operating conditions and sample characteristics detailed in Table 1.

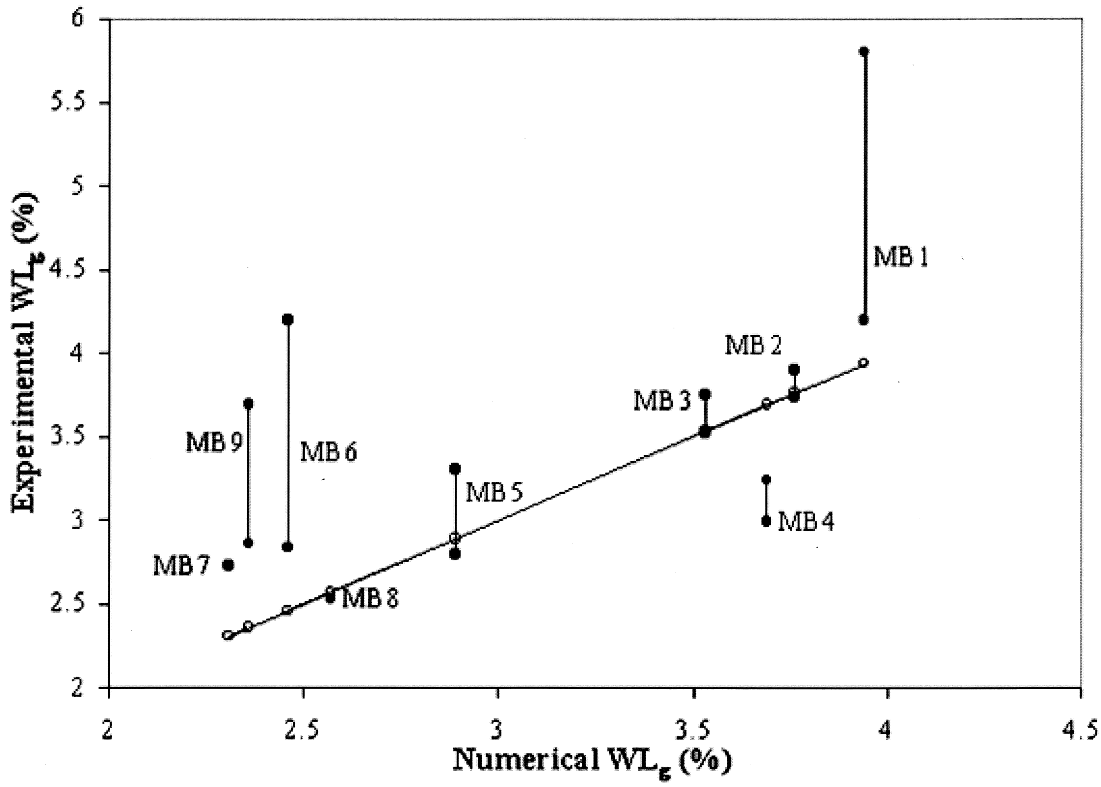

Figure 5. Global experimental (●)and predicted (○) weight loss of meat balls. Operating conditions and sample characteristics detailed in Table 2.

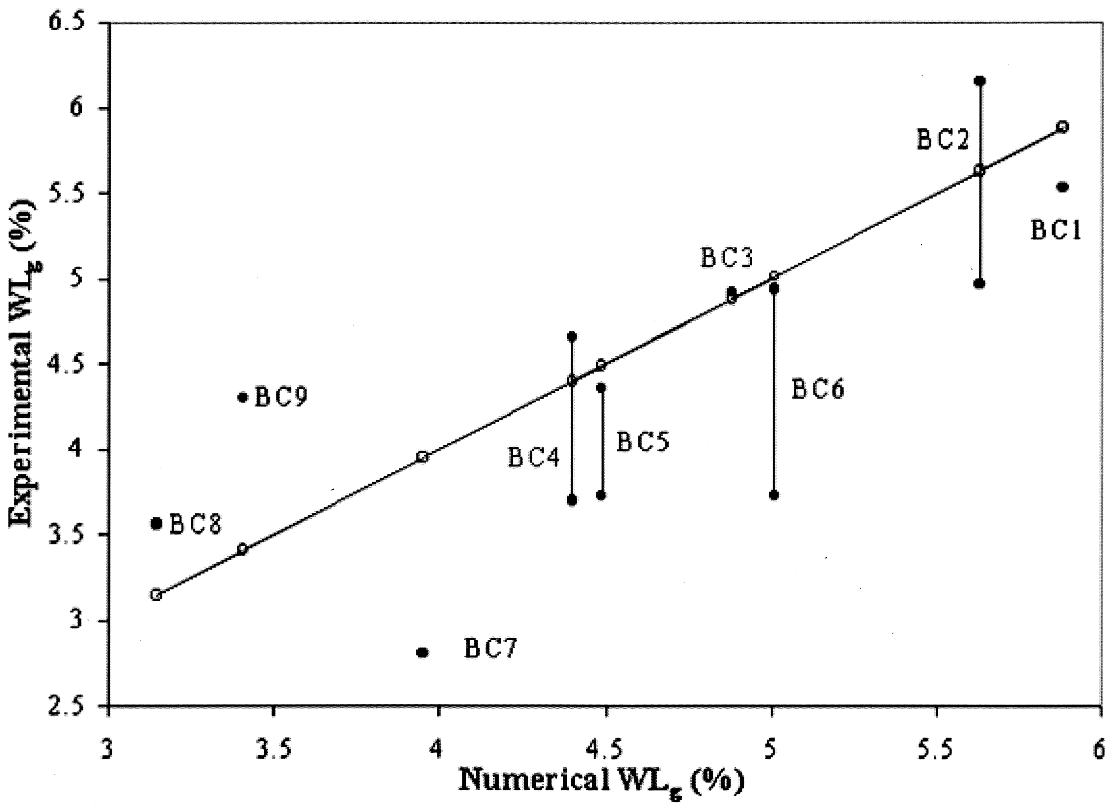

Figure 6. Global experimental (●) and predicted (○) weight loss of beef cylinders. Operating conditions and sample characteristics detailed in Table 3.

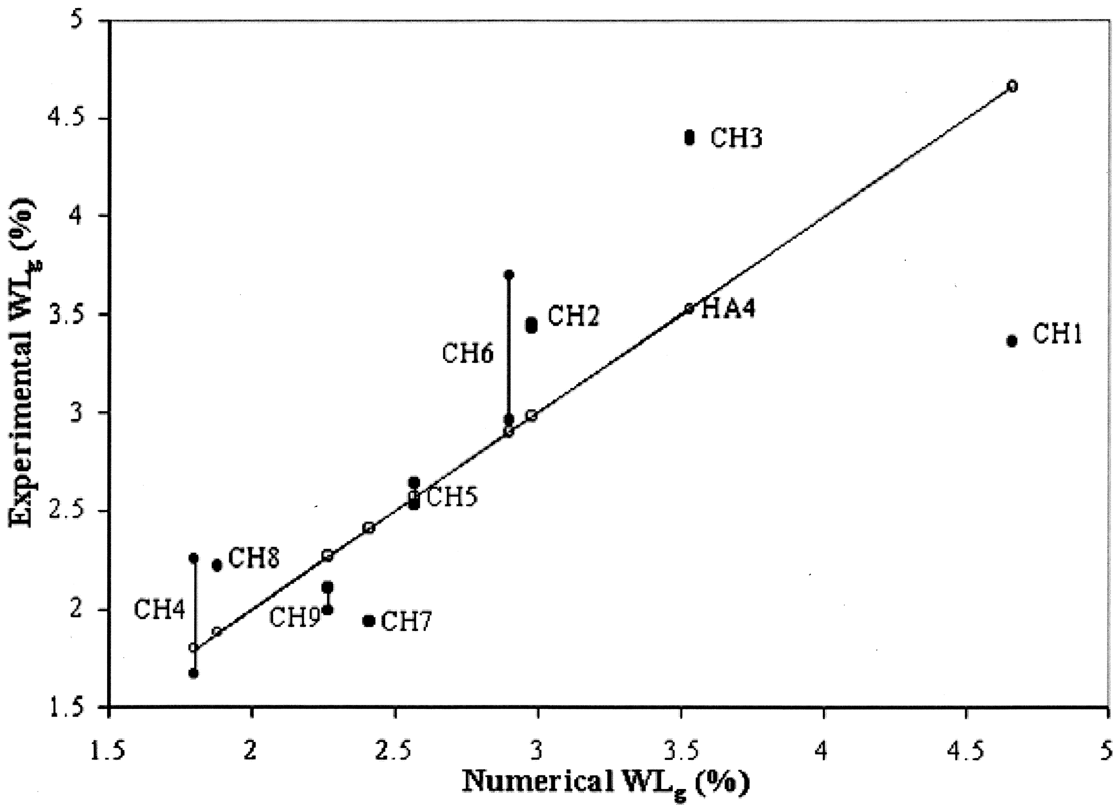

Figure 7. Global experimental (●) and predicted (○) weight loss of chicken breasts. Operating conditions and sample characteristics detailed in Table 4.

Table 6. Experimental results of freezing time t_f, weight loss during freezing WL_f and global weight loss WL_g; and numerical global weight loss $WL_{g,\text{num}}$, for conditions detailed in Table 1 (hamburgers).

Condition	Sample	t_f (min)	W_o (g)	WL_f (%)	WL_g (%)	$WL_{g,\text{num}}$ (%)
HA1	S1	46.9	129.09	1.56	2.49	3.15
HA1	S2	46.9	126.47	2.12	3.42	3.15
HA2	S1	60.5	135.86	1.65	2.96	3.32
HA3	S1	86.2	126.00	1.77	4.84	4.77
HA4	S1	33.2	132.00	1.09	2.32	2.40
HA5	S1	44.6	126.97	2.45	3.03	3.68
HA5	S2	44.6	141.70	2.34	3.37	3.68
HA6	S1	54.1	110.20	2.11	3.34	2.86
HA7	S1	40.2	160.47	1.84	2.35	2.12
HA7	S2	40.2	150.55	1.57	2.46	2.12
HA8	S1	49.4	156.26	2.17	2.39	2.12
HA8	S2	49.4	159.10	1.48	2.22	2.12
HA9	S1	66.7	150.70	1.75	2.73	2.04

Table 7. Experimental results of freezing time t_f, weight loss during freezing WL_f and global weight loss WL_g; and numerical global weight loss $WL_{g,\text{num}}$, for conditions detailed in Table 2 (meat balls).

Condition	Sample	t_f (min)	W_o (g)	WL_f (%)	WL_g (%)	$WL_{g,\text{num}}$ (%)
MB1	S1	71.2	74.47	1.40	4.20	3.94
MB1	S2	71.2	74.70	1.29	5.80	3.94
MB2	S1	89.0	74.44	1.80	3.74	3.76
MB2	S2	89.0	74.39	1.72	3.90	3.76
MB3	S1	135.0	75.19	2.05	3.52	3.53
MB3	S2	135.0	73.60	1.65	3.75	3.53
MB4	S1	54.2	74.35	1.40	3.24	3.69
MB4	S2	54.2	74.76	0.87	2.99	3.69
MB5	S1	65.0	74.76	2.06	2.80	2.89
MB5	S2	65.0	74.30	2.73	3.30	2.89
MB6	S1	98.0	74.30	2.56	4.20	2.46
MB6	S2	98.0	74.30	2.23	2.84	2.46
MB7	S1	45.0	77.36	0.28	2.53	2.57
MB8	S1	51.6	78.66	1.52	2.73	2.31
MB9	S1	76.2	79.56	1.02	3.69	2.36
MB9	S2	76.2	74.00	0.97	2.86	2.36

predicted values. These follow the variation trend and average value in WL_g.

Variable operating conditions influenced both energy and mass transfers (Figures 8 and 9). Air velocity, affected the values of energy and mass transfer coefficients, whereas temperature influenced, in addition, the driving forces for both transfer types. However, no oscillations were observed as response to the type of operating conditions in the weight loss curves, for both situations. Possibly, the amplitude of variations was below the sensitivity of the strain gauges utilised. The percent weight losses kept within

Table 8. Experimental results of freezing time t_f, weight loss during freezing WL_f and global weight loss WL_g; and numerical global weight loss $WL_{g,\mathrm{num}}$, for conditions detailed in Table 3 (beef cylinders).

Condition	Sample	t_f (min)	W_o (g)	WL_f (%)	WL_g (%)	$WL_{g,\mathrm{num}}$ (%)
BC1	S1	50.0	40.40	1.71	5.53	5.88
BC2	S1	65.0	53.20	2.06	4.97	5.63
BC2	S2	65.0	49.79	1.88	6.15	5.63
BC3	S1	100.0	41.30	2.98	4.92	4.88
BC4	S1	34.5	45.95	1.37	4.66	4.40
BC4	S2	34.5	49.75	1.30	3.70	4.40
BC5	S1	42.8	48.69	1.33	3.73	4.49
BC5	S2	42.8	44.52	1.36	4.36	4.49
BC6	S1	70.0	53.49	1.83	3.73	5.01
BC6	S2	70.0	59.59	2.13	4.94	5.01
BC7	S1	29.2	46.49	1.55	2.81	3.95
BC8	S1	37.5	36.98	1.20	3.56	3.15
BC9	S1	61.1	42.90	1.18	4.30	3.41

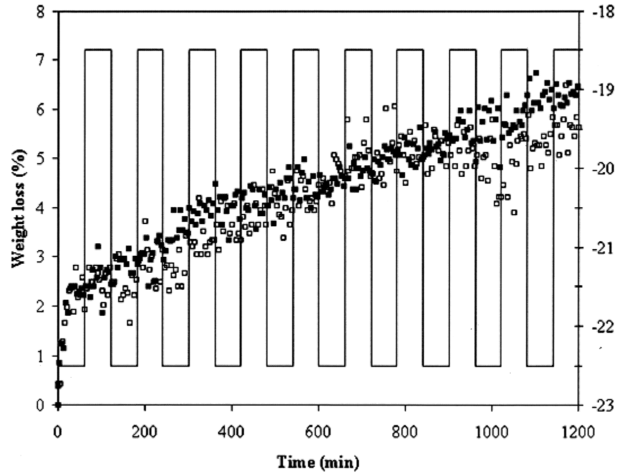

Figure 8. Weight loss of a beef cylinder during freezing and storage (sample VA1) at variable (■) and constant temperature (□). Air temperature (—).

Table 9. Experimental results of freezing time t_f, weight loss during freezing WL_f and global weight loss WL_g; and numerical global weight loss $WL_{g,\mathrm{num}}$, for conditions detailed in Table 4 (chicken breasts).

Condition	Sample	t_f (min)	W_o (g)	WL_f (%)	WL_g (%)	$WL_{g,\mathrm{num}}$ (%)
CH1	S1	53.5	200.02	2.16	3.36	4.66
CH2	S1	57.3	153.06	1.68	3.46	2.98
CH2	S2	57.3	132.29	1.63	3.43	2.98
CH3	S1	76.6	124.89	1.90	4.38	3.53
CH3	S2	76.6	120.83	1.88	4.41	3.53
CH4	S1	37.0	128.93	1.67	2.25	1.80
CH4	S2	37.0	130.59	1.36	1.67	1.80
CH5	S1	43.7	135.84	1.68	2.64	2.57
CH5	S2	43.7	130.96	1.73	2.53	2.57
CH6	S1	58.4	144.52	1.41	2.96	2.90
CH6	S2	58.4	123.31	1.69	3.70	2.90
CH7	S1	31.0	139.74	1.87	1.93	2.41
CH7	S2	31.0	144.28	1.34	1.94	2.41
CH8	S1	34.0	128.24	1.20	2.22	1.88
CH9	S1	46.6	134.41	1.04	2.11	2.27
CH9	S2	46.6	140.95	1.33	1.99	2.27

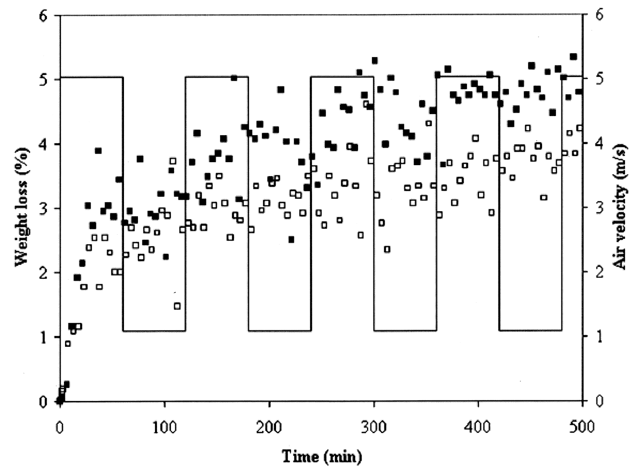

Figure 9. Weight loss of a beef cylinder during freezing and storage (sampleVA2) at variable (■) and constant temperature (□). Air velocity (—).

the same range in both constant or variable operating conditions.

In fact, the differences observed in WL for fixed and variable conditions are of the same order – or even lower – than those found for replicate samples (Tables 6–9). Therefore, the behaviour of the samples was seemingly alike that observed in constant air temperature and velocity, whose values were equal to the averages taken for the variation range used in the time-varying experiments.

The measured WL%, with a maximum of 2.98% during freezing (BC3) and of 6.15% as global weight loss (BC2), indicate that WL is a parameter that needs to be taken into account to plan or optimise freezing processes.

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