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Numerical Investigation into the Product's Weight loss and Display Shelf life inside the Serve-over Cabinet

Abas Hadawey[a]*, Savvas Tassou[b], Shatha Haddowe[a], Raveendran Sundararajan[a]

[a]London South Banks University, London SE1 0AA, United Kingdom
[b] Brunel University London, Institute of Energy Futures, RCUK Centre for Sustainable Energy use in Food chains (CSEF), Uxbridge UB8 3PH, United Kingdom

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Abstract

One of the most important aspects of chilled food deterioration in delicatessen cabinets economically is associated with drying, rather than spoilage mechanism, especially for unwrapped products. Investigating the effects of the bacterial spoilage and moisture migration for chilled-unwrapped food product such as sandwiches, which have short display shelf life, and knowing the optimum boundary conditions that provide longer displays shelf life can significantly contribute to reduction of wastage of this type of product during its display, and operate refrigeration systems in the most efficient manner. Recent years have seen an increase in customer demand for fresh convenience food, which has resulted in a major increase in the volume of sales of unwrapped products. Surface drying has been identified as the main reason for commercial loss from unwrapped chilled food in display cabinets. Surface drying increases weight loss and leads to colour changes that are undesirable. A 2D Computational Fluid Dynamic model was constructed for the serve-over display cabinet that includes the weight loss from products inside the cabinet. The model was used to investigate the effect of the environmental boundary conditions on the drying rate and display shelf life. Validation was carried out by comparison of measured results of the product temperature, drying rate and display shelf life of the product inside the cabinet, to those predicted by the simulations. The results show that improving the operating boundary conditions inside the display cabinet can improve the food quality, reduce the drying rate of the food product and increase the display shelf life.

Keywords: CFD; Server over display cabinet; Drying rate; Display shelf life; Food waste.

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* Corresponding author. Tel.: +44 (0)20 7815 7537.
Email address: hadaweya@lsbu.ac.uk

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1. Introduction

Chilled foods have been available since the 1960s; the UK market for chilled ready meals has grown from an estimated £173 million in 1988 to £11876 million in 2017 [1]. However, over the past 20 years, the market has been driven by the huge social, economic and demographic changes that have influenced our eating habits. The most common types of display cabinet for chilled food applications are open vertical multi-deck and serve-over (delicatessen). The vertical multi-deck display cabinet became very popular in the 1940s due to its large display area and easy access to the product. The attractive display manner in which food is displayed in serve-over cabinets has become popular in supermarkets and food retail outlets, due to the easy manner with which customers can be served.

Surface drying has been identified as the main reason for commercial loss from unwrapped chilled food in display cabinets. Surface drying increases weight loss and lead to colour changes that are undesirable. Weight loss has also been identified as the most important cause for the end of display shelf life of meat, fish and their products [2]. It was found by [3] that the discolouration was the most important limiting factor controlling the display shelf life of pre-packed meat and a relationship was established between weight loss during display and colour changes. Evaluating the weight loss of any food item by a mathematical model requires knowledge of the mass transfer coefficient of that type of food. Many investigations have been carried out to establish the variation of drying rate as a function of the environmental boundary conditions. Some of these investigations were experimental, involved mainly meat and meat products, and resulted in recommendations for increasing product shelf life and minimising weight loss. While other investigations attempted to develop mathematical models to calculate the drying rate as a function of the environmental conditions and product variables such as shape and water activity [4, 5 and 6].

A 2D-CFD-model of the serve over display cabinet has been constructed in order to model the evaporating losses from a meat baguette sandwich. The model was validated and used to investigate the air characteristics inside the serve over display cabinet, taking into consideration the effect of the environmental boundary conditions on the drying rate and display shelf life.

2. Theoretical Background

The rate at which a food product loses weight through its surface depends on two related processes: evaporation, in which, convection transfers moisture from the surface of the product to the surrounding air, and diffusion, where water from within the food moves to the surface. The mass transfer coefficient represents the resistance of the food surface against losing water vapour. The rate of evaporation is proportional to the difference between the water-vapour pressure in equilibrium with the surface and that of the cooling air. The equilibrium vapour pressure of the product's surface is related to its temperature and its water activity, which is defined as the ratio of the water vapour pressure in equilibrium with the product's surface to that of the water at the same temperature [7]. Dalton's law represents the mass transfer rate dM/dt at the air-body interface [8].

$$dM/dt = AK_e(P_s - P_a) \qquad (1)$$

where A is the surface area of the food, K_e is the mass transfer coefficient, P_s the partial pressure of water vapour in the boundary layer over the product surface and is defined by [9].

$$P_s = a_w . P_{ws} \qquad (2)$$

where a_w is the water activity at the product surface, P_{ws} is the saturation vapour pressure of water at the product surface and can be satisfactorily approximated from the temperature of the product surface using the Antonine equation [10].

$$P_{ws} \approx \exp\ [23.4795 - 3990.5/(T + 233.833)] \qquad (3)$$

In addition, P_a which is the partial pressure of water vapour in the bulk air and can be found using the formula given by [9].

$$P_a = Hr.P_{wa} \qquad (4)$$

where Hr is the relative humidity, which represents the ratio of the actual water vapour pressure to the saturation water vapour pressure. P_{wa} is the saturation vapour pressure of water at the bulk air and can be obtained by using Antonine equation at the bulk air temperature.

3. Model Description

3.1. Modelling the product

The essential part of modelling the display cabinet is the way that the product is modelled in the CFD model. Different types of food can be displayed in the cabinet. However, a meat baguette sandwich, consisting of baguette and meat (beef) as filling was considered in this investigation. Fig.1a shows a typical meat baguette sandwich.

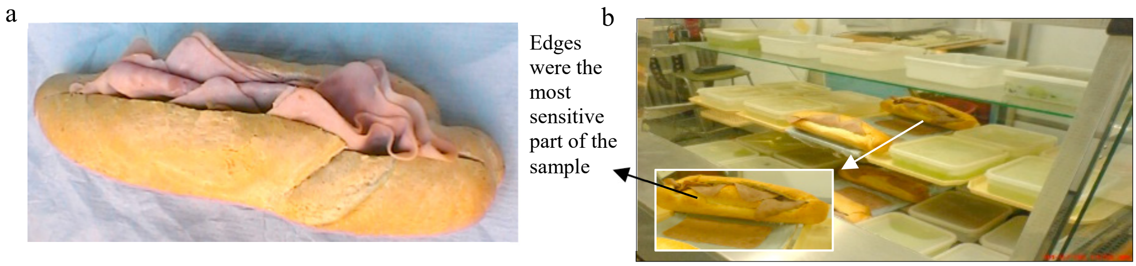

Fig. 1. (a) Typical meat baguette sandwich (b) Beef sample displayed on its own and as a filling

For a meat (beef) baguette sandwich, the beef is the most sensitive component to the display shelf life. To evaluate this, a trial test was carried out in the cabinet using a beef slice on its own and beef as a filling in a baguette sandwich. The results of the test conclusively showed that in both cases the edges of the samples were most affected through drying out. The display shelf life was almost the same for both cases as shown in Fig. 1b. A 2D CFD model is used to model the display cabinet, a cross section through the middle section of the display cabinet was considered. The representation of the product in the CFD model is shown in Fig. 2a.

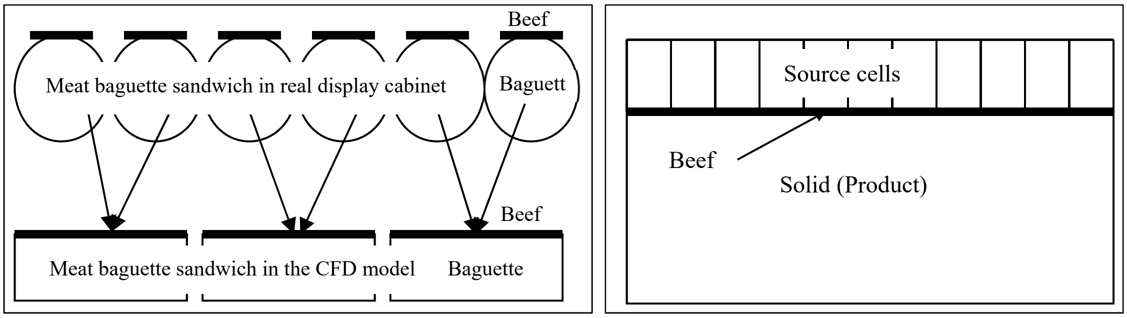

Fig. 2. (a) Representation of the sandwiches in the 2D CFD model of the serve-over display cabinet
(b) Cross-Section of the Beef Baguette Sandwich with Water Vapour Source Cells

3.2. Modelling the Evaporating Loss from the product Inside the Cabinet

Fluent has been used to model the evaporating losses from unwrapped meat baguette sandwiches placed in a display cabinet. Mass transfer from any food item depends on evaporation, where the water vapour transfers from the product surface to the surrounding air and on diffusion, where the water from within the food moves to the surface. The moisture content of the food product has a significant effect on the rate of mass transfer within the food and from the surface to the surrounding air. The process of weight loss is not a steady state process; it is a function of the environmental boundary conditions and food characteristics. As the evaporating process continues, the moisture content of the food component will decrease. However Fluent was used to model the evaporation, but fluent cannot model the mass transfer inside a solid. Modelling the evaporating losses therefore, only considers the evaporation from the food surface during the steady state period of the evaporating process. Modelling the evaporating losses in Fluent involved adding a source of water vapour (H_2O) on the food surface. The cells that are in direct contact with the food surface are therefore, considered to be a source of water vapour (H_2O). Fig. 2b shows the modelling concept. Equation (1) was considered in the CFD modelling. The source cells at the top of the beef where the source equation was implemented and the beef was modelled as a solid object. The User define function option in Fluent was considered to implement equation (1) in fluent to calculate the evaporating losses. Since this cabinet was designed to provide cooling for the bottom and middle shelves only, the top-shelf sandwiches were not considered in the calculation of evaporating loss. The evaporating losses inside the display cabinet will contribute to the latent load of the display case by increasing the amount of water vapour (mass fraction of H_2O) entering the evaporator coil (air-on side). The drying rate kg/sec was evaluated by obtaining the mass flow rate of the evaporated water vapour from the beef inside the cabinet by running the CFD model with and without the source of H_2O, the difference of the water vapour mass flow rate at the air-on section for both models represents the amount of water vapour evaporated.

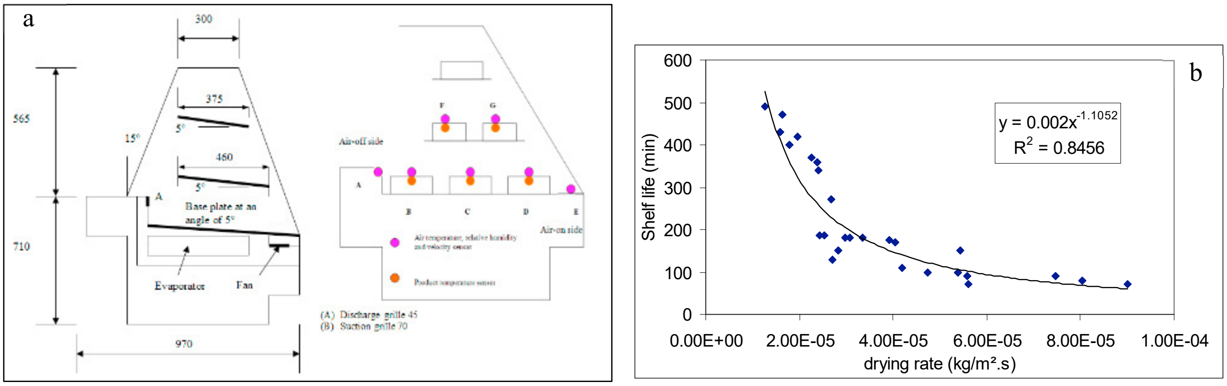

Fig. 3. (a) Cross section and dimensions (mm) of serve-over display cabinet (b) Variation of beef display shelf life with its drying rate

Eq. (1) represents the drying rate of the food product in kg/s and it is a function of the mass transfer coefficient, temperature, water activity, and the mass fraction of H_2O in the surrounding air. Thermal properties of beef was obtained from [11]. The mass transfer coefficient K_e equation for beef was obtained from [12] and the water activity for beef is 0.98. The display shelf life of beef inside the display cabinet can be predicted from the results of the CFD model, using the data of [13] (see Fig. 3b).

3.3 Modelling the Serve-Over Display Cabinet

The evaporator section including the fans was not considered in the CFD modelling. Uniform mass flow rate was assumed through the evaporator coil air-off section. Controlled environmental chamber was used to carry out the experimental work of testing the serve-over display cabinet. The dimensions of the test chamber are 7 m long, 3.5 m wide and 3 m high, large enough so that the walls of the test chamber will not restrict the airflow around and out of the cabinet in accordance with European Standard EN441.

Serve-over display cabinet: The serve-over display cabinet was designed to distribute refrigerated air to the lower two shelves only. Air from the evaporator below the base shelf is blown upwards through an angled upward air curtain outlet at the back of the serve-over cabinet. By its momentum, the air is carried beneath the top shelf where the air continues forward over the products heading towards the front glazing. The air is drawn into the suction grille at the bottom of the glazing and into the evaporator again. The structure of the server-over display cabinet is shown in Fig. 3a. The cabinet was loaded according to EN441 specification (BS EN441, 1995), the cabinet was loaded with water containers to provide thermal capacity. For the position of measured data, real meat samples (100 x 80 x 1 mm) were used. A computer-based data logging system is used to record the climatic conditions in the test chamber, product temperatures and air temperatures in the display cabinet at regular intervals. The measured data for the serve-over display cabinet included the surface product (meat) temperature at different positions inside the display cabinet and temperature, velocity and relative humidity for the following positions:

- Air leaving the evaporator (air-off side) (A)
- Air entering the evaporator (air-on side) (E) and
- Air at position just 20 mm above the centre of each product (meat) (B, C, D, F, G), shown in Figure 3a.

Since a 2D CFD model was used to model the cabinet, data was collected in the middle section of the display. At test conditions of 25°C and 40% RH, results for serve over display cabinet were collected to validate the 2D CFD model. Table 1 shows the inputs to the steady state 2D-CFD model.

Table 1. Inputs to 2D CFD Model

Evaporator coil air-off temperature (K)		275.5
Evaporator coil air-off moisture content (mass fraction of H_2O or water vapour) (kg/kg)		0.0033
Ambient test temperature (K)		298
Ambient test moisture content (mass fraction of H_2O or water vapour) (kg/kg)		0.0083
Emissivity of walls of test chamber and product		0.7
Product conductivity (W/m. K)		0.2279
Evaporator coil air-off velocity (m/s)		1.48
Turbulent model	Renormalisation group $k-\epsilon$ model	
Radiation model	Discrete ordinates (DO) model	

The display shelf life was obtained by following the procedure, drying rate values obtained from the CFD model and with help of Fig. 3b. Comparison data of the display shelf life were obtained and it can be concluded that the display shelf life was related to the drying rate, higher drying rate provide short display shelf life while lower drying rate results in longer display shelf life, as shown in Table 2.

Table 2 Comparisons of the experimental drying rate and display shelf life with the simulation results at 25 °C and 40 % RH

Position	Drying rate predicted by CFD ($kg/s.m^2$)	Experimental drying rate ($kg/s.m^2$)	Shelf life predicted by CFD (min)	Experimental shelf life (min)
D	4.82 e-5	4.60 e-5	118	125
C	4.52 e-5	4.23 e-5	126	135
G	5.34 e-5	5.05 e-5	105	110
B	6.35 e-5	6.10 e-5	87	90
F	5.78 e-5	5.60 e-5	96	100

4. Results and Discussion

4.1 Temperature Distribution inside the Serve-Over Display Cabinet

Temperature contour for the serve over display cabinet is shown in Figure 4a. It is clear that the top shelf product has the highest temperature (the test cabinet was designed to provide cooling for the bottom and middle shelves only). The lowest product temperatures were found to be at the bottom shelf, while the temperature of the product on the middle shelf recorded higher temperature compared to the product on the bottom shelf. It was also noticed that the product temperature distribution in the cabinet is non-uniform.

The ambient warm air will affect the cold air leaving the evaporator coil air-off section, while heat transfer through the front glass appears to affect the product temperature at the front part of the shelves. The products adjacent to the front glass are of slightly higher temperature compared to the products at the rear of the shelves.

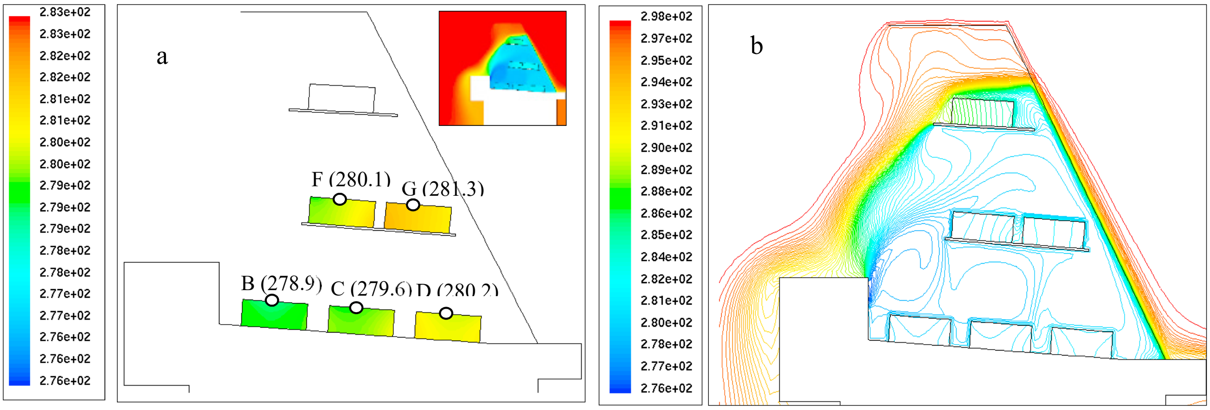

Fig. 4. (a) Temperature *(K)* contour for the serve over display cabinet (b) Temperature isolines *(K)* for the cabinet

The temperature isolines for the cabinet are presented in Figure 4b. It can be seen that the temperature isolines in the infiltration area, where the forced and natural convection, are mixed and very dense. This means that there is a large temperature gradient, which can induce significant large transfers of heat and mass between the cold rear upward air curtain and the warm surrounding air. Figure 4b, explains that the air curtain will act as a barrier to separate the environment of the display cabinet from its surroundings. The stream of the air curtain flow that covers the middle shelf will be subjected to the effect of the surrounding air (warm air); so higher product temperature is expected on the middle shelf compared to the product on the lower shelf (bottom). The flow of the air curtain will mix with the surrounding air, and flow towards the low-pressure area at the outlet (evaporator coil air-on section). Part of the surrounding air adjacent to cold air curtain will spill outside the cabinet, due to its higher density.

4.2 Effect of Evaporator air-off Temperature

The effect of the evaporator coil air-off temperature at constant evaporator coil air-off velocity of 1.48 m/s and relative humidity of 73 %, on the drying rate and the display shelf life of the considered product is presented in Figure 5a, for product location inside the display cabinet see figure 3a.

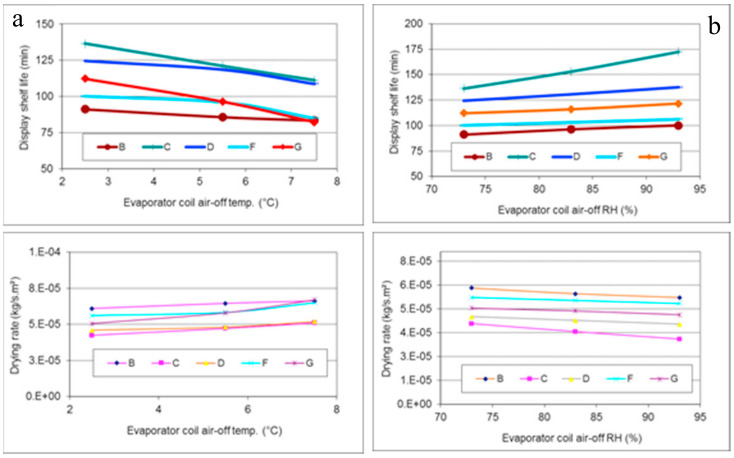

Fig. 5. (a) Effect of evaporator air-off temperature on the drying rate and the display shelf life (b) Effect of evaporator coil air-off relative humidity on the drying rate and the display shelf life

Results show that increasing the evaporator coil air-off temperature increases the drying rate of the product and results in a shorter display shelf life. Increasing the evaporator air-off temperature from 2.5 °C to 5.5 °C reduced the range of display shelf life from (95-135 min) to (88-120 min).

Increasing the evaporator air-off temperature from 5.5 °C to 7.5 °C reduced the range of display shelf life from (88-120 min) to (80- 105 min). The simulation results show that for the considered range of evaporator coil air-off temperature, increasing the evaporator coil air-off temperature by 1 °C in the range of (2.5-5.5 °C) will result in an increment by around 1.5 °C in the local boundary conditions and reduce the display shelf life by around 5 min (average variation). While in the range of (5.5-7.5 °C), increasing the evaporator coil air-off temperature by 1 °C will result an increment by around 2.5 °C in the local boundary conditions and reduce the display shelf life by around 7 min (average variation).

4.3 Evaporator Coil Air-off Relative Humidity

Figure 5b shows the effect of the evaporator air-off relative humidity on the drying rate and the display shelf life (at constant evaporator coil air-off temperature of 2.5 °C and velocity of 1.48 m/s) of the considered product inside the display cabinet. It can be seen that increasing the evaporator coil air-off relative humidity reduces the drying rate inside the display cabinet and results in longer display shelf life. Increasing the evaporator coil air-off relative humidity from 73 % to 83 % increased the range of display shelf life inside the display cabinet from (92-135 min) to (96-155 min). In the meantime increasing the evaporator coil air-off relative humidity from 83 % to 93 % increased the range of display shelf life inside the display cabinet from (96-155 min) to (100-170 min). The results gave nearly constant range of display shelf life for the considered evaporator coil air-off relative humidity, with minor discrepancy for the product at position C. This could be attributed to the boundary conditions at position C which is less influenced by the effect of surrounding air and heat transfer through the front glass. The simulation results show that for the considered range of evaporator coil air-off relative humidity, increasing the evaporator coil air-off relative humidity from 73 % to 83 % will result an increment by around 10 % in the local relative humidity and the display shelf life increased by 10 min, while increasing the evaporator coil air-off relative humidity from 83 % to 93 % increased the local relative humidity by 8% and the display shelf life increased by 8 min

4.4 Evaporator Coil Air-off Velocity

At constant evaporator coil air–off temperature of 2.5 °C and relative humidity of 73 %, the drying rate of the product inside the display cabinet has been affected by the variation of the evaporator coil air-off velocity and affected the product display shelf life as shown in Figure 6.

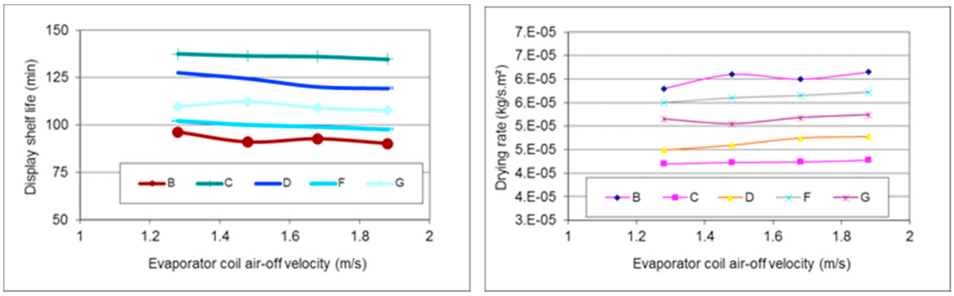

Fig. 6. Effect of evaporator coil air-off velocity on the drying rate and the display shelf life

The results show that increasing the evaporator coil air-off velocity (for the considered range) increases the drying rate slightly and reduces the display shelf life. For the considered range of evaporator coil air-off velocity, increasing the evaporator coil air-off velocity from 1.48 m/s to 1.68 m/s increased the range of local velocities from (0.18-0.36 m/s) to (0.2-0.38 m/s) and the range of display shelf life also decreased from (88-138 min) to (87-132 min). The effect of the evaporator coil air-off velocity on the local velocity boundary conditions was accompanied by the effect of the local temperatures, increasing the evaporator coil air-off velocity results in an increment in the local velocities and reductions in the local temperatures. To provide a defined effect for the evaporator coil air-off velocity on the display shelf life, the local temperatures need to be kept constant and varying the local air velocity.

5. Conclusions

Surface drying increases the weight loss and leads to colour changes that are undesirable and results in shorter display shelf life. Weight loss was affected by air relative humidity, velocity and temperature. Weight loss occurred at constant rate for a finite period, after which the rate of weight loss decreases. The period of constant weight loss rate is related to the moisture content of the food. A direct relationship was found between the drying rate and display shelf life. Reducing the drying rate provides longer display shelf life.

The CFD model was able reasonably to predict the drying rate of unwrapped food product inside a refrigerated display cabinet under different boundary conditions of air temperature, velocity and relative humidity. The relative humidity had the most prevalent effect on the drying rate. Temperature changes had smaller effect on drying rate compared to the changes in either relative humidity or air velocity. Air velocity directly affects the drying rate and this is related to the relative humidity. The magnitude of the effect increases as relative humidity decreases. The display shelf life was mostly affected by air relative humidity and velocity.

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