Reflective Glass Effect on Energy Consumption and Food Quality in Delicatessen Cabinets

*[a]Dr **Alex Paurine**, PhD, CEng, MIMechE
[b]Prof **Graeme Maidment**, PhD, CEng, MIMechE
[a]Dr **Issa Chaer** PhD, CEng, FInstR

[a]The School of Built Environment and Architecture, London South Bank University,
[b]The School of Engineering, London South Bank University,
103 Borough Road, London, SE 0AA

* Corresponding author: Tel.: +44 207 815 7604
E-mail address: paurina2@lsbu.ac.uk

Abstract

Retail supermarkets are responsible for around 3% of total electrical energy consumed in the United Kingdom and the most energy is used in refrigeration systems, particularly for operation of open displays such as delicatessen cabinets which consume approximately 50%. Although the cabinets are energy intensive, they are commonly used in supermarkets for displaying unwrapped chilled food stuffs. These cabinets are associated with the weight loss and quality deterioration of food stuffs being reported frequently as the cause for their high operational costs. This paper presents an investigation on the cause and rectification of weight loss in delicatessen cabinets. Specifically, the paper describes the effective use of low emissivity glass in reducing the impact of the thermal infrared radiation on the food temperatures and energy consumption.

Keywords: Refrigeration; Emissivity, Delicatessen Cabinet; Weight loss; Energy Consumption.

Nomenclature

A_s radiating surface areas (m^2)	$Q_{r(s-fs)}$ radiant heat transfer from radiating surfaces to food surface (W)
A_{fs} effective food surface area (m^2)	T_a temperature of the ambient ain in the cabinet (°C)
$F_{H(s-fs)}$ Hottel factor from radiating surfaces to food surface (-)	T_{fs} temperature of the food surface in the cabinet (°C)
F_{s-fs} Configuration factor from radiating surfaces to food surface (-)	T_s temperature of the radiating surfaces (°C)
h_{fg} enthalpy of vaporization (kJ/kg)	α_c mass transfer coefficient (kg/m^{2}Pas)
m_f mass of the food sample (kg)	ε_{fs} emissivity of food surface (-)
$\dot{m}_m$ rate of moisture transfer from the food (kg/s)	ε_s emissivity of the radiant surfaces (-)
P_a partial vapour pressure of the ambient air (Pa)	λ thermal conductivity of the food product (W/mK)
P_f partial vapour pressure on the food samples (Pa)	σ Stefan-Boltzmann constant (W/m^{2}K^4)
Q_f rate of radiant heat into the food product (W)	

1. Introduction

The increasing demand for use of delicatessen cabinets in supermarkets represents an increase in energy consumed in the refrigeration of chilled food products. This paper addresses the operation of delicatessens and their role in food preservation that includes prevention of weight loss. The major contributing factors for weight loss which include thermal infrared radiation are investigated and evaluated. An experimental investigation that demonstrates the effect of radiant exchanges on food quality and temperatures within the cabinet is discussed and summarised. Practical solutions for minimising the radiant effect using low emissivity TEC 15 glass technology are detailed in this paper. The use of this technology is further justified from an economic perspective which includes low carbon food print and hence reduced running costs of delicatessen cabinets.

2. The nature and role of delicatessen cabinet

Delicatessen cabinets have been used for many years as a way of retailing and displaying unwrapped perishable food products in grocers' shops[7]. An increase in consumer demand for fresh food combined with a growth in convenience food stuffs has resulted in a greater emphasis on the sale of products from delicatessens by some supermarket stores. These are used to display mainly chilled fresh fish and meats that include cooked, fresh, continentals and pates.

The roles of these cabinets in the supermarket include; preventing food products becoming unfit (i.e. deteriorating and hence leading to change in the appearance, odour, taste or weight of the food products) for human consumption by preserving them as near as possible to their fresh initial state and therefore maintaining commercial value and thereby evading an economic loss. It should be noted that, most of food products in delicatessen cabinets are sold on weight basis, and therefore a small percentage in weight loss can result in a significant loss of profit. In a typical delicatessen cabinet, this can be as high as 5% of the total mass retailed[11].

3. Effect of environmental variables on deterioration in delicatessen cabinets

Unwrapped food products that are exposed to air tend to lose weight by means of water evaporation (loss of moisture content) from the surface. This process was described by Radford et al[11], who carried out an extensive experimental study of weight loss from slabs of chilled meat in a wind tunnel under closely controlled conditions of air temperature, velocity and relative humidity (RH). Figure 1 illustrates the evaporative drying process of a typical unwrapped food product.

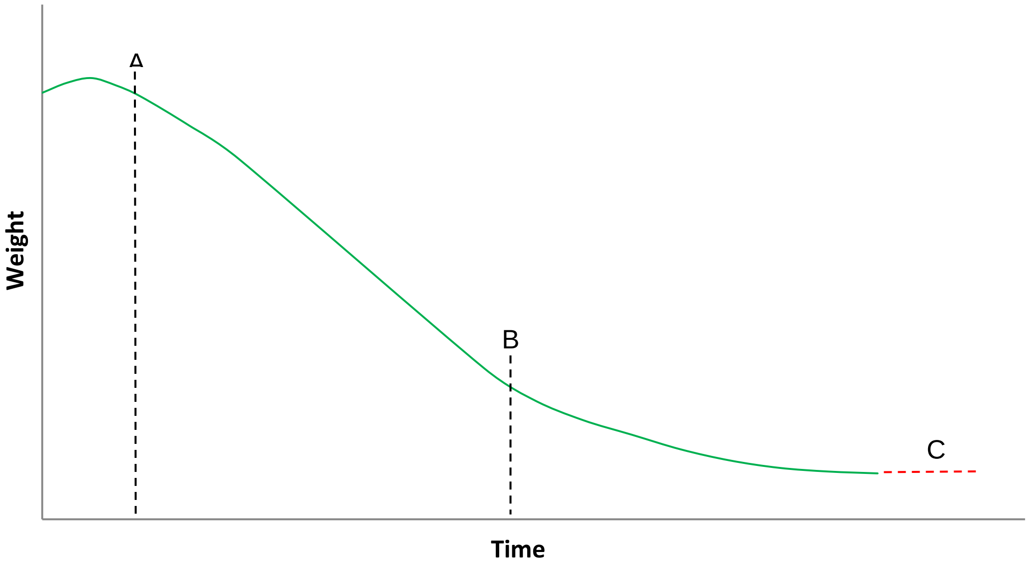

Figure 1; Typical drying curve for unwrapped food product

After a short settling down period at point A, the food surface comes into equilibrium with the refrigerated air stream and the constant rate drying period begins. This continues until point B is reached, when the rate of moisture transfer from the product to its surface becomes less than the loss from the surface, and the surface begins to dry out. The rate at which unwrapped food product loses moisture during the constant rate drying period was simulated by Dalton's law:

$$\dot{m}_m = \lambda A_{fs}(P_f - P_a) \qquad \text{Eqn. 1}$$

At point B, the rate of drying reduces and the falling rate period is entered. In the falling rate period B-C, the mass transfer becomes controlled by the diffusion from the core to the surface, and this is best described by Fick's law[5]. Point C shown on the graph represents the critical or equilibrium moisture content.

4. The influence of radiant exchanges on food temperatures in delicatessen cabinets

The traditional optimum conditions for food are analogous with those used in human thermal comfort applications [2], although the traditional optimum food conditions make no reference to the radiant environment. Albeit the thermal radiation had previously not been considered important in the operating costs of delicatessens, its influence in chilled food applications has been cited by Gill[6], Hawkins et al[8] and Nesvadba[10]. Using the simulation work carried out by Maidment [9] and the thermo-economics modelling tool by Tozer and Missenden[12], it was shown that the radiant interchange has a very significant effect on food product temperatures and hence the operating costs of delicatessen cabinets.

The radiant sources into the cabinet were therefore identified and their significance analysed. The display glass was investigated and shown to be virtually opaque to the infrared contribution from the store environment, whereas the radiation from the store lighting shown to have little direct effect. Significant radiant contributions were identified from three sources. These included radiation from the warm surface of the light emitting diodes (LEDs) used in the internal display lighting, radiation from the warm inside surfaces of the display glass and radiation through the rear opening of cabinet from the warm surfaces outside the cabinet. Figure 2 illustrates the heat transfer to and from the food samples in the cabinet.

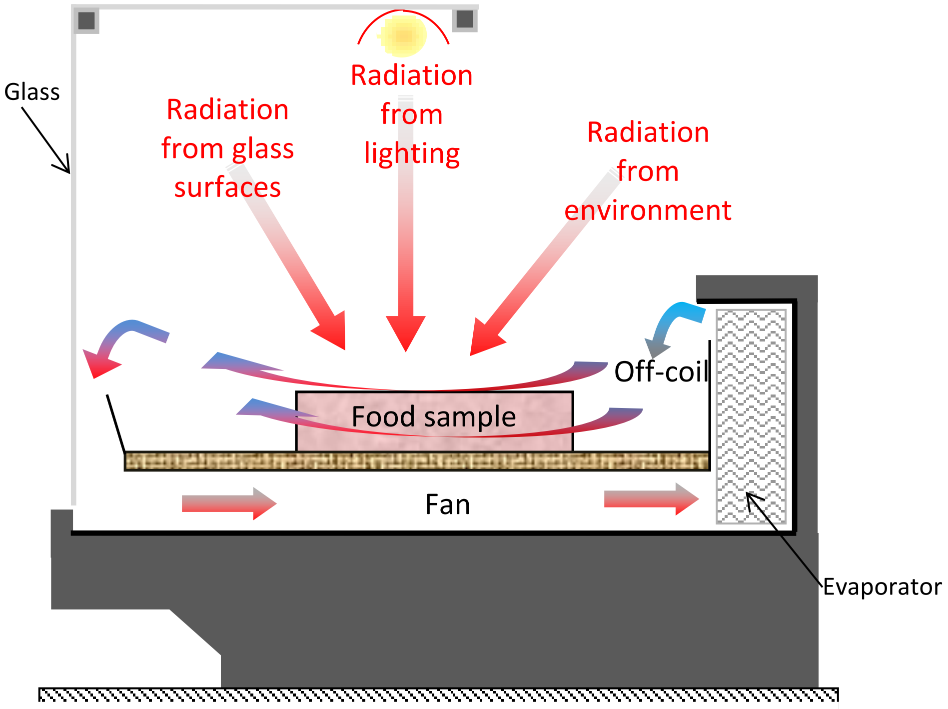

Figure 2 - Diagram showing heat exchanges in a delicatessen cabinet

The parameters listed in Table 1 were considered in a base case mathematical Engineering Equation Solver (EES) model for a traditional delicatessen cabinet.

Item No.	Model input data	
i)	Average food surface temperature	2 to 4°C
ii)	Food surface emissivity values	0.9
iii)	Glass surface emissivity values	0.9
iv)	Internal air circulations	Forced convection
v)	Off-Coil air temperature onto the food	-1 to 1°C
vi)	External Environment	28°C, 45%RH

Table 1 - Input data for base case scenario

Simulation of operating conditions in a typical delicatessen cabinet was carried out using a simple EES model which incorporated equation 2. This describes the cooling of the food and includes the evaporation of water and convective heat transfer from the standard M (measurement) package surface. This cooling effect counteracts the radiation heat gain to the food.

$$Q_f = m_f h_{fg} + \alpha_c A_{fs} (T_{fs} - T_a) \qquad \text{Eqn. 2}$$

Using the model, it was established that the average simulated (food) M-packages surface temperature was consistently 3K higher than the average refrigerated air temperature.

Since the temperature and relative humidity of air were known, it was possible to specify the air condition on a psychrometric chart in Figure 3 below. However, the food condition was calculated using the average food temperature and by assuming that during the display life, the RH on the food surface tends to approach the saturation line. This assumption was consistent with the results by Daudin and Swain[4] and was further confirmed with experimental measurement from the delicatessen cabinet.

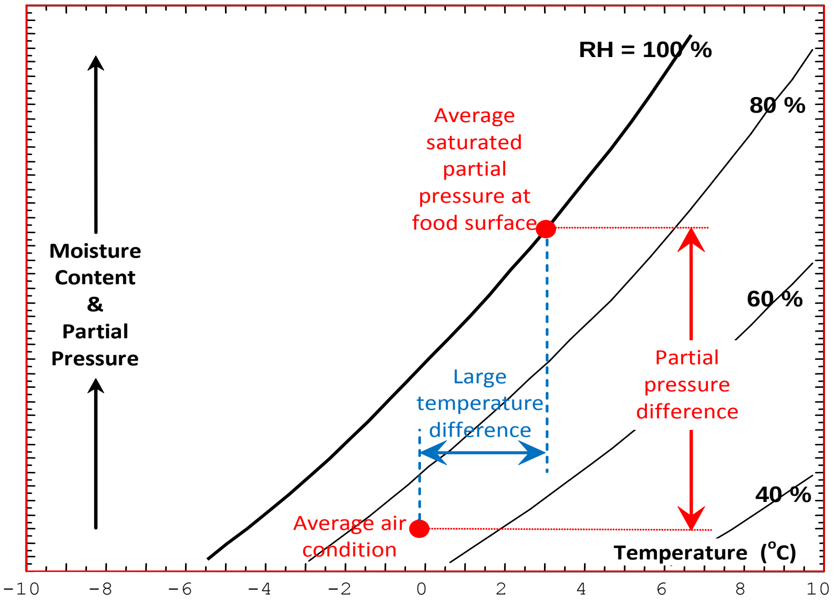

Figure 3 - Psychrometric chart showing high radiation case

In order to account for the influence of thermal radiation on food products temperatures and to validate the modelling results indicated in Figure 3, a low emissivity aluminium film was introduced. The film was used to isolate radiation from all the primary sources (i.e. room surfaces, cabinet glass and LEDs) as indicated in Figure 4 below.

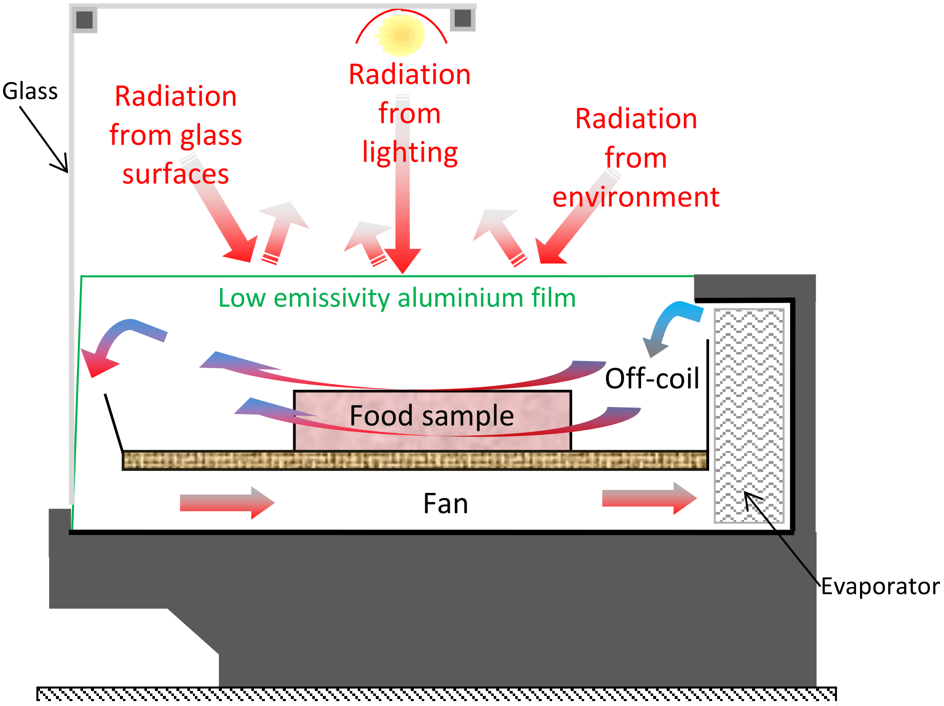

Figure 4 - Diagram showing heat exchanges in a delicatessen cabinet with low emissivity aluminium film

Following the isolation with the aluminium film, the food products in Figure 4 were observed to be almost at equilibrium with the base and refrigerated air and thereby indicating that the higher initial food product temperature was as a result of the thermal radiation.

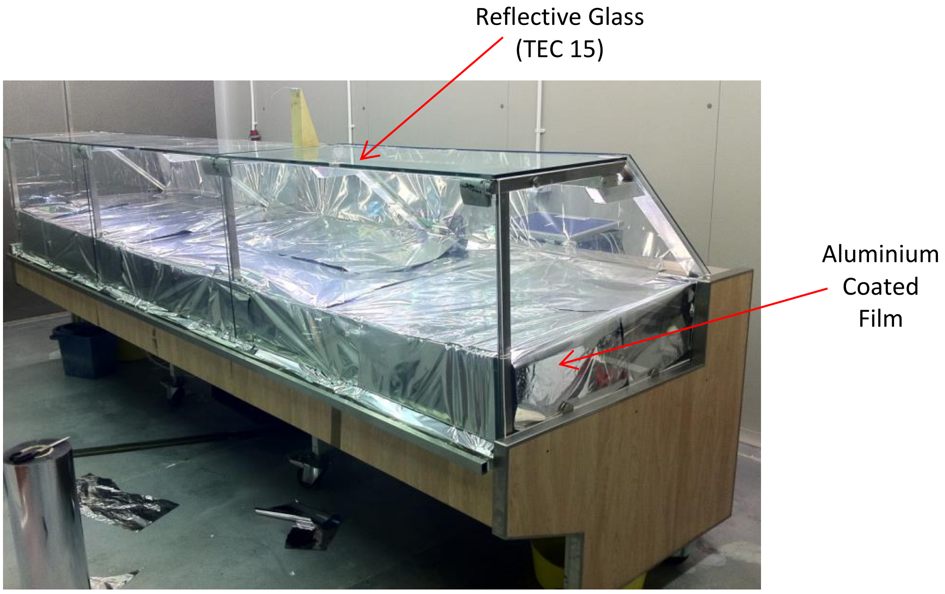

Figure 5 - Photograph showing a delicatessen cabinet with low emissivity glass and aluminium film

The above shown delicatessen cabinet was tested in an environmental chamber in accordance with British standards[1]. The cabinet was packed with a range of food products which included six M-Packages and with thermocouples for temperature recordings.

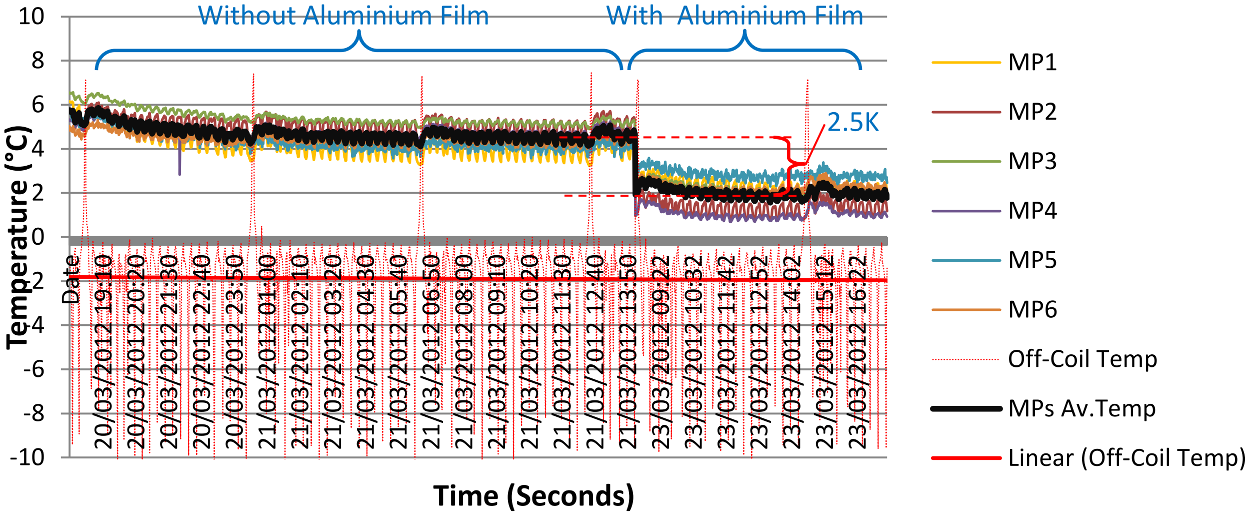

Figure 6 - Diagram showing temperatures of M-Packages and refrigerated air

It should be noted that; of the six M-Packages (MPs) considered in the analysis, MP2, MP3 and MP4 were wrapped in aluminium foils to stop any unaccounted for radiant heat and temperatures of the packages were allowed to drop until they converged and hence signifying the absence of radiant heat. Note that; the small temperature difference noticed between the food products and refrigerated air is due to the heat conduction through the cabinet. It is illustrated in Figure 6 that exclusion of radiant heat into the M-Packages led to decrease in temperature by 2.5K which is consistent with model results represented in Figure 3. Therefore, the large temperature difference between the food and refrigerated air as illustrated in Figure 3 is mainly due to the large radiant effect. Figure 3 also highlights the large difference in moisture content between the food and the air, which occurs partly as a result of the high temperature difference. Since moisture content and vapour partial pressure are proportional[3,13], this produces a large partial pressure difference in the Dalton's law equation and therefore high evaporation loss.

5. Significance of radiant heat sources

The relative contribution of each radiant source was shown to be dependent on the position of the food within the cabinet. This is because the radiant exchange between each source and the food is dependent on the Stefan-Boltzmann law indicated in equation 3

$$\mathrm{Q_{r(s-fs)}} = \mathrm{F_{H(s-fs)}} \sigma \mathrm{A_{fs}} (\mathrm{T_s^4} - \mathrm{T_{fs}^4}) \qquad \text{Eqn. 3}$$

Where, the term $F_{H(s\text{-}fs)}$ is referred to as Hottel or Curly factor that includes a view or shape factor term $F_{s\text{-}sf}$ which is defined by equation 4.

$$\mathrm{F_{H(s-fs)}} = \left(\frac{\mathrm{A_s}}{\mathrm{A_{fs}}} \left(\frac{1}{\varepsilon_{\mathrm{fs}}} - 1 \right) + \frac{1}{\varepsilon_{\mathrm{s}}} + \frac{1}{\mathrm{F_{s-fs}}} - 1 \right)^{-1} \qquad \text{Eqn. 4}$$

Since the shape factor is dependent on position, the contribution of each source will vary. By analysing the respective shape factors and validating the measurement at different positions along the cross section of the cabinet, the relative contribution of each radiant source was established. The approximate breakdown of radiant heat generated by the cabinet LEDs, room surfaces through rear access openings and display glass were established using equation 3 as 15, 42 and 43% respectively and consequently necessitating the need for improved display glass.

6. Minimizing the radiation exchange in a delicatessen cabinet

The identified radiant exchanges into the cabinet were further investigated to minimise their contribution. Practical means for minimising the radiant effects were investigated using new technology including a TEC 15 glass with low emissivity value ($\varepsilon = 0.2$) and low temperature LEDs systems. The EES model was used for simulation of the reflective surfaces and in this case; two scenarios were considered for analysis, i.e.

reflective surface being on the outside and on the inside. When the reflective surface was modelled facing inwards, the average food surface temperature dropped significantly in comparison with that of the reflective surface facing outwards. Figure 7 illustrates the impact of low emissivity glazing on the food surface temperature in a traditional delicatessen cabinet.

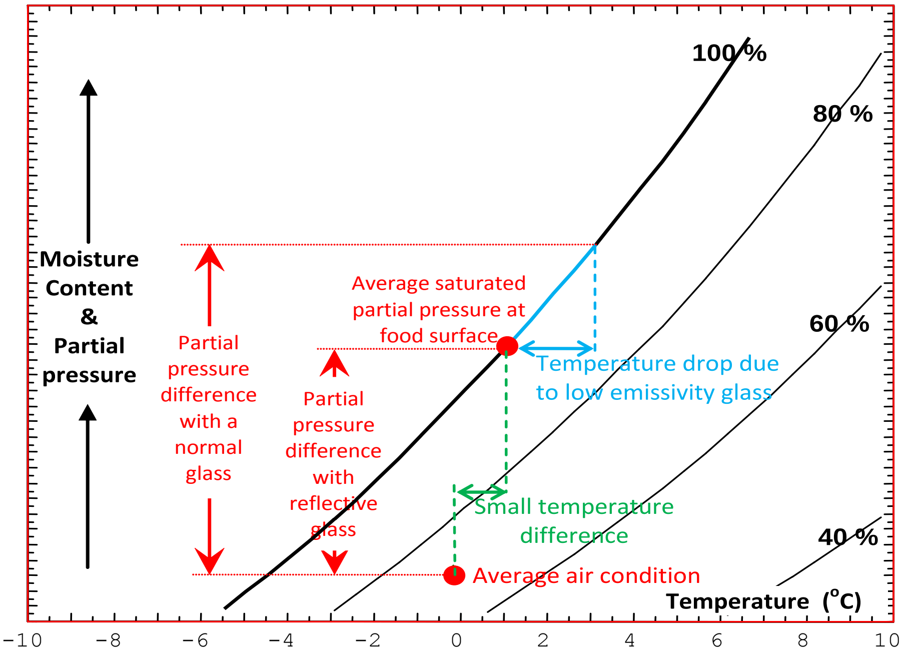

Figure 7 - Psychrometric chart showing low radiation case

Due to limited radiant exchanges between the inside surface of the reflective glass and the unwrapped food products, the model predicted lower radiant heat input into the food. This envisaged a lower temperature difference between the food and the air and hence a lower saturation temperature and pressure at the food surface.

The model results were confirmed by the experimental results obtained by testing a standard delicatessen display cabinet with TEC 15 glass inside an environmental chamber. The retail environment was replicated during the experiment and a range of temperatures were recorded. Figure 8 shows the experimentally recorded temperatures of the M-Packages and off coil temperatures.

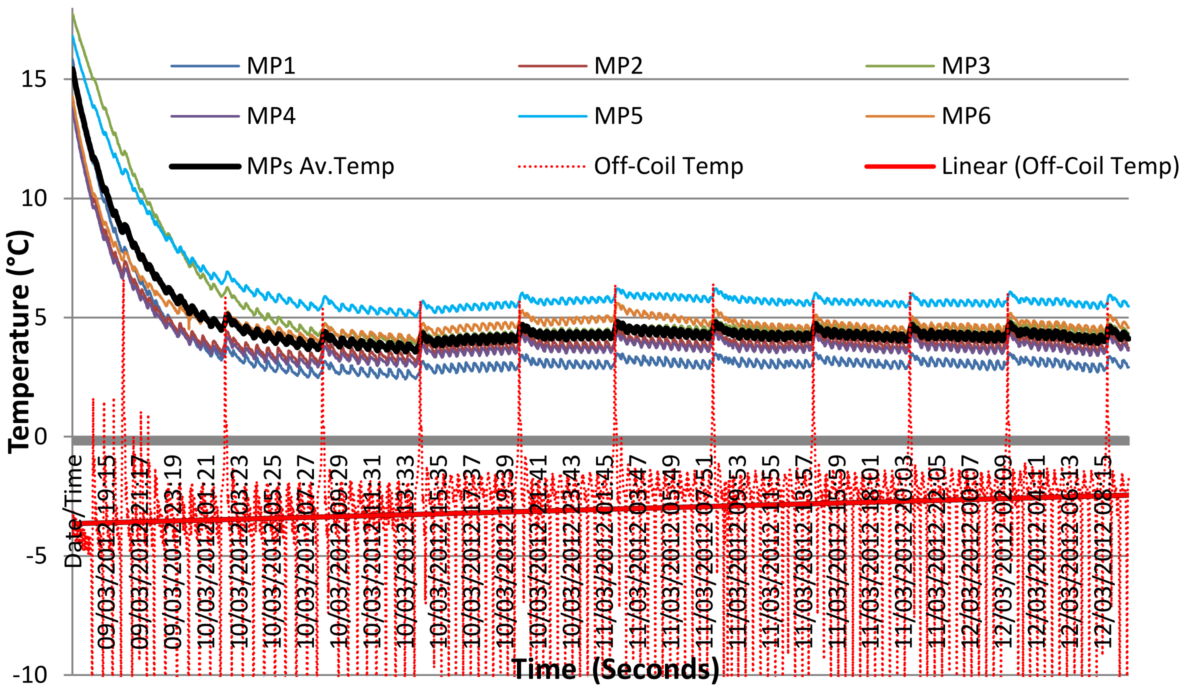

Figure 8 - Diagram showing temperatures of M-Packages and off-coil air

Table 2 summarises all the recorded temperatures including those of the inside and outside glass surfaces, off-coil air into the cabinet and M-packages.

TEC 15 Glass (ε = 0.2)	Configuration		Off-coil Average Air Temperature (°C)	Average Outside Glass Temperature (°C)	Average Inside Glass Temperature (°C)	Food Product Average Temperatures (°C)
Facing Outwards	With Rear Opening Glass	NO	-1.5	26.6	26.0	11
		YES	-2.9	27.7	27.2	6.5
Facing Inwards		NO	-1.7	29.6	29.1	9
		YES	-3.0	27.7	27.2	4.4

Table 2 - A summary of experimental results

Although, it was established experimentally that the average glass temperature gradients between the reflective glass surfaces (i.e. inside and outside) for all considered scenarios were marginal, it was conclusive that the low emissivity TEC15 glass reduced the temperatures of the M-packages. The effect on M-packages temperatures was noticeable when the reflective surfaces of the glass were facing inwards. These results are supported by equations 3 and 4 where the Hottel factor does decrease considerably by decreasing the glass surface emissivity value and therefore decreasing the overall radiant heat input into the M-Packages. Also, the experimental results in Table 2 are consisted with the model results in Figure 8, where the average food surface temperature was predicted to drop by 2K as a result of using reflective glass correctly.

7. Impact of low emissivity glass on the weight loss and energy consumption

In this part of investigation, the impact of low emissivity glass on weight loss and energy consumption was carried out. Based on the EES model results in Figures 3 and 7, it was predicted that the partial pressure in the air inside the cabinet was virtually constant irrespective of glass type used. Therefore, a lower saturation pressure indicated in Figure 7 resulted to a lower partial pressure difference and consequently lower weight loss. In order to validate the model results, an experiment for measuring the weight loss was carried out where realistic food substitutes (sliced sandwich ham samples) were used Instead of M-Packages for testing. A control experiment was setup using a standard plane glass on a traditional delicatessen cabinet and the weight loss of the food samples were recorded over time. The experiment was replicated by replacing the glass with low emissivity TEC 15 glass where also the weight loss measurements were recorded over time and the results are presented in Figure 9 below.

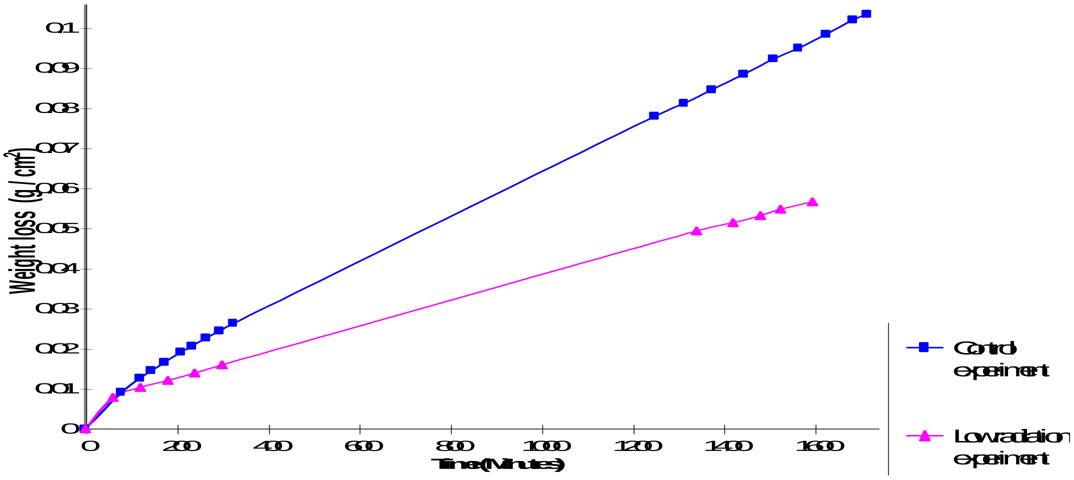

Figure 9 - Weight loss per unit area from samples in the control & low radiation experiments

It was observed in Figure 9 that, the food products in low radiation (TEC 15 glass cabinet) case produced a considerably lower rate of weight loss in comparison with (control case) traditional delicatessen cabinet with plane glass. The results indicated that the influence of thermal radiant into the delicatessen cabinet can be reduced significantly (by approximately 50%) when low emissivity glass are optimised and implemented correctly. As the capital cost of implementing the changes to the radiant environment is minimal, reducing the weight loss by 50% will considerably improve the profitability of delicatessen cabinets.

With reference to Table 2, it can be seen that fitting the glass reduces food temperatures by a maximum of 6.6K. If instead the evaporator temperature for the refrigeration system was allowed to rise by 1K, the COP of the system would increase by 3% [5] and this would reduce energy consumption by the same percentage. In addition, with the use of TEC15 glass, there will be a reduced radiant heat into the cabinet that leads to higher evaporating temperature and hence requiring lower cooling loads and higher suction pressures, both of which result to lower energy costs

8. Conclusions

The experimental results showed that the unfavourable radiant heat transfers to the food was mainly from the inside surface of the display glass and through the open serving back. The solutions for solving the problem were investigated and this included using coated/reflective glass in a typical delicatessen cabinet to reduce internal radiative heat exchanges. Benefits were found to be moderate and fairly similar from either glazing the rear access window with plane glass or using reflective glass. The most significant benefits were achieved with reflective glazing all round, including the rear access. However, any measure that involves a glazing rear access may be inconvenient for typical day-to-day consumer serving operations.

Furthermore, it was conclusive that the lower heat gain to the food as a result of using low emissivity glass would lead to lower food surface temperature for the same off-coil air temperature and hence the potential energy saving of atleast 13.5%. Also, there would be improved food safety such as lower bacterial growth rates and consequently a prolonged better quality of the food products. Other benefits of using reflective glass would include; the potential to use smaller refrigeration capital plants and improved profitability (cost savings) by nearly 2.5% of turnover.

References

[1-]British Standard (BS EN ISO 23953-2), Refrigerated display cabinets - Classification, requirements and test conditions, British Standards Institution (BSI), 2015, ISBN 0 580 46827 5

[2-]CIBSE Guide, Design Data Published by Chartered Institution of Building Services Engineers, London, 1986, Vol. A, pp. 1 - 4.

[3-]Coulson, J. M., Fluid flow, heat and mass transfer, Chemical Engineering, Fifth Edition, Vol. 1, 1995.

[4-]Daudin, J.D. & Swain, M.V.L., Heat and Mass Transfer in Chilling and Storage of Meat, Int. J. Food Engineering, 1990, pp. 95 -115.

[5-]Davies, G.F., Man, C.M.D., Andrews, S.D., Paurine, A., Hutchins, M.G., Maidment, G.G., Potential life cycle carbon savings with low emissivity packaging for refrigerated food on display, Int. J. food Engineering, 2012, Vol. 109, Issue 2, pp. 202 – 208.

[6-]Gill, J., An investigation into the chemical and physical changes taking place in chilled foods during storage and distribution. Part A – Greenhouse Effect, Technical Memorandum No. 465, Campden Food Preservation Research Association, 1987.

[7-]Griffiths, E., Refrigeration Principles and Practice, Published by George Newnes Ltd, London, pp. 218-227, 1951.

[8-]Hawkins, A.E., Pearson, C.A. & Raynor, D., Advantages of low emissivity materials to products in commercial open display cabinets, Proc. Inst. Refrig. 69, Sessions 1972-1973, pp. 54-64.

[9-]Maidment, G.G., Optimisation of Chilled Unwrapped Foods on Display, PhD Thesis, South Bank University, 1998.

[10-]Nesvadba, Radiation heat transfer to products in refrigerated displays, I.I.F. – I.I.R. Commissions C2, D3 – Aberdeen, 1984-5.

[11-]Radford, R.D., Herbert, L.S. & Lovett, D.A., Chilling Of Meat - A Mathematical Model For Heat & Mass Transfer, Proceedings of Meat workers Conference, 1976.

[12-]Tozer, R.M., & Missenden, J.F., Thermo-Economics Applied to Building Services, CIBSE National Conference, Harrogate, 1996.

[13-]Gulati, T., Datta, A.K., Doona, C.J., Ruan, R.R., Feeherry, F.E., Modeling *moisture* migration in a multi-domain *food* system: Application to storage of a sandwich system, Food Research International, Volume 76, Part 3, October 2015, Pages 427-438