TEMPERATURE AND ENERGY PERFORMANCE OF OPEN REFRIGERATED DISPLAY CABINETS USING HEAT PIPES SHELVES

Jouhara H.[*, 1], Nannou T.K.[1], Balemboy C.[1], Tassou S.A.[1], Lester S.P.[2]
*Author for correspondence
[1] Institute of Energy Future, RCUK Centre for Sustainable Energy Use in Food Chains (CSEF),
College of Engineering, Design and Physical Sciences,
Brunel University London
UB8 3PH
United Kingdom
E-mail: hussam.jouhara@brunel.ac.uk
[2] Flint Engineering Limited, The Paddocks, Five Ashes, Mayfield TN20 6JL, UK

ABSTRACT

In this paper an innovative design of open display cabinet's shelves, based on flat heat pipe technology is presented. Their influence on the energy consumption of the cabinet and their effect on enhancing the preservation conditions of food products are analysed, as well. The experimental work was carried out using two identical commercial open display cabinets; one cabinet equipped with conventional/commercial shelves while the other one equipped with the new actively-cooled flat heat pipe shelves. Both cabinets were placed inside an ISO-certified environmentally controlled test chamber and experiments were carried out under stable environmental conditions of 20°C temperature and 50% humidity (ISO Class 0). Food block simulators and real food products were used for the tests. The temperature distribution inside the real food products and the power consumption of the cabinets were measured for the cabinets' set point of 2.0°C. The experimental outcomes were that the use of the heat pipe shelves can homogenise the temperature profile of the products, reduce the air temperature variations inside the cabinet's void and improve the heat transfer between the cabinet, the shelves and the products. Moreover, the heat pipe shelves facilitated the reduction of the electrical energy consumption of the cabinet by 12% approximately, which paves the way to a very reasonable commercial case for the new shelf design. Finally, in order to investigate the possibility of these selves extending the self-life of foodstuffs, a primary analysis examining the acidity levels (pH) of the products was conducted. The experiments showed that almost all products placed on the heat pipe shelves, after 21 days of experiments, had almost the same pH values, even 20 days beyond their expiration date.

INTRODUCTION

Retail food outlets are among the largest consumers of electric energy in the UK. Their energy consumption is estimated around 2,000 kWh/m^2/year, depending on the sales area of the store, the business practices, the store configuration, the shopping activity and the equipment used in-store for preserving and displaying food products [1]. It is essential to note that almost half percent of that energy is consumed by refrigeration equipment only, while the rest is consumed by other supporting systems (air-condition, etc.).

The most common type of refrigerators used in supermarkets and retail stores worldwide is vertical open type display cabinets. This type of cabinet is equipped with a recirculating air curtain that acts as an aero-thermodynamic barrier between the inside domain of the cabinet and the external environment, allowing at the same time the display of the food products without imposing any physical restrictions between them and the consumers. However, the heat conduction between the food products and the shelves, in the conventional design of the cabinets is relatively poor, causing the inefficient cooling of food products in sites where the products are in direct contact with the shelf. In addition, they often show large temperature variations and significant temperature rises during defrost cycles.

The legislation of UK Government, in compliance with ISO 23953:2005 states that all foodstuffs shall be maintained at a temperature below 5°C [2]. However, existing cabinet designs are not capable of maintaining minimum temperatures without causing localised freezing somewhere in the cabinet [3]. Studies of Consumer's Association have showed that 70% of foodstuffs in retail display cabinets are stored at temperatures above 8°C, while 60% of the products are maintained at a temperature of 10°C or more [4]. Therefore, the improvement of refrigeration systems is crucial.

The way that refrigeration works is by preventing or retarding the deterioration, spoilage and growth of pathogens in the food. However, the ultimate goal of refrigeration systems is not only to secure the edibility of foodstuff, but to preserve the food products at the peak of their quality, regarding their appearance, odour, taste and vitamin content, as any detectable changes of any of these factors reduces the commercial value of the product and entails economic loss.

OPEN DISPLAY CABINETS PERFORMANCE AND FOOD SPOILAGE

Over the years a lot of research has been conducted investigating the performance of retail food cabinets regarding their ability to maintain the quality of products. *Gill et al.* studied the effects of temperature and aging of packs of beef displayed in multi-shelf retail cabinets [5]. They showed that in general older packages of beef were cooler than newer, packages at the back of shelves were cooler than packs placed at the fronts and packages on intermediate shelves were cooler that the packs of top or bottom shelves. *Evans et al.* evaluated the performance of open front display cabinets and they noticed that the majority (97%) of maximum temperature packs are located at the front and the largest number of them (60%) are placed at the front of the base of the cabinet [6]. The conventional design of refrigeration cabinets provides poor heat conduction between food products and shelves, resulting insufficient and not uniform cooling of the core temperatures of the food. According to research food temperatures in the same cabinet can vary between up to 10°C [7,8].

Maidment et al. succeed to address the design malfunctions of display cabinets by a new approach. They showed that better heat transfer rates between the food product and the shelf can be achieved, by positioning the product in direct contact with a cold base [9]. In this way the efficiency of the cabinet is improved, its energy consumption is reduced and the food quality and safety are enhanced. Some years later *Maidment et al.* simulated the application of a superconductive heat pipe shelf in a retail cabinet [10]. Later on, *Wang et al.* continued the work of *Maidment et al.*, by implementing Phase Changing Materials (PCMs) into the structure of the heat pipe shelf for better heat transfer [10]. *Lu et al.* conducted a comparison between the conventional shelves used on the display cabinets, a new structure of heat pipes shelves and the heat pipes shelves combined with appropriate PCMs [11]. They found that only the incorporation of the heat pipe self in the refrigerator was able to reduce the food core temperatures by 3 to 5.5°C compared to the conventional shelf's design, while the shelf with both heat pipes and PCMs managed to lower the food temperature fluctuations during the defrost cycles by 1.5°C and improve the overall uniformity of the food temperature distributions; however the heat pipe shelves showed no contribution in reducing the cabinet's energy consumption.

THE INNOVATIVE HEAT PIPE SHELF

Heat pipe based heat exchangers find application in many industries as heat recovery and energy savings systems, while their operation has been investigated by several researchers [12–18]. Heat pipes are considered to be thermal super conductors due to the high heat rates they transfer across small temperature gradients. On their simplest form heat pipes are called '*thermosyphons*' and their operation relies on gravity, whereas the heat is transferred only from the lower to the upper end of the pipe. A heat pipe which allows the bi-directional transfer of heat is called '*wickless*'. The main structure of heat pipes is an evacuated tube partially filled with a working fluid that exists in both liquid and vapour phase. When a high temperature is applied at the evaporator section of the heat pipe, the working fluid existing in the liquid phase evaporates and flows with high velocity towards the cooler end of the pipe – the condenser. As soon as the vapour reaches the condenser section, condenses and gives up its heat. Then the liquid working fluid returns to the evaporator part of the pipe, by the influence of gravity [13]. A series of straight heat pipes joined in one structure can be considered as a heat recovery device. Its advantages are high thermal conductivity, passive and reliable operation, uniform temperature distribution, affordable cost and no need for external pumping system as in the conventional exchangers.

The prototype actively cooled shelves used in the experiments were constructed based on two patents of *Dr Hussam Jouhara* [19,20]. The surface in which food products are place is composed by aluminium heat pipes, using ammonia (NH_3) as working fluid. The operating principle of heat pipes and the design of the shelf are shown in figure 1.

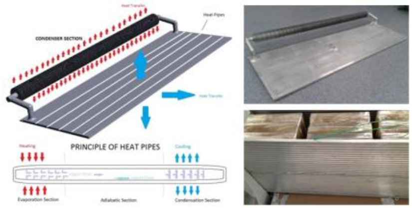

Figure 1 Actively-cooled shelf and operation principle of heat pipes

The innovative design of the heat pipe shelves introduces three more heat transfer mechanisms in the existing refrigeration systems; one due to the conduction from the heat pipe's upper surface to the food placed on it, one due to the natural convection between the food and the bottom surface of the shelf that is located above the food and one due to the radiation heat transfer from the food to the cold surfaces of the heat pipe shelves.

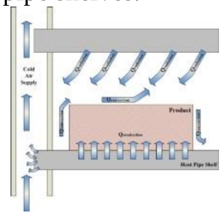

Figure 2 Heat transfer mechanisms of the heat pipe shelf

EXPERIMENTAL TESTING

For the experiments, two identical merchandised open display cabinets were used. One cabinet was equipped with its conventional/commercial shelves, while the other cabinet was incorporated by the innovative actively-cooled shelves. Both of the cabinets' metal back panels were replaced by wooden panels; the wooden replicas had the exact same perforated design, achieving better accuracy and like-for-like test conditions. The original back panels of the cabinets needed to be replaced because the prototypes of the innovative shelves did not fit in the existing design of the cabinet. Both of the cabinets were placed inside a test chamber with controlled environmental conditions (ambient temperature of 20°C and 50% humidity), while their position and experimental procedure was decided in compliance with the ISO23953:2005 requirements [2].

The food products selected for conducting the spoilage experiments were ready-to-eat lasagne (300g), unsalted butter (250g), soft cheese (300g), coleslaw (250g) and taramasalata (250g), while the amount of products and their position on the shelves were determined based on their packaging dimensions and the ISO requirements.

Therefore, the layout of both cabinets loaded with the real food products consisted of 96 units of lasagne, 48 units of soft cheese, 16 units coleslaw, 36 units of unsalted butter and 60 units of taramasalata. The products were placed on the top, middle and base shelves of the cabinets. The two remaining shelves of the cabinets were loaded with food blocks filled with tylose, a material which simulates the thermal behaviour of food, in order to achieve uniform air distribution within the preservation area of the cabinet. The dimensions of the food block were 203 x 105 x 51mm and the number of food blocks on each shelf was decided based on the total height of the real food products on the rest of the shelves.

Figure 3 illustrates the position of the products in the cabinets and the approximate shelf life of each product used in the experiments.

Figure 3 Cabinets' food layout

A total of 28 K-type thermocouples were connected to a DAQ system to measure and record the core temperatures of the products, the surface temperatures of the conventional and actively cooled shelves the back panel temperature of the cabinet and the ambient air temperature. 24-h tests were running recording the power consumption of the cabinets and the core temperatures of the food products. Thermocouples were placed on products in contact with the shelf placed in the front row of the shelves, products in contact with the shelf in the back row, products on top of each product column in the front row and products on top of each product column in the back row of the shelves, as it is shown in figure 4.

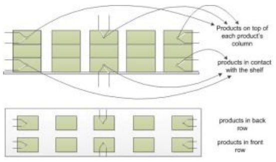

Figure 4 Different positions of food products with thermocouples within the cabinet

The microbiological analysis of the food products was conducted based on their acidity values, also known as pH values. The food products were removed from their designated cabinet and their sealed packaging was removed. Then a pen type pH meter was used to measure the pH values directly from the food samples. The process was repeated four times and averaged for every sample taken was calculated, in order to achieve more accurate results.

RESULTS

Temperature Distribution

The following graphs illustrate in blue colour the temperature changes for the products placed in contact with the shelf on the back row, in red colour the products placed on top of each product column on the back row of products, in green colour the products placed in contact with the shelf on the front row, while the purple line shows the temperature profile of the products placed on top of each product column for the front row of products.

The first two graphs demonstrate the temperature profiles of lasagne placed on the top conventional and heat pipe shelves, according to their position in the shelf. As a reminder, lasagnes were placed on the left hand side of the cabinets.

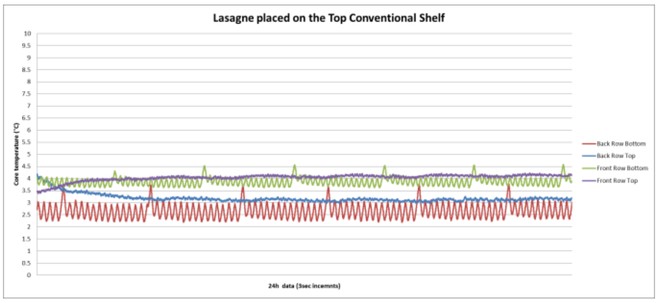

Figure 5 Temperature profiles of lasagne placed on the top conventional shelf according to their positions on the shelf

The bottom lasagne in the front and back row on the conventional shelf were more affected by the defrosting cycles of the cabinets and showed large and often temperature fluctuations, while there was a significant temperature gradient (1.16°C) between them. The products on top of the front and back column were not affected from the defrosting periods and overall showed fewer temperature variations, while their temperature gradient was 0.83°C.

The bottom lasagne on the top heat pipe shelf were again more affected by the defrost cycles of the cabinet, showing some temperature variations and a temperature gradient of 0.32°C. The products on top of the front and back column were not affected from the defrosting periods and overall showed fewer temperature variations, while their temperature gradient was 0.8°C.

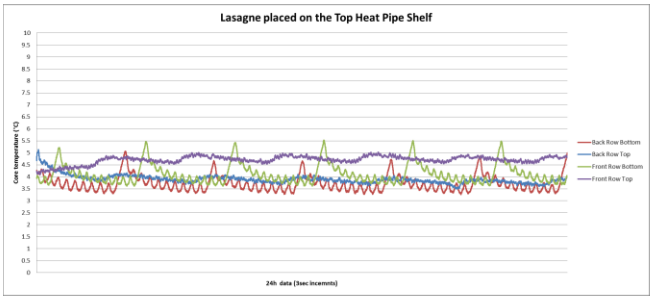

Figure 6 Temperature profiles of lasagne placed on the top heat pipe shelf according to their positions on the shelf

The next two graphs demonstrate the temperature profiles of soft cheese placed on the top conventional and heat pipe shelves, according to their position in the shelf. As a reminder, soft cheeses were placed on the centre of the cabinets.

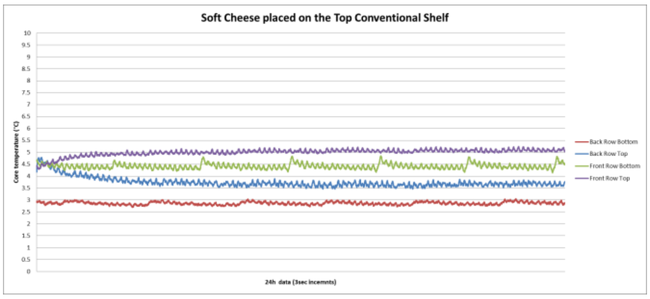

Figure 7 Temperature profiles of soft cheese placed on the top conventional shelf according to their positions on the shelf

The defrost cycles of the cabinet showed no impact on the soft cheese placed on the conventional shelf, except for the products placed in contact with the shelf in the front row of the shelf. All of the products showed regular temperature fluctuations, while the temperature gradient between the front and back row of the bottom soft cheeses was 1.46°C and the temperature gradient of the top products of front and back row was 1.24°C.

The bottom soft cheese on the top heat pipe shelf were again more affected by the defrost cycles of the cabinet, showing some temperature variations and a temperature gradient between the front and back row of 0.62°C. The products on top of the front were not affected from the defrost periods, while the products on top of the back row showed some temperature rise during the defrost periods. The temperature gradient between the front and back row top products was 1.31°C.

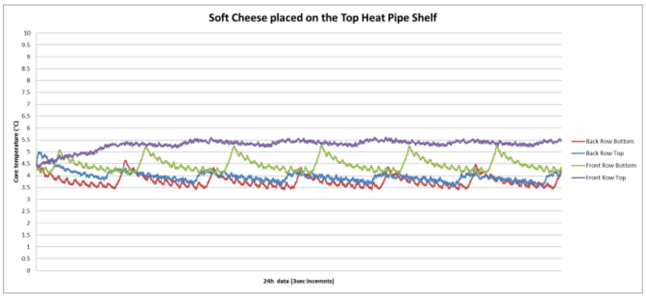

Figure 8 Temperature profiles of soft cheese placed on the top heat pipe shelf according to their positions on the shelf

The next two graphs refer to the temperature profiles of coleslaw placed on the top conventional and heat pipe shelves, according to their position in the shelf. As a reminder, coleslaws were placed on the right hand side of the cabinets.

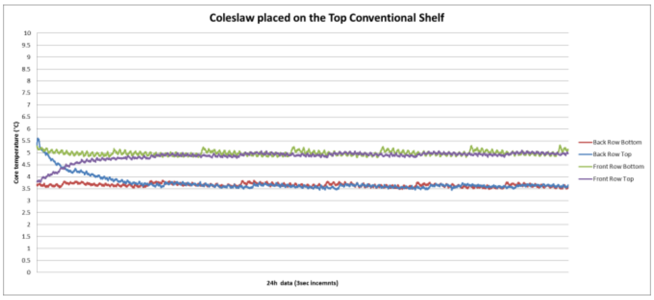

Figure 9 Temperature profiles of coleslaw placed on the top conventional shelf according to their positions on the shelf

The bottom and top coleslaw of the back row, as well as the bottom and top coleslaw of the front row on the conventional shelf showed almost identical temperature profiles, with no effects from the defrost of cabinets. The temperature gradient between the front and back row bottom products was 1.37°C, while the temperature gradient between the front and back row top products was 1.09°C.

The similar thermal behaviour for the coleslaw placed on the heat pipe shelf was observed, however the defrost periods of the cabinet were more obvious. The temperature gradient between the front and back row bottom products was 0.82°C, while the temperature gradient between the front and back row top products was 0.75°C.

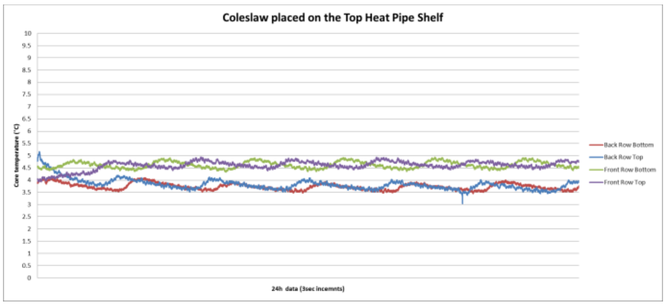

Figure 10 Temperature profiles of coleslaw placed on the top heat pipe shelf according to their positions on the shelf

The next two graphs demonstrate the temperature profiles of taramasalata placed on the middle conventional and heat pipe shelves, according to their position in the shelf. As a reminder, taramasalata were placed on the left hand side of the cabinets.

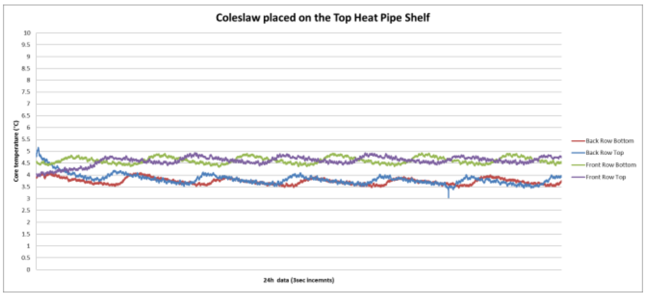

Figure 11 Temperature profiles of taramasalata placed on the middle conventional shelf according to their positions on the shelf

In the conventional shelf only the bottom back row products were affected from the defrost cycles of the cabinet, while they showed a very uniform temperature distribution. The products placed on other positions of the shelf showed often and significant temperature fluctuations. The temperature gradient between the front and back row bottom products was 0.90°C, while the temperature gradient between the front and back row top products was 0.91°C.

For the heat pipe shelf temperature gradients were higher. Between the front and back row bottom products the gradient was 1.29°C, while the temperature gradient between the front and back row top products was 0.95°C.

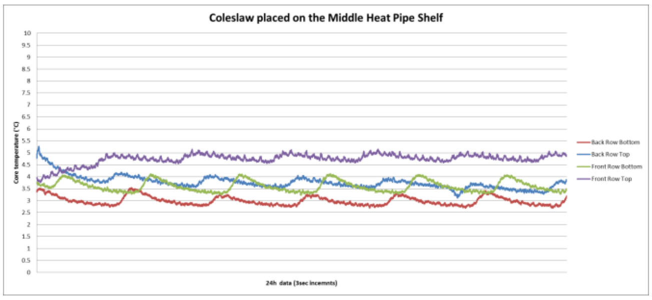

Figure 12 Temperature profiles of taramasalata placed on the middle heat pipe shelf according to their positions on the shelf

The next two graphs show the temperature profiles of lasagne placed on the middle conventional and heat pipe shelves, according to their position in the shelf. As a reminder, lasagnes were placed on the centre of the cabinets.

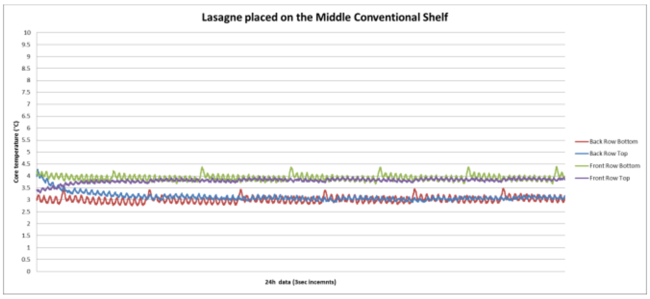

Figure 13 Temperature profiles of lasagne placed on the middle conventional shelf according to their positions on the shelf

The bottom and top lasagne of the back row, as well as the bottom and top lasagne of the front row on the conventional shelf showed almost identical temperature profiles, with small effects of defrost cycles on the bottom products only. The temperature gradient between the front and back row bottom products was 0.86°C, while the temperature gradient between the front and back row top products was 0.66°C.

For the heat pipe shelf temperatures were different. Between the front and back row bottom products the gradient was 0.34°C, while the temperature gradient between the front and back row top products was 1.05°C.

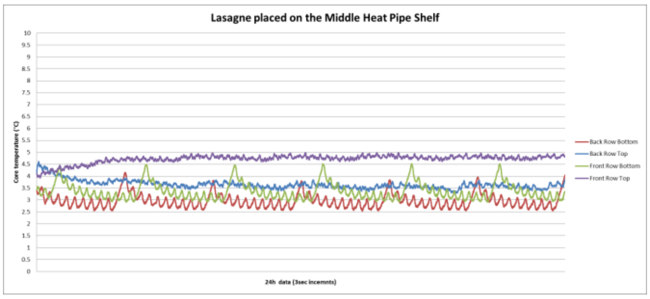

Figure 14 Temperature profiles of lasagne placed on the middle heat pipe shelf according to their positions on the shelf

The next two graphs show the temperature profiles of butter placed on the middle conventional and heat pipe shelves, according to their position in the shelf. As a reminder, butters were placed on the right hand side of the cabinets.

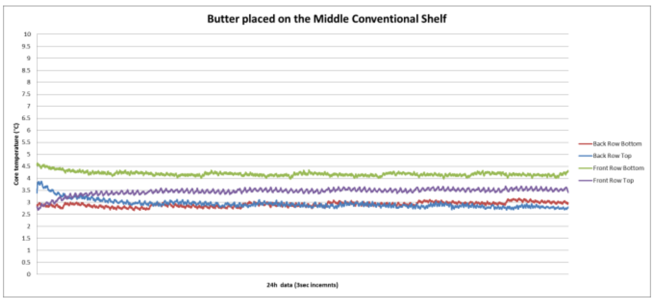

Figure 15 Temperature profiles of butter placed on the middle conventional shelf according to their positions on the shelf

The defrost cycles of the cabinet showed no impact on the butter placed on the conventional shelf. All of the products showed regular temperature fluctuations, while the temperature gradient between the front and back row of the bottom butter was 1.19°C and the temperature gradient of the top products of front and back row was 0.49°C.

The bottom back and front row and the top back row butter on the heat pipe shelf showed similar temperature distribution. Between the front and back row bottom products the gradient was 0.03°C, while the temperature gradient between the front and back row top products was 1.08°C.

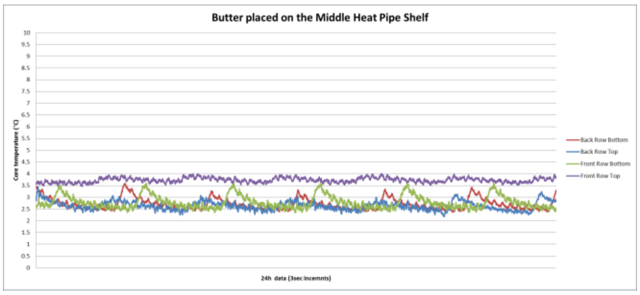

Figure 16 Temperature profiles of butter placed on the middle heat pipe shelf according to their positions on the shelf

The next two graphs show the temperature profiles of soft cheese placed on the base conventional and heat pipe shelves, according to their position in the shelf. As a reminder, soft cheeses were placed on the left hand side of the cabinets.

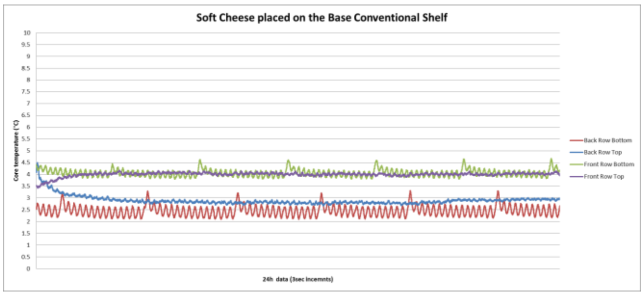

Figure 17 Temperature profiles of soft cheese placed on the base conventional shelf according to their positions on the shelf

The bottom and top lasagne of the back row, as well as the bottom and top lasagne of the front row on the conventional shelf showed similar temperature profiles, with some effects of defrost cycles on the bottom products only. The temperature gradient between the front and back row bottom products was 1.56°C, while the temperature gradient between the front and back row top products was 1.08°C.

For the heat pipe shelf temperatures were different. The bottom products on the front and back row were significantly affected by the defrost cycles. Between the front and back row bottom products the temperature gradient was 0.89°C, while the temperature gradient between the front and back row top products was 1.29°C.

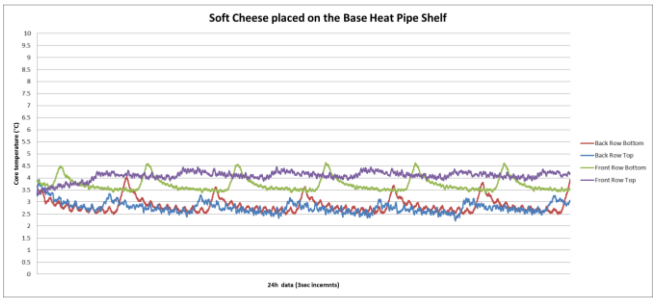

Figure 18 Temperature profiles of soft cheese placed on the base heat pipe shelf according to their positions on the shelf

The next two graphs show the temperature profiles of taramasalata placed on the base conventional and heat pipe shelves, according to their position in the shelf. As a reminder, taramasalatas were placed on the centre of the cabinets.

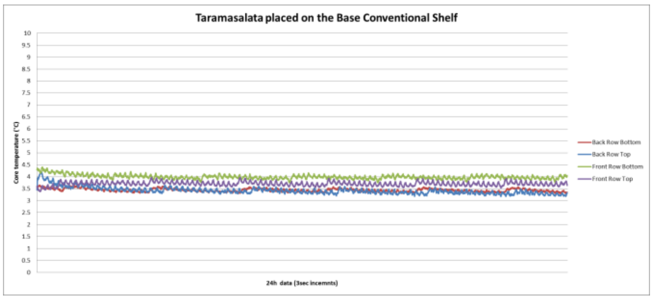

Figure 19 Temperature profiles of taramasalata placed on the base conventional shelf according to their positions on the shelf

All products temperature profiles were similar for the conventional shelf. The temperature gradient between the front and back row bottom products was 0.7°C, while the temperature gradient between the front and back row top products was 0.54°C.

All products temperature profiles were similar for the heat pipe shelf, however the temperature gradients were higher and the defrost effects were more significant. Between the front and back row bottom products the temperature gradient was 0.87°C, while the temperature gradient between the front and back row top products was 0.71°C.

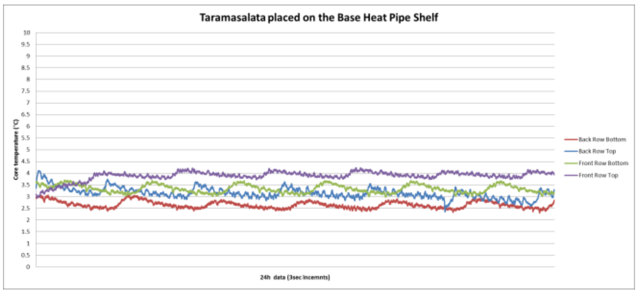

Figure 20 Temperature profiles of taramasalata placed on the base heat pipe shelf according to their positions on the shelf

Finally, the next two graphs show the temperature profiles of coleslaw placed on the base conventional and heat pipe shelves, according to their position in the shelf. As a reminder, coleslaw were placed on the right hand side of the cabinets.

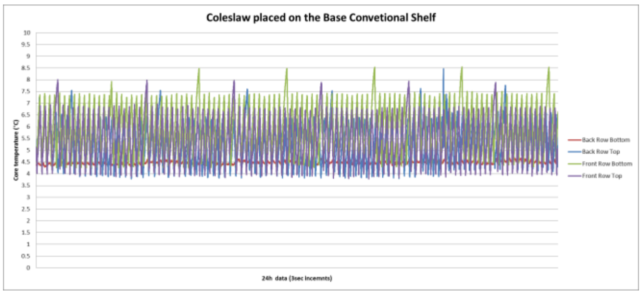

Figure 21 Temperature profiles of coleslaw placed on the base conventional shelf according to their positions on the shelf

Only the bottom back row coleslaw showed stable temperature distribution. In all other positions the products were characterised by enormous and often temperature fluctuations. The temperature gradient between the front and back row bottom products was 1.56°C, while the temperature gradient between the front and back row top products was 0.18°C.

All products temperature profiles were similar for the heat pipe shelf, however the defrost effects were more significant. Between the front and back row bottom products the temperature gradient was 0.85°C, while the temperature gradient between the front and back row top products was 0.88°C.

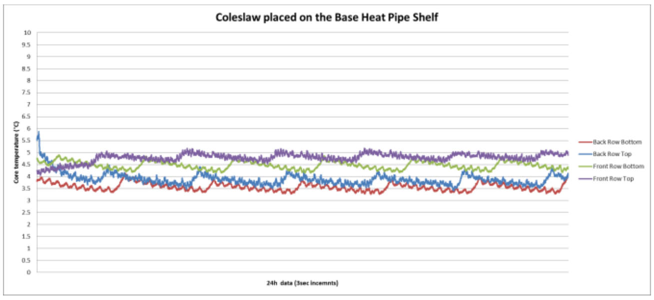

Figure 22 Temperature profiles of coleslaw placed on the base heat pipe shelf according to their positions on the shelf

Power Consumption

The average daily electrical power consumption of the cabinet equipped with the heat pipe shelves was approximately 7.6 kWh, while the average electrical power consumption of the cabinet equipped with the conventional shelves was approximately 8.6 kWh, for 24 hours of operation.

As a result, the implementation of heat pipe shelves provided an average daily energy saving rate of 11.63%. With the electricity price being at 0.1127 £/kWh (≈ 0.1435 €/kWh) for industrial consumers in the UK [21], cabinets equipped with the heat pipe shelves could save supermarkets annually £478.40 per cabinet. This value may seem low, but if someone considers how many cabinets an average supermarket has, this simple heat pipe shelf implementation could save great amounts of energy and money.

Acidity Levels

Almost all the products placed on the heat pipe shelves – except of lasagne placed on the top shelf – maintained approximately the exact same acidity levels as they were collected the first day of experiments, even 20 days beyond their expiry date.

Especially, soft cheese placed on the middle heat pipe shelf and taramasalata placed on the base heat pipe shelf had exactly the same pH value as the first day of their placement on the cabinet; while the difference between the acidity levels of all the other products placed on the heat pipe shelves did not exceed the 0.1 (except of lasagne placed on the top shelf).

Moreover, interesting is the fact that butters placed on the middle conventional shelf of the cabinet, 16 days before their expiration date, showed a big deviation in acidity levels, from day 0 to day 21.

On the other hand, the products placed on the conventional shelves showed differences in the acidity levels between the first and the last days of experiments around 0.2-0.7.

Table 1 pH values of products – First and last days of the experiments

		First Day	Last Day		
Shelf	**Food product**	**Initial pH values**	**pH values of products placed on the *heat pipe shelves***	**pH values of products placed on the *conventional shelves***	**Days beyond or before products expiry date**
Top Shelf	Lasagne	5.9	5.0	5.1	19 beyond
	Soft cheese	4.9	4.9	4.5	51 before
	Coleslaw	4.7	4.8	5.0	20 beyond
Middle Shelf	Taramasalata	4.7	4.8	4.4	21 beyond
	Lasagne	5.9	5.5	5.2	19 beyond
	Butter	6.4	6.3	5.9	16 before
Base Shelf	Soft cheese	4.9	4.8	4.5	51 before
	Taramasalata	4.7	4.7	4.9	21 beyond
	Coleslaw	4.7	4.6	4.4	20 beyond

DISCUSSION

A comparison between a conventional vertical open refrigeration cabinet and an identical cabinet equipped with actively-cooled heat pipe shelves, in terms of performance regarding their power consumption and their ability to maintain food products in low storage temperatures, has been represented in this paper.

According to the experimental results the implementation of heat pipe shelves managed to achieve more uniform temperature distribution along the shelves and the cabinet, more gradual cooling down profiles, fewer temperature fluctuations and lower food temperature preservation, a fact which had an important impact on the food product quality, based on their pH values.

Overall, the use of the heat pipe shelves has led to lower temperature gradients between the different positions of the products within the cabinet, compared to the conventional shelves. The only exceptions were for the top products on the front rows of the left hand side of the middle shelf and the centre of the base shelf.

In terms of energy and economic savings, the cabinet equipped with the heat pipe shelves showed an average energy saving of 12%, which corresponds to economic gain of almost £480 per year per cabinet.

The higher core temperatures of the food products for both cabinets' configurations were observed for the top products placed on the front row of the shelves. At the same time, the lowest temperatures were observed for the products in contact with the shelves placed on the back row.

Moreover, according to the results from the experiments, always the top heat pipe shelf and the products placed on it had the higher temperatures, while the cabinet equipped with the conventional shelves showed the exact reversed behaviour. The lowest temperatures were achieved in the top shelf, while the hottest shelf was the base.

For the cabinet equipped with the heat pipe shelves, the products on the left hand side showed the higher temperatures, while the products with the lowest temperatures were placed on the right hand side of the cabinet. The products placed on the conventional shelves again showed the reversed behaviour. The products placed on the left hand side of the cabinets had the lowest temperatures, while the higher temperatures were found for the products on the left hand side. The following figures illustrate the above observations.

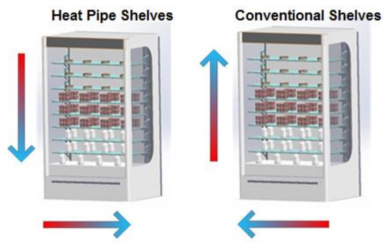

Figure 23 Temperature distribution of the cabinets

Finally, the acidity test of the products showed that the products placed on the heat pipe shelves maintained their initial acidity levels, after 21 days of experiments. Even the products beyond their expiry days showed a difference of 0.1 compared to their pH values on the first day of their placement on the cabinet, while the difference for the products placed on the conventional shelves showed differences between 0.2-0.7.

Although a specific estimation of how many days the heat pipe shelves can extend the shelf life of food products could not be concluded in this initial investigation due to time constrains, the experimental results are really promising. Further experiments and more advanced microbial testing should be conducted to determine exactly the mechanisms by which pathogens are developed and to compare the bacterial growth of the products placed on the conventional and the heat pipe shelves.

REFERENCES

[1] Tassou SA, Ge Y, Hadawey A, Marriott D. Energy consumption and conservation in food retailing. Appl Therm Eng 2011;31:147–56. doi:10.1016/j.applthermaleng.2010.08.023.

[2] British Standard. ISO 23953-2:2005 Refrigerated display cabinets - Part 2: Classification, requirements and test conditions. vol. 3. European Standard: European Standard; 2005.

[3] Bailey C, Cauvain S. Refrigeration of baked foods and legislative developments. Inst. Refrig., 1994, p. 61–8.

[4] Food Standards Agency. Guidance on Temperature Control Legislation in the UK- EC Regulation 852/2004 2007. http://www.food.gov.uk/multimedia/pdfs/tempcontrolguiduk.pdf.

[5] Gill C., Jones T, Houde A, LeBlanc D., Rahn K, Holley R., et al. The temperatures and ages of packs of beef displayed in multi-shelf retail cabinets. Food Control 2003;14:145–51. doi:10.1016/S0956-7135(02)00058-0.

[6] Evans JA, Scarcelli S, Swain MVL. Temperature and energy performance of refrigerated retail display and commercial catering cabinets under test conditions. Int J Refrig 2007;30:398–408. doi:10.1016/j.ijrefrig.2006.10.006.

[7] Willocx, Hendrick, Tobback. A primary survey into the temperature conditions and residence time distribution of minimally processed MAP vegetables in Belgian retail display cabinets. Int J Refrig 1994:436–44.

[8] Brimelow, Ridgway. Optimal food process design and control. Food Control 1990:4–5.

[9] Maidment G, James R, Missenden J, Tozer R. Food has feelings too! - the influence of enviromental comfort criteria on the condition of unwrapped chilled food on display. Chart Inst Build Serv Eng CIBSE Natl Conf 1999:59–69.

[10] Maidment GG, Missenden JF, Karayiannis TG, Wang F. An investigation of a novel cooling system for chilled food display cabinets. Proc Inst Mech Eng Part E J Process Mech Eng 2005;219:157–65. doi:10.1243/095440805X8610.

[11] Lu YL, Zhang WH, Yuan P, Xue MD, Qu ZG, Tao WQ. Experimental study of heat transfer intensification by using a novel combined shelf in food refrigerated display cabinets (Experimental study of a novel cabinets). Appl Therm Eng 2010;30:85–91. doi:10.1016/j.applthermaleng.2008.10.003.

[12] Jouhara H, Anastasov V, Khamis I. Potential of heat pipe technology in nuclear seawater desalination. Desalination 2009;249:1055–61. doi:10.1016/j.desal.2009.05.019.

[13] Danielewicz J, Sayegh MA, Śniechowska B, Szulgowska-Zgrzywa M, Jouhara H. Experimental and analytical performance investigation of air to air two phase closed thermosyphon based heat exchangers. Energy 2014;77:82–7. doi:10.1016/j.energy.2014.04.107.

[14] Jouhara H, Meskimmon R. Experimental investigation of wraparound loop heat pipe heat exchanger used in energy efficient air handling units. Energy 2010;35:4592–9. doi:10.1016/j.energy.2010.03.056.

[15] Naghavi MS, Ong KS, Mehrali M, Badruddin IA, Metselaar HSC. A state-of-the-art review on hybrid heat pipe latent heat storage systems. Energy Convers Manag 2015;105:1178–204. doi:10.1016/j.enconman.2015.08.044.

[16] Jouhara H, Robinson AJ. An Experimental Study of Small-Diameter Wickless Heat Pipes Operating in the Temperature Range 200°C to 450°C. Heat Transf Eng 2009;30:1041–8. doi:10.1080/01457630902921113.

[17] Fadhl B, Wrobel LC, Jouhara H. CFD modelling of a two-phase closed thermosyphon charged with R134a and R404a. Appl Therm Eng 2015;78:482–90. doi:10.1016/j.applthermaleng.2014.12.062.

[18] Reay DA, Kew PA MR. Heat Pipes: Theory, Deign and Applications. 6th ed. Butterworh Heinemann; 2014.

[19] Jouhara H, Lester S. Heat pipe solar roof. 1410924.3, 2014.

[20] Jouhara H, Tassou S. Heat pipe shelf. 1423037.9, 2014.

[21] Eurostat. Electricity prices by type of user - EUR per kWh 2015:ten00117. http://ec.europa.eu/eurostat/tgm/table.do?tab=table&plugin=1&language=en&pcode=ten00117.