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Temperature and energy performance of open refrigerated display cabinets using heat pipe shelves

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Abstract

The paper describes 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 analyzed. 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. 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 homogenize the temperature profile of the products 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. Finally, a primary of the acidity levels (pH) of the products was conducted. The experiments showed that almost all products placed on the heat pipe shelves, after 20 days of experiments, had almost the same pH values, even 20 days beyond their expiration date.

Keywords: Heat pipe refrigeration shelves; open display cabinets; food preservation

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1. Introduction

Retail food outlets are among the largest consumers of electric energy in the UK. Their energy consumption is estimated around 2,000 kWh/m2/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 localized freezing somewhere in the cabinet. 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 [3]. 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.

2. 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 [4]. 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 [5]. 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 [6].

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 [7]. 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 [7]. 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 [7]. 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 [8]. 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.

3. 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 [9–14]. 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 'thermosiphons' 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 vapor 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 vapor 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 [10]. 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 [15,16]. The surface in which food products are place is composed by aluminum 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.
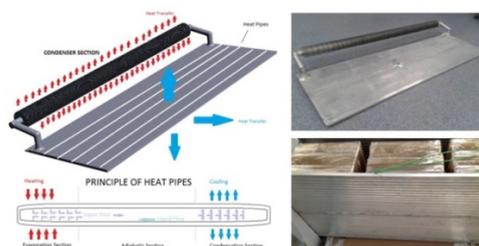

Fig. 1. Actively-cooled shelf and operation principle of heat pipes

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.
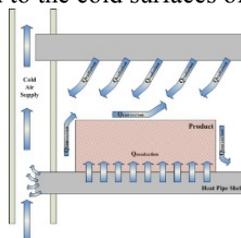

Fig. 2. Heat transfer mechanisms of the heat pipe shelf

4. 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.
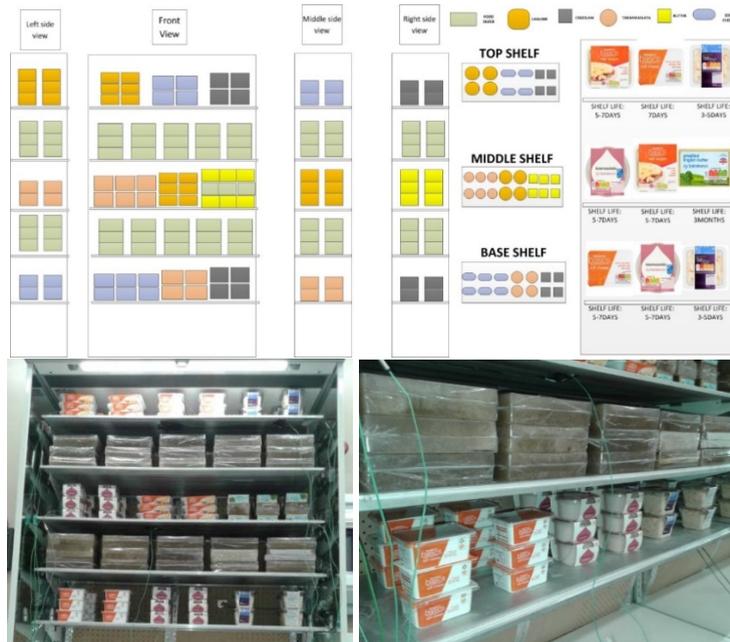

Fig. 3. Cabinets' food layout

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.
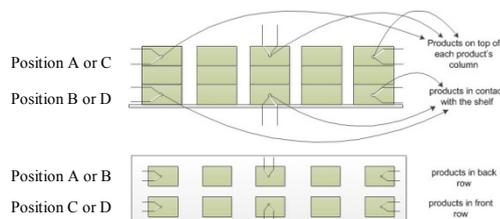

Fig. 4. Different positions of food products with thermocouples within the cabinet
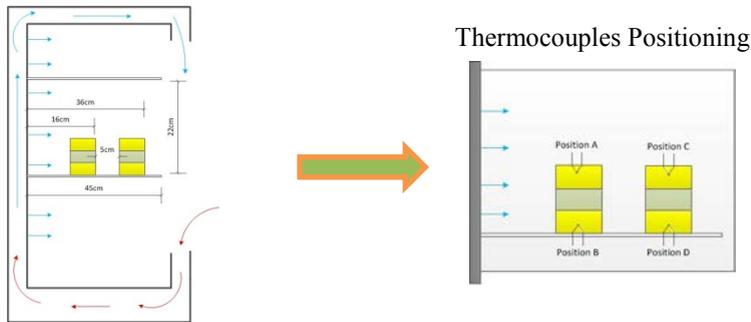
Fig. 5. Diagram of the experiment (side and front view)

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.

5. Results

5.1. Temperature distribution

Table 1 below shows the lowest and highest temperatures of each product according to their position on the cabinets. The majority of products displayed on the heat pipe shelves show lower core temperatures comparing to the products displayed on the conventional shelves, with the exception of the products placed on the top shelf. Finally, it is observed that always the products in contact with the shelf (positions B and D) in the case of the heat pipe shelves show the lowest temperatures. However, in the case of the conventional shelves different hot spots occur in unexpected positions, such as the majority of products in position D for the middle and bottom conventional shelves.

Table 1. Maximum and minimum product temperatures and positions achieved on the heat pipe and conventional shelves

	Product	Heat Pipe Shelves Temperatures		Conventional Shelves Temperatures	
		Lowest	Highest	Lowest	Highest
Top Shelf	Lasagne	3.7°C Position B	4.7°C Position C	2.7°C Position B	4.0°C Position C
	Soft cheese	3.7°C Position B	5.3°C Position C	2.9°C Position B	5.0°C Position C
	Coleslaw	3.6°C Position B	4.7°C Position C	3.6°C Position B	5.0°C Position C
Middle Shelf	Taramasalata	2.2°C Position B	4.7°C Position C	3.0°C Position B	4.2°C Position C
	Lasagne	2.8°C Position B	4.7°C Position C	3.0°C Position B	3.8°C Position D
	Butter	2.6°C Position B	3.7°C Position C	3.0°C Position A	4.0°C Position D
Base Shelf	Soft cheese	2.8°C Position B	4.1°C Position C	2.4°C Position B	4.1°C Position D
	Taramasalata	2.6°C Position B	3.8°C Position C	3.6°C Position A	3.8°C Position D
	Coleslaw	3.5°C Position B	4.7°C Position C	4.5°C Position B	6.0°C Position D

Figure 6 shows the average temperatures of each product, on each position placed on the cabinets. The blue coloured line represents the average temperatures of the products displayed on the heat pipe shelves, while the red coloured line represents the average temperatures of the products displayed on the conventional shelves. Four different positions are analysed, two in contact with the shelf (positions B and D) and two in the top of each product column (positions A and C).
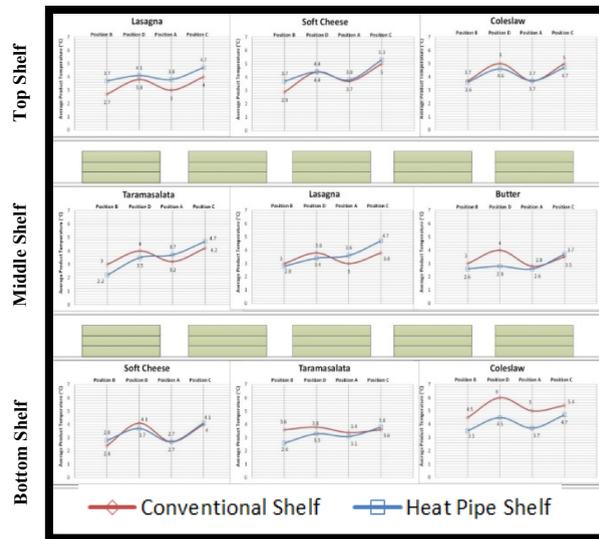
Fig. 6. Average temperatures of products placed on the heat pipe (blue line) and the conventional (red line) shelves for every position of the shelf

From figure 6 the following outcomes can be concluded:
a. The average core temperatures of the products displayed on top heat pipe shelf show less fluctuation compared to the same products placed on the conventional shelves. More specifically, the average core temperatures of the products placed on the heat pipe shelf for the positions B, D and A show similar values, even though the products placed on the position A are not in contact with the cold base. In contrast, the same products placed on the conventional shelves show large temperature variations in all the positions.
b. The most linear and lower temperature results are observed for the middle shelves.
c. In the case of the conventional shelves the lowest core temperatures are observed for the back row products (positions B and A), no matter if they are placed in contact with the shelf (position B) or on top of a product column (position A). On the other hand, the products placed on the heat pipe shelves show similar low temperatures for all the positions, except the position C. A potential explanation is that the air curtain flow of the cabinet equipped with the heat pipe shelves was obstructed, so the cooling was not efficient for the front row top column products.
d. The biggest core temperature differences are observed for the coleslaw placed on the bottom shelves on the right side of the cabinets. Products displayed in both shelf's configurations showed higher temperatures, however, the coleslaw placed on the heat pipe shelf did not exceed the 4.5°C, in contrast with the coleslaw placed on the conventional shelves, which reached the temperature of 6°C; a value that is out of the limit set by the British Standards [2].

Figure 7 provides a better understanding of the mechanisms behind the more stable and lower temperature profiles of the products displayed on the heat pipe shelves, as it was shown in table 1 and figure 6. Figure 7 represents the thermal profiles of the surface of the conventional (red coloured line) and the heat pipe (blue coloured line) shelves.
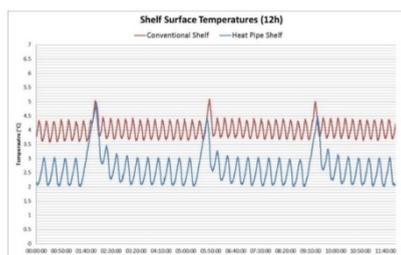

Fig. 7. Thermal profiles of the surface of conventional (red line) and heat pipe (blue line) shelves

The thermal profiles of the shelves surfaces can be translated into the compressor cycles of the freezers. The three high peaks in the graph indicate the defrost cycles of the cabinet, as the compressor switches off and the temperature in the cabinet is increased. The smaller temperature fluctuations represent the frequency of the compressors' operation; each temperature rise indicates that the compressor was switching off. As it can be seen, the compressor of the cabinet equipped with the heat pipe shelves works for longer periods, but less intense. However, the compressor of the conventional cabinet is constantly switching on and off trying to maintain the temperature of the cabinet on the set point. Finally, the graph shows that the heat pipe shelves experience greater temperature rise, however they manage to maintain their temperature almost 2°C lower than the conventional shelves, even though the cabinets are operating on the same set point and on the same environmental conditions.

5.2. 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. Their difference in the electricity consumption can be explained by the analysis of the compressors' cycles, described in the previous section. The compressor of the cabinet equipped with the heat pipe shelves works less frequent, but more efficient than the compressor of the conventional cabinet, which leads to an energy saving. As a result, the implementation of heat pipe shelves provided an average daily energy saving rate of 12%. With the electricity price being at 0.12 £/kWh ($\approx$ 0.1435 €/kWh) for industrial consumers in the UK [17], cabinets equipped with the heat pipe shelves could save supermarkets annually £44 per cabinet. This value may seem low, but if someone considers the number of cabinets an average supermarket has then this simple heat pipe shelf implementation could save great amounts of energy and money.

5.3. 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 to 0.7.

Table 2. pH values of products – First and last days of the experiments

		First Day		Last Day	
	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

6. Conclusions

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 heat pipe shelves achieved 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 center 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 £44 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 behavior. 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 behavior. 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.

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.

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] 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.
[4] 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.
[5] 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.
[6] 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.
[7] 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.
[8] 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.
[9] 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.
[10]   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.
[11]   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.
[12]   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.
[13]   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.
[14]   Reay DA, Kew PA MR. Heat Pipes: Theory, Deign and Applications. 6th ed. Butterworh Heinemann; 2014.
[15]   Jouhara H, Lester S. Heat pipe solar roof. 1410924.3, 2014.
[16]   Jouhara H, Tassou S. Heat pipe shelf. 1423037.9, 2014.
[17]   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.