Applied Thermal Engineering 30 (2010) 85–91

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Experimental study of heat transfer intensification by using a novel combined shelf in food refrigerated display cabinets (Experimental study of a novel cabinets)

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ARTICLE INFO

Article history:
Received 6 July 2008
Accepted 6 October 2008
Available online 22 October 2008

Keywords:
Display cabinet
Heat pipes
Phase change material (PCM)
Experimental study

ABSTRACT

Open-type display cabinets are widely used in supermarkets for chilling and displaying food. These cabinets use convective heat transfer to cool the food, and they often show uneven food temperature distribution and obvious food temperature rise during defrost process. A novel design for display cabinet's shelf is proposed in this paper. In the new design heat pipes of new structure and appropriate phase change materials (PCM) are equipped in the shelf. Comparison tests of two prototypes (one with heat pipe only and the other with both heat pipe and PCM) and original cabinet have been conducted. The tests results show that improved heat transfer and lower food temperature are achieved by the two new shelves. The new shelf with heat pipes only leads to lower food core temperatures of approximately 3.0 to 5.5 °C compared to the original design. The new shelf with both heat pipes and phase change materials reduces 1.5 °C of food temperature rise during defrost period and improves the uniform of food temperature distribution while the energy consumption is basically the same as that of the original cabinet.

1. Introduction

Supermarket is a large user of electric energy, of which above 50% is consumed by refrigeration equipment [1,2] which provides cooling for retail cabinets to chill and freeze foods. The purpose of these cabinets is both to display food products and maintain food at a certain temperature level for good conservation conditions. This certain level requires small temperature differences among different foods. However in most open-type display cabinets in supermarkets there often is a big temperature difference and/or a significant temperature rise. These disadvantages are difficult to overcome such that the British Standards BS EN 441-4 [3] has to accept a temperature increase to 15 °C for a short period.

The display cabinet is composed of three main components, including refrigeration system, display cabinet body and air curtains. Over the last ten years, some studies were conducted to investigate evaporator performance in display cabinets. Major contributions to the work include Chandrasekharan et al. [4], Datta and Tassou [5] and Thybo et al. [6]. The effects of air curtain characteristics on the display cabinet performance were studied by Field and Loth [7], Navaz et al. [8,9]. Chandrasekharan et al. [4] developed a model to simulate a finned-tube display cabinet evaporator. The model was expected to be used as a design tool for improving the evaporator performance on different frosting conditions. Field and Loth [7] used the particle image velocimeter (PIV) techniques to study the entrainment characteristics of air curtains. They observed the flow features of air curtains with Reynolds numbers ranging from 1500 to 8500. Later Navaz et al. [9] studied the efficiency of air curtain in maintaining the display cabinets and food products at a prescribed temperature, and identified some parameters that have significant impacts on reducing the amount of entrained air without impairing the overall display cabinet performance. In order to improve cabinet performance, attentions have been paid on some other aspects [10–18]. For example, Ge and Cropper [10] investigated performance comparison of a display cabinet system using refrigerant R404A and R22. Their results show that an R404A display cabinet needs greater cooling load and refrigerant mass flow rate than R22 at specified operating condition; Gill et al. [11] studied the influence of temperature on beef pack conservation ages in multi-shelf retail cabinets; Faramarzi et al. [12] pointed that the heat transfer can be strengthened to a certain extent by changing the style of food stack.

In spite of intensive researches in the past several decades, there is still much dissatisfaction in current cabinet design. Firstly, in the conventional design of cabinets air convective heat transfer is used to cool the food, and in such design the heat conduction between foods and shelves is relatively poor. So the core temperatures of the food which touch with the shelves can not be reduced effectively. Secondly, the heat transfer rate from cold storage area to

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doi:10.1016/j.applthermaleng.2008.10.003

food is low and not uniform. So, there are wide food temperature ranges, which have been noticed by many authors. Grill et al. [11] measured food temperature in the same cabinet and found that it varied from −2 to 10.6 °C. Willocx et al. [19] found food temperatures between 3.2 and 15 °C at different positions in the same cabinet. Thirdly, frost accumulation on the evaporator reduces the heating capacity of the cabinet. In order to maintain adequate cabinet performance, the evaporator needs to be defrosted periodically. In display cabinet, the defrost operation is often in the form of natural defrost during which the refrigeration system does not work and the food temperatures rise accordingly.

Many researchers committed themselves to lower the food temperature, reduce the food temperature difference and food temperature rise during defrost period by optimizing the components of refrigeration system, air curtain and food stack style. For example, Maidment et al. [16] indicated that it was possible to get better heat transfer effect to the food by providing additional cooling which can strengthen heat transfer to the food, and numerical simulation was conducted into the application of a superconductive heat pipe shelf in a retail cabinet. Wang et al. [20] did a detailed theoretical and experimental analysis regarding using heat pipes on the display shelf, also PCM being introduced into further investigation, however, they did not test it and no further results have been published since then.

In this paper, stimulated by the concepts proposed in [16,20], an improved design of open-type display cabinet shelf has been realized by using heat pipes of new structure to significantly enhance heat transfer and drastically reduce temperature difference levels. Furthermore, in order to lower core food temperature rise during defrost period, appropriate phase change materials (PCM) have been successfully selected and filled into a cabinet shelf. And thereby a novel combined shelf by using heat pipes and phase change materials (PCM) has been formed and tested. Some positive results have been obtained which are presented below.

2. Temperature distribution measurement for a conventional display cabinet

In this section some temperature distributions measured by the authors in a conventional display cabinet are presented to reveal the disadvantages in temperature uniformity commonly existed in the present-day commercial cabinets. A typical diagram of open-type display cabinet is shown in Fig. 1. The evaporator is in the back of the cabinet and the fans blow air through the duct at the cabinet rear part from the evaporator. A small fraction of the air is sometimes fed into the units through a perforated plate at the back of the cabinet. The bulk of the air is directed into the display area as a jet, to form two air curtains across the cabinet opening. The air curtains create a non-physical barrier between the cold air in the cabinet and the ambient air outside. Some perishable food is stored and displayed on shelves at required storage temperature, and cooling is provided by cold air from perforated plate and air curtains. The experiment was carried out in a test room and the room ambient temperature was 17 °C. The food temperatures were measured according to British Standards BS EN 441-4 [3].

The temperature variations with time in core of products on different shelves are measured and the results are shown in Fig. 2. It can be found that the food temperature on shelf 1 is higher than 5 °C that is not satisfactory. For example the UK food hygiene legislation in 1990 requires that all sensitive foodstuffs refrigerated in display cabinets should be maintained at a temperature below 5 °C [21]. It is also revealed that temperature difference in vertical direction is very large. As can be seen from Fig. 2 the maximum temperature difference occurs between shelf 1 and shelf 3 and is about 9 °C, and the minimum difference is 1.5 °C which occurs between shelf 3 and shelf 4. These results are very common as has been indicated in the experimental results of Faramarzi et al. [12].

Fig. 3 shows that the food temperatures distribution from back to front of shelf 4. The food temperature on the back of the shelf is the lowest (−0.3 °C) and that in the front is the highest (2.3 °C). The food temperature gradient is mainly caused by the following operational condition: the foods at the back of the shelf are cooled by the cold air entering the cabinet from the perforated plate while the front foods are mainly affected by the warm environment outside the display cabinet. In addition the radiation due to light further enhances such temperature difference.

The spanwise temperature distributions (from right to left) on shelf 4 are shown in Fig. 4. The food temperature difference from right to left of the shelf 4 is about 2.5 °C. Temperature gradients from right to left across the cabinet are typically caused by a poor distribution of cold air.

In order to reveal the defrost effect on the food temperature special measurement was taken by measuring temperatures at 48 experimental points in M packages positioned at different locations shown in Fig. 5. Fig. 6 illustrates the effect of defrost on the product temperature of the open vertical display cabinet over four defrost cycles. The temperature peaks occur 4 times a day and the typical temperature rises are in the range from 1 to 3 °C. The food temperature rise is caused during the operation of the evaporator

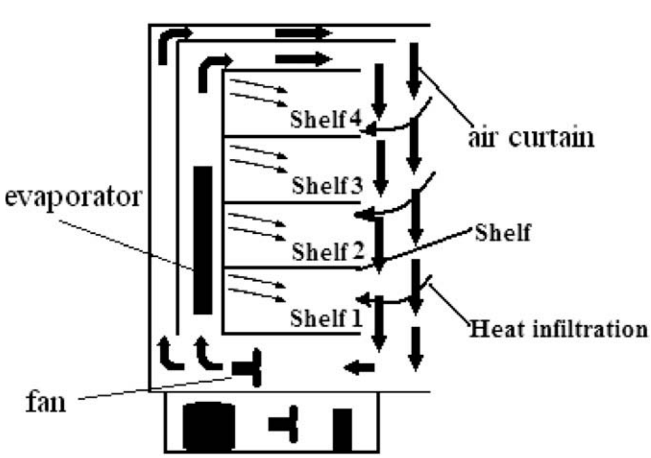

Fig. 1. Schematic of a conventional display cabinet.

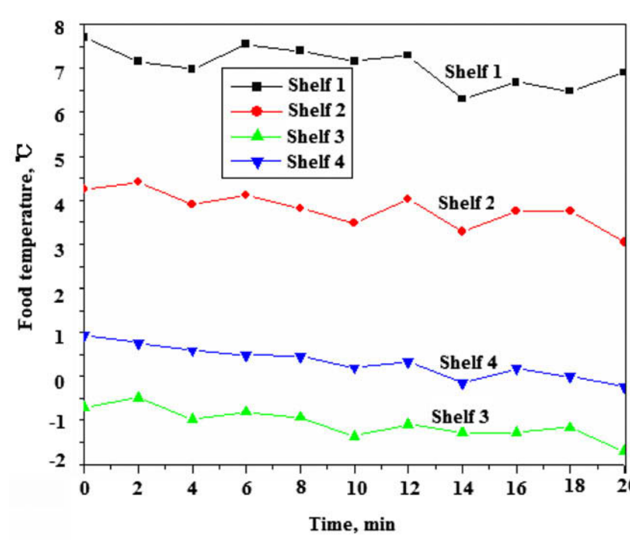

Fig. 2. Temperature distributions in different shelves of a conventional cabinet.

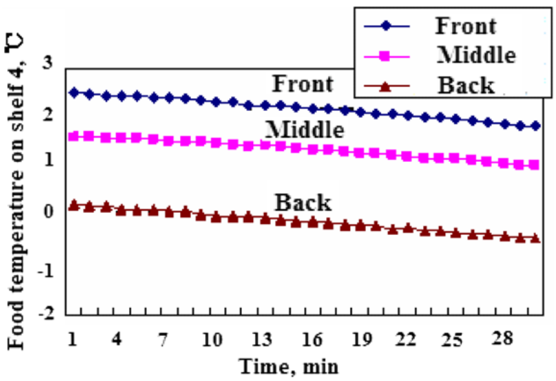

Fig. 3. Average food temperature distributions from back to front on shelf 4.

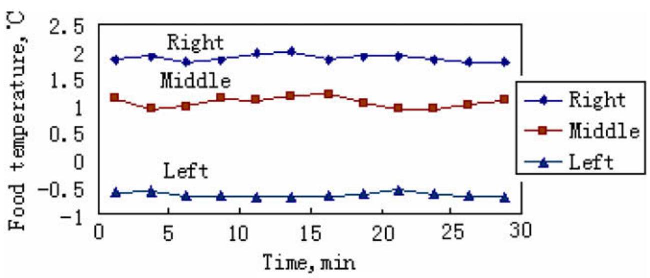

Fig. 4. Average food temperature distributions from right to left on shelf 4.

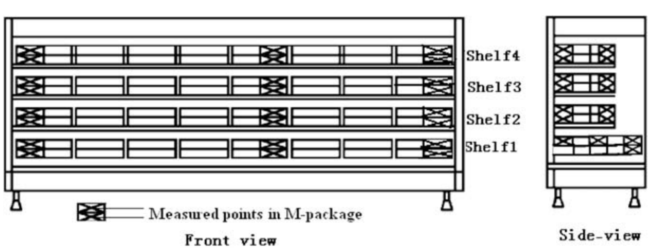

Fig. 5. The experimental points measured in conventional cabinet.

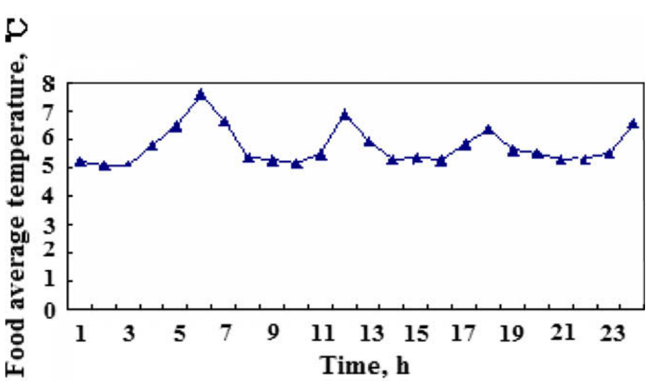

Fig. 6. The effect of defrost on average product temperature.

because the cooling capacity reduces with frost accumulation on the evaporator. Furthermore, during defrost period refrigeration system does not work, and a lot of heat infiltrates from outside warm environment. Such temperature variation events have a bad effect on food safety.

3. A novel shelf design by using heat pipes for display cabinet

In this section the present authors propose a novel design idea of display cabinet using heat pipes as the tool for improving food temperature uniformity. A special display cabinet has been made according to this idea and experimental measurement has been conducted. In the following a brief introduction of heat pipe and its usage in the display cabinet will firstly presented, followed by description of measurement process and the measurement results and discussion.

3.1. The principle of heat pipes and application in display cabinets

Heat pipes have been widely used in waste heat recovery [22–24], where the high uniformity of the surface temperature of the heat pipe is used to increase the temperature difference between the heat transfer surface and the fluid. For our case heat pipes are employed at the undersurface of the shelf 4 to remedy the non-uniformity in temperature distribution. A heat pipe consists of a sealed container, a small amount of working fluid and a wick structure [25]. The length of heat pipe is divided into three parts: evaporator section, adiabatic section and condenser section (Fig. 7). When heat is added into the evaporator part, the working fluid evaporates and migrates to condenser part, and then the condensed liquid returns to the evaporator section by capillary action. Heat pipe technology is a highly efficient passive heat transfer tool with an equivalent thermal conductivity being about approximately 500 times than that of copper [26]. The employment of heat pipes by positioning them at undersurface of shelf normal to the spanwise direction can significantly reduce the temperature non-uniformity of the shelf undersurface, which is in turn helpful to reducing food temperature gradients from back to front.

As shown in Fig. 8,the evaporator sections of heat pipes are fixed at display cabinet shelf undersurface, and condenser sections are positioned through the display area back panel into the supply air channel. Then heat can be transferred from shelf and food to the heat pipe by conduction and radiation. But during defrost period, hot air flows across condenser sections of heat pipes, and condenser sections exchange their role with evaporator sections. That leads to a reverse heat transfer from the hot air of the defrosting stream to the display area, which obviously deteriorates food safety. In order to alleviate this problem, we design condenser section with some inclination without inner wick materials as shown in Figs. 7 and 8 to make condensed liquid returns to heat source quickly in the normal working time. However, during the frosting time the inclination is helpful to suppress the evaporated vapor in the condenser part of the heat pipe into the evaporator part, so that the reverse heat transfer can be eliminated significantly. It should be noted that the proposed structure of heat pipe is really new. The heat pipe used in [16] was horizontally situated, and in

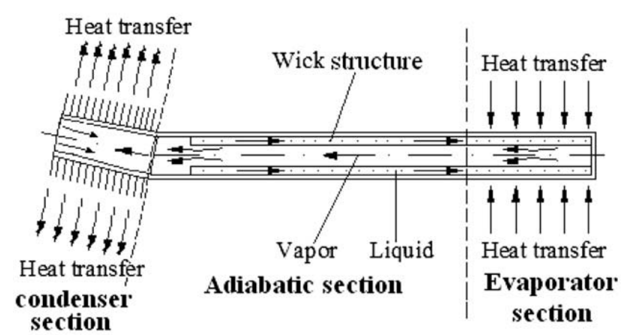

Fig. 7. Principle of operation of a heat pipe.

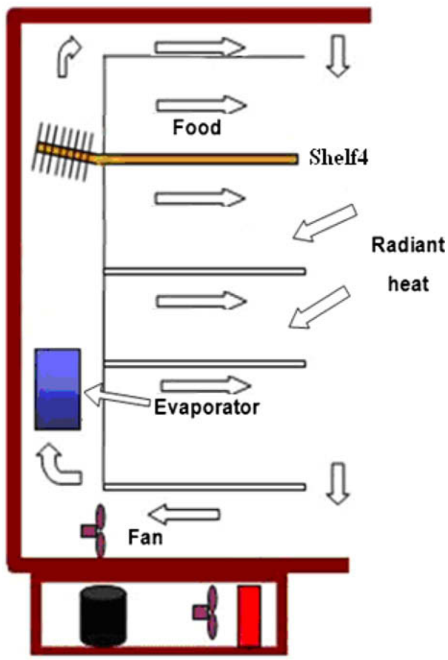

Fig. 8. A typical multi-deck type display cabinet with heat pipes.

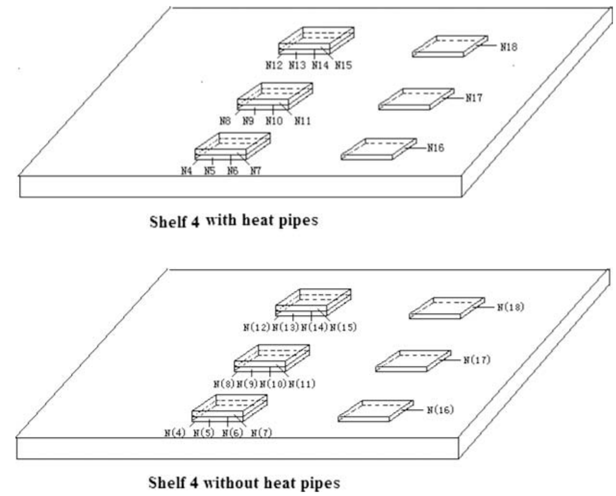

Fig. 9. Schematic of the food samples.

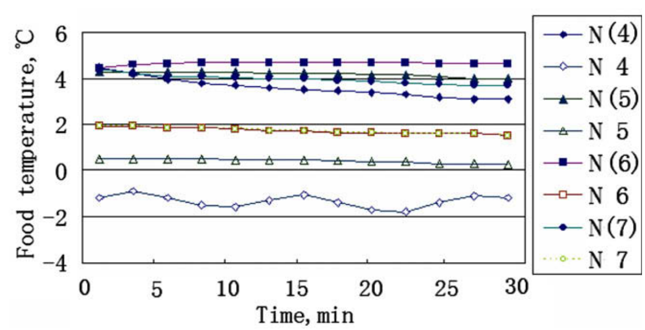

Fig. 10. Food temperatures on the same position with and without heat pipes (N4-7).

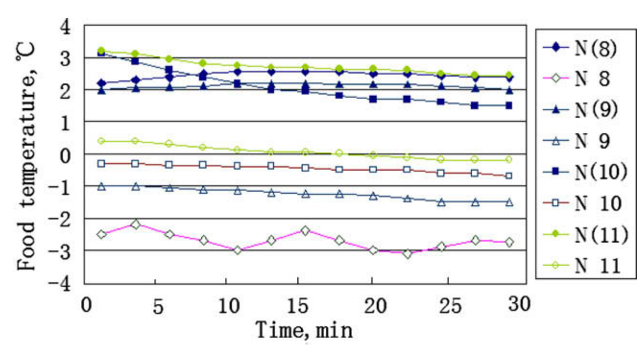

Fig. 11. Food temperatures on the same position with and without heat pipes (N8-11).

[20] the heat pipe was inclined with condenser part being in the lowest position.

3.2. Experimental investigations of display cabinet shelf with heat pipes

To demonstrate the benefits of supplementary conductive cooling to food by using heat pipes fixed at the undersurface of a shelf with a spanwise spacing of 100 mm, the temperature of food samples in such a shelf was measured and compared with temperature measurements of food samples in the same place of a shelf without heat pipes. The experiment was carried out within a typical convective multi-deck type display cabinet, for which shelf 4 was chosen to conduct such a comparison study as shown in Fig. 8. During the experiments, the average ambient conditions within the laboratory were 17 °C dry bulb, 12.5 °C wet bulb of temperature and 995 mbar of atmosphere.

Food temperatures were measured by using K-type thermocouples which were placed at the centre of the "M-package" food samples in accordance with BS EN 441-4: 1995 [3]. The food samples are constructed from tylose with their dimensions of 200 mm × 100 mm × 50 mm shown in Fig. 9. The thermocouples were calibrated between their work temperature range (from −5 to 10 °C) with a step of 5 °C against a NPL thermometer in an ice bath with a temperature of 0 °C. The maximum measurement error associated with the thermocouples was ±0.15 °C.

3.3. Results and discussion

The temperature variations with time of 15 locations were tested under the condition with heat pipes (N4-18) and without heat pipes (N(4)-(18)). The selected positions are shown in Fig. 9. Typical results of the experiments are shown in Figs. 10–13. The temperature variation with time in the same position for sample (N4-7) and N(4)-(7)) is shown in Fig. 10. It is shown that in the measured time period, the core temperature of the food sample N4 with heat pipes is 5 °C lower than N(4) without heat pipes and the core temperature of the food sample N6 is 3 °C lower than N(6). The temperatures are reduced to 3.5 degree averagely. Similar results for N5-18 are shown in Figs. 11–13, respectively. Generally, the tests results indicate that the core temperature of the food sample reduction of approximately 3.0 to 5.5 °C can be achieved. It is well-known that food temperature reductions would have a significant effect on food safety particularly if food can be kept below 4 °C, which is the lowest temperature that the vast majority of bacteria can proliferate [21]. An efficient cooling of the food may also be enable the refrigeration system to operate at higher evaporation temperature and this lead to a reduction of energy consumption.

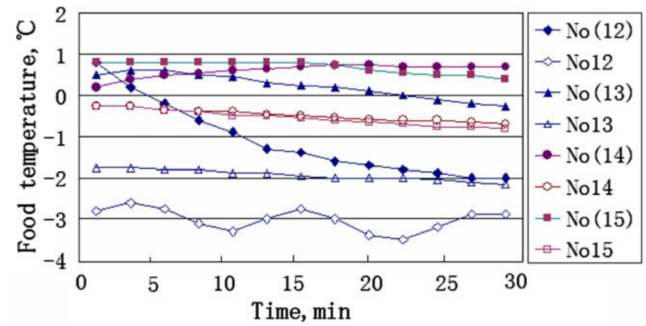

Fig. 12. Food temperatures on the same position with and without heat pipes (N12-15).

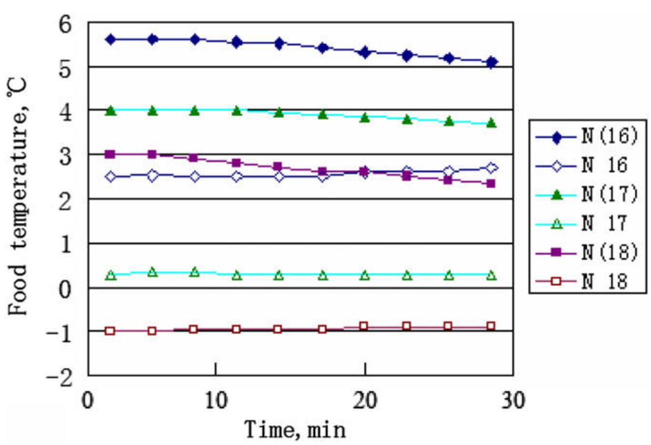

Fig. 13. Food temperatures on the same position with and without heat pipes (N16-18).

4. Phase change materials application in a combined display cabinet shelf

4.1. The design of innovative display cabinet shelf

In spite of heat pipes applied in an open-type display cabinet can lead to a significant reduction in core food temperature during the working cycle, there is obvious core temperature rise of the food during defrost period. To reduce drastically food temperature rise during defrost period, a technical concept is proposed that phase change material (PCM) be filled in the display cabinet shelves, which has a high latent heat between solid and liquid phase change. In the normal working time, the PCM is solidified when it is cooled from cold air. And during defrost time, the PCM melts and absorbs heat from the cabinet, leading to a reduction of its temperature rise. In this study, de-ionized water added with borax is used as PCM, and the phase change temperature varies with the increase of weight ratio of borax (Fig. 14). As can be seen there when the weight ratio of borax is 2%, the highest phase change temperature (−0.5 °C) can be achieved. And therefore, PCM in this design are constructed from de-ionized water (98%) and borax (2%). In order to test the effects of both PCM material and heat pipe, a special shelf with nine cavities filled with PCM and eight heat pipes are restructured for the testing display cabinet as shown in Fig. 15.

4.2. Experimental investigations of combined display cabinet shelf with heat pipes and PCM

Tests are carried out in the specified climate room that is similar to experimental investigations of display cabinet shelf only with

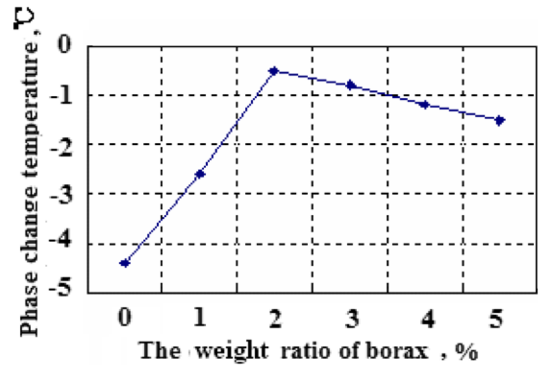

Fig. 14. The phase change temperature of PCM.

heat pipes. The experimental points measured in the study are the same as shown in Fig. 5 but only shelf 4 is the novel combined shelf. The collected data points from the two-minute intervals are averaged into one-hour blocks for each 24-hour period. The defrost cycle is 6 h. Tests have been performed to compare a series of conventional shelf to the new combined shelf in the same display cabinet.

4.3. Results and discussion

Fig. 16 shows the average temperature variation measured at the core of the food. The food temperatures all rise during defrost time because of the higher cooling load following each defrost in three systems: original cabinet, cabinet with heat pipe and cabinet with heat pipe & PCM When the heat pipe and PCM are combined, the average product temperature fluctuates more smoothly, and the food temperature rise during defrost time reduces by 1.5 °C (from 1.8 to 0.3 °C) compared to conventional cabinet. The temperature fluctuation of the system with combined heat pipe and PCM is less than that with only heat pipe. This is because the PCM can absorb some heat due to its thermal capacity during the defrost time. During frost time PCM releases some cold load which is stored in it to compensate the heat load released from the refrigeration system during the defrost time. It should be noted that the temperatures shown in Fig. 16 is the food temperature. The PCM temperature during the defrost period is lower than that of food, hence, phase change of PCM occurs during the defrost period which had been observed via s small glass window set up in the shelf.

The food temperature differences between front-back row and right-left of three designs (including original design, design only with heat pipe and design with heat pipe combined PCM) are shown in Fig. 17. It can be found that the temperature difference between front-back parts is reduced by 1.4 °C (from 3 °C to 1.6 °C) for design with heat pipe and PCM compared to original design and the corresponding temperature difference between right–left is 1.7 °C from 2.5 to 0.8 °C. Generally speaking, the temperature difference can be reduced with the two proposed design compared with the original design and the temperature difference reduction is more significant for right-left part than front-back part.

The cabinet power variation with time of original and reconstructive cabinet (using a combined shelf) is shown in Fig. 18. The power of cabinet with a combined shelf is basically the same as the original cabinet power. It means that the using of heat pipes and phase change materials (PCM) can lead to a temperature reduction of core food, an improvement of temperature distribution uniformity and a reduction in temperature rise during defrost period without energy penalty. The lower and more uniform food temperature obtained by using heat pipes and PCM without energy

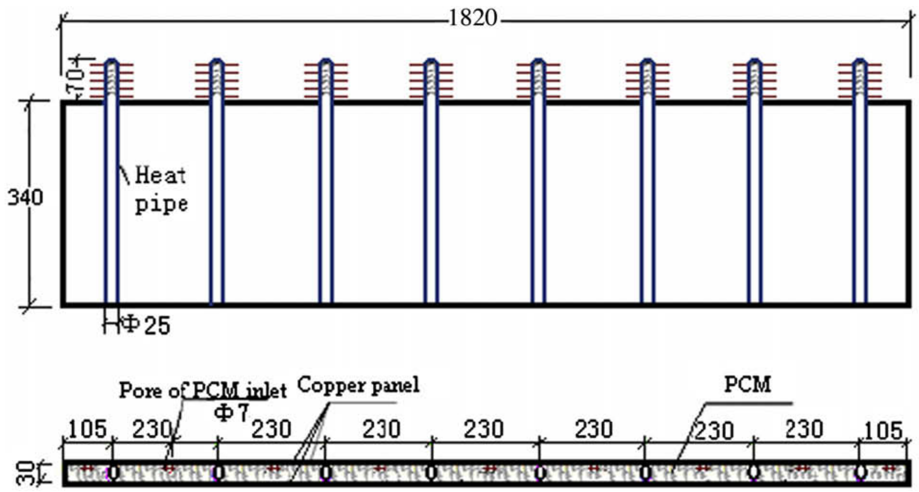

Fig. 15. The re-constructed shelf 4 with heat pipes and PCM.

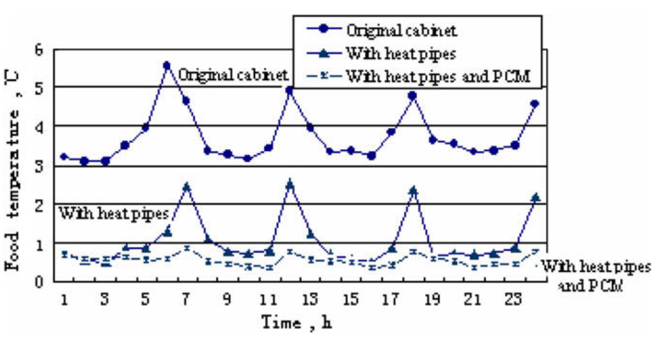

Fig. 16. Food temperature variation with time.

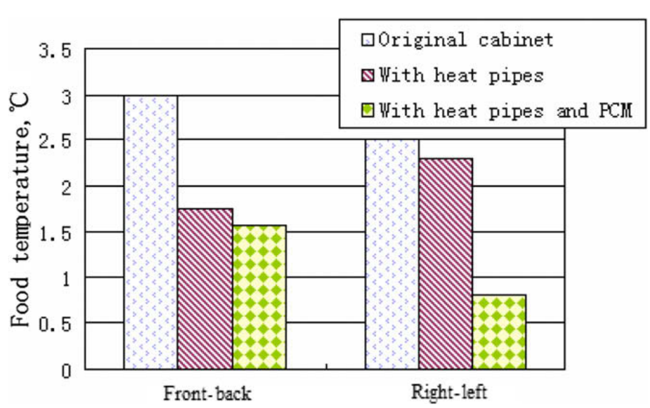

Fig. 17. Space food temperature differences between the conventional shelf and combined shelf.

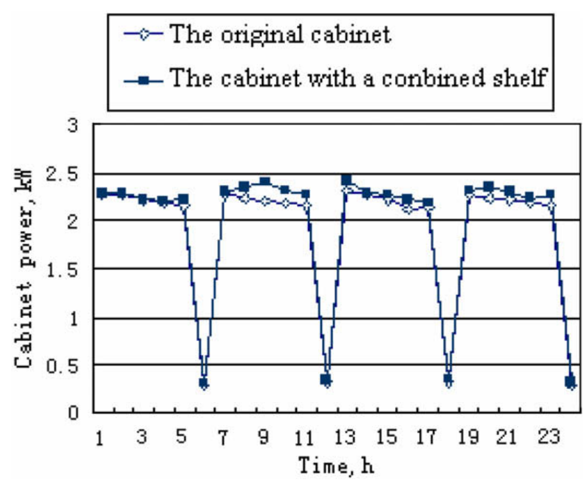

Fig. 18. Cabinet power consumption.

penalty may imply that it is possible to raise the evaporation temperature in a certain extent while still keep the required cooling conditions for the cabinet.. According to Faramarzi and Woodworth [27], for every 1 °C increase in evaporation temperature that can be achieved in a display cabinet, the coefficient of performance (COP) of refrigeration system connected to the display cabinet can be improved by 14 percent.

5. Conclusions

An innovative combined cabinet shelf (using heat pipes with new structure and appropriate PCM) is proposed and the corresponding performance is verified with experiments. It can be concluded that heat pipes with inclined condenser in one end used in a refrigerated display cabinet can produce a profound effect in reduction of food temperatures by approximately 3.0 to 5.5 °C. Furthermore, the use of heat pipes combined with PCM can reduce food temperature rise by 1.5 °C during defrost period and improve food temperature uniformity. The lower and more uniform food temperature obtained without energy penalty in this novel design presents very significant advantages in terms of energy reductions and food quality improvement.

Further research is necessary to choose more appropriate heat pipe working fluid and PCM, and to reveal the way of an approximate optimum design for different display cabinet. These works are underway in the authors group as the continuing research.

Acknowledgements

The fifth and sixth authors acknowledged the support from the National Key Project of Fundamental Research of China (G2007CB206902, G2006CB601203). The first author would like to thank Professor G.G. Maidment of London South Bank University for his help in research when the first author was a visiting scholar in LSBU.

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