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Experimental investigation of the performance of cool storage shelf for vertical open refrigerated display cabinet

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ABSTRACT

In order to improve the performance of refrigerated display cabinet, decrease the food temperature, improve the uniformity of food temperature and restrain the temperature fluctuation during the defrosting time, a new kind of composite shelf is designed for the food vertical open refrigerated display cabinet (VORDC), which is based on the heat pipe technology and the cool storage characteristics of phase change materials (PCMs) among the heat pipes. Experimental results show that the novel composite shelf can enhance the heat transfer between food and shelf, reduce the core temperature of food, decrease temperature fluctuation in defrosting process and reduce the temperature difference along height, width and depth direction. Compared with the normal shelf, the temperature differences of food packages on both sides of the composite shelves (RT3, RT4 and RT5) are reduced by 40%, 80% and 40%, respectively. The average temperature of food packages is reduced by 13.7–32% and the temperature fluctuation of food packages is reduced by 53.3–83.3% during defrosting. For these kinds of composite shelves, the temperature of food packages of RT4 composite shelf is lowest, and the average temperature of food packages at each layers and rows are controlled in 5 °C. This novel composite shelve can effectively reduce the temperature rise during defrosting, and improve the performance of VORDC obviously.

1. Introduction

Temperature heterogeneity, with non-uniform airflow in the vertical open refrigerated display cabinet (VORDC) has been investigated in many studies. This heterogeneity was partly due to the position of the product inside the cabinet, the fluctuation of the ambient temperature in the supermarket and the surrounding condition of the display cabinet [1], another important factor is the structure of the VORDC, for instance, the rear row near the perforated back panel (PBP) was submitted to lower air temperature compared with the front row [2]. This heterogeneity could directly influence the food quality, safety and the shelf life. In order to provide high organoleptic quality of products, it is necessary to decrease the inner temperature and improve its uniformity inside the VORDC [3].

Evans et al. [4] observed that the most high temperature packages (97%) were located on the front and the largest numbers (60%) of them were at the front base. The temporal variation of the air temperature inside the display cabinet was partly due to the "on/off" compressor cycle and partly to the incoming ambient air via vortices. The latter one contributed to the rapid velocity fluctuations which were greatest in the mixing layer of the air curtain [5]. Morelli et al. [6] investigated that 70% of the time-temperature profiles of the product exceeded 7 °C and considered it as the maximum acceptable temperature. Kou et al. [7] presented thermograph mapping of spatial and temporal temperature profiles of a commercial open refrigerated display cabinet in detail, the results showed that the effect of ambient temperatures and the relatively large temperature variation between samples located on the front rows and those at the back rows appeared to be the major technical challenges hindering the compliance of Food and Drug Administration Food Code without freezing the products. The thermal barrier between the refrigerated display cabinet and the ambient environment was provided by one or more air curtains. Cold air curtains could provide not only cooling capacity but also insulation from ambient air. These air curtains could cause a significant entrainment of warm air [8]. Gaspar et al. [9] reported that the infiltration load through the air curtain was responsible for a major percentage of about 72%. The indoor environment greatly influenced the performance of the VORDC through the air curtains. A

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survey showed that for a 5% reduction in store relative humidity, the display cabinet refrigeration load was reduced by 9.25%, and the total store energy load was reduced by 4.84% [10]. Chang et al. [11] pointed out that the food package temperature rose about 0.6 °C when the ambient temperature increased by 2 °C. The food package temperature rose about 0.9 °C, when the ambient humidity increased by 20%. Laguerre et al. [12] studied the influence of ambient under different temperatures and reported that the influence of radiative temperature was more significant for the load located at the front of VORDC. Some researchers also investigated the performance of the VORDC from the view of its structure, Wu et al. [13] performed the back panel structure on the performance of fluid flow and heat transfer of vertical open refrigerated display cabinets (VORDC), the results showed that the suitable porosities in the back panel among the shelves could improve the uniformity of products temperature in the VORDC. Wu et al. [14,15] applied a multi-scale approach to investigate the effect of heating, ventilation and air conditioning (HVAC) system on the energy consumption of the VORDC and the HAVC, their results showed that the energy input in the VORDC system decreased by 23.4%, and the highest product temperature reduced by 0.4 °C when the diffuser supply air velocity of the HVAC system increased from 2.0 m/s to 3.5 m/s.

In recent years, researchers had investigated the feasible application of different kinds of phase change materials (PCMs) to improve the performance of the VORDC and domestic refrigerators [16–18]. PCMs were capable of storing and releasing large amounts of energy by melting and solidifying at a certain temperature and were characterized by their transition temperature range, their transition were related with enthalpies, a measure of the internal energy storage, and their conductivity, relating with the energy transfer rate [19]. Equipment integrated with PCMs had the potential to increase the energy efficiency of the system and made significant contributions to electrical energy consumption. This could be achieved by reducing compressor cycling frequency and on/off cycling losses. The storage ability of the refrigeration equipment maintained the product temperature within a safe temperature range in case of electrical power failure [20]. Azzouz et al. [21,22] experimentally investigated the performance of a household refrigerator using a PCM. In order to improve the efficiency of the refrigerator, the PCM was placed on the backside of the evaporator. This could provide a storage capacity allowing several hours of refrigeration without power supply. The analysis of the results showed a significant improvement of performance compared with a conventional system. Alzuwaid et al. [23] investigated the performance of a refrigerated display cabinet integrated with the PCMs. The PCMs (water gel) were charged into two single panel radiators, installed immediately after the cabinet evaporator in the main back flow channel. The results showed that it could be achieved up to 5% of energy savings and lower cabinet temperatures by installing the PCMs radiators. Furthermore, the utilization of PCMs in the shelf of VORDC and freezers had been studied in nowadays. Lu et al. [24] proposed a novel design for the VORDC's shelf which the heat pipes and appropriate PCM were equipped in the shelf. The food temperature in the new shelf with heat pipes and PCMs (de-ionized water added with borax) was reduced by 1.5 °C during defrosting period, and the new shelf improved the food temperature distribution characteristic while the energy consumption changed little. In general, refrigerated food products were often stored between 0 °C and 6 °C. Thus, the phase change temperature of PCMs should be chosen in the range of 4–8 °C [25]. The PCMs were therefore liquid at room temperature so its handling was complicated and became an issue for some applications. The thermal energy storage of PCMs as sensible or latent heat was an efficient way to conserve energy [26]. While, storage of latent heat using organic PCMs offered greater energy storage density in comparison to inorganic materials [27,28].

From the above literature reviews, it can be seen that previous researchers have make great efforts to improve the performance of VORDC by optimizing structure and refrigerated system. However, few literatures take into account of the organic PCMs for the cool storage to improve the performance and the uniformity of food temperature of VORDC. So this paper considers candidate PCMs for application in the VORDC for product temperature ranges from 0 °C to 6 °C, where the latent heat of PCMs plays an important role in preserving perishable food.

2. Test facilities and experimentation

2.1. Phase change materials

The storage of latent heat using organic phase change materials (PCMs) offers great energy storage density than that of inorganic materials [27], three kinds of organic PCMs (RT3, RT4 and RT5) are selected in the present investigation. These PCMs are paraffin waxes produced by RUBITHERM Company. These PCMs are made up of different straight-chain alkanes, including *n*-dodecane, *n*-tridecane, *n*-tetradecane, *n*-pentadecane, *n*-hexadecane, heptadecane, *n*-octadecane, etc. Three kinds of PCMs are composed of different weight ratio of alkanes mentioned above. The thermal physical properties of PCMs are shown in Table 1. Partial enthalpy distribution of the PCMs is provided by the company [29]. The phase change temperatures of three PCMs are 2.5 °C, 3.8 °C and 5.2 °C, respectively.

2.2. Heat pipes

Heat pipes have been widely used in the waste heat recovery, and also in some applications for food storage. In this paper, heat pipes are employed at the undersurface of the shelf to remedy the non-uniformity of temperature distribution. The heat pipe consists of evaporator section and condenser section, these two sections form a sealed container. A small amount of working fluid and a wick structure are filled in the sealed container. The operation principle of the heat pipes is shown in Fig. 1. The fin height of condenser section is 10 mm, the fin pitch of condenser is 3 mm, and the fin number of condenser is 20. Here the working fluid used in heat pipes is methanol. The wick structure is copper wire net, the number of the copper wire net is 6, and the net mesh number is 60. As shown in Fig. 1, the evaporator section of heat

Table 1
Thermal properties of phase change materials.

	RT3	RT4	RT5
Melting area/°C	2–5(mean peak: 4)	2–4(mean peak: 4)	1–6(mean peak: 5)
Solidification area/°C	3–1(mean peak: 3)	4–2(mean peak: 4)	6–1(mean peak: 5)
Heat storage capacity ±7.5%/(kJ/kg)	198(−5 to 10 °C)	182	198
Specific heat capacity/(kJ/kg K)	2	2	2
Solid density/(kg/m^3)	880	880	880
Liquid density/(kg/l)	0.77	0.77	0.77
Heat conductivity/(W/(m K))	0.2	0.2	0.2