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The novel use of phase change materials in an open type refrigerated display cabinet: A theoretical investigation

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HIGHLIGHTS

- 2D CFD models were developed for a refrigerated display cabinet with or without integrated PCM.
- The simulation results showed that energy savings could be achieved for the cabinet with PCM.
- Further benefits included greater stabilization of product temperatures for the cabinet with PCM.
- The validated models can be used to evaluate the cabinet performance and control strategies.

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ABSTRACT

In this paper, 2D CFD models have been developed for a prototype refrigerated open type multi-deck display cabinet with and without integrated phase change material (PCM). The models can predict the effect of adding a PCM container on cabinet efficiencies, air temperature distributions, product temperatures and air flow patterns inside the cabinet at a range of operating conditions including space air temperatures and evaporator air velocities. To validate the cabinet models, the prototype cabinet was mounted in an air conditioned chamber and extensive experiments were conducted at constant space air temperature and relative humidity. The cabinet models have therefore been validated through comparison with experiment results for air temperatures at different locations of the airflow path and of food products. Simulation results show that significant energy can be saved through the installation of a PCM container. Further benefits include greater stabilization of product temperatures during defrost periods for the modified display cabinet. Consequently, the validated models can be used to explore and analyse the cabinet performance and control strategies at various operating and design conditions.

1. Introduction

Open multideck refrigerated display cabinets (MDC) are extensively used in retail stores in the United Kingdom and around the world to store and display dairy and chilled food products within permitable temperatures. Such cabinets are common and preferable in terms of saving floor space whilst simultaneously maintaining a sizeable retailing surface. The total length of these display cabinets can reach up to 100 m in a typical superstore, altogether contributing considerably to its overall energy consumption. In the UK, around 35–45% of the total energy consumption of a typical supermarket is used for refrigeration purposes, and around 70% of this refrigeration energy is required for MDCs [1]. Correspondingly, such consumption can indirectly contribute towards a vast amount of CO_2 emissions. Meanwhile, if supermarket refrigeration systems were charged with HFC refrigerants such as R404A, a significant amount of CO_2 will be directly produced due to unavoidable refrigerant leakage. All these concerns are driving the demand for the development of sustainable refrigeration technologies, with particular focus on the MDCs in supermarkets.

Conventionally, there are a number of technology options to reduce the MDC cooling load and thus improve unit performance. These include the optimal air curtain designs, better air flow distributions inside the cabinet, appropriate refrigerant selections and high efficient cabinet evaporators etc. [2–4]. It is known that of the total cooling load in an MDC, over 70% is produced by infiltration from the external space to the cabinet inside through the air curtain. One way to reduce the infiltration load is to modify the air flow rate from the air curtain jet. Based on a validated 3D CFD model of an MDC, it was found that the optimum mass flow rate of the air curtain should account for about one third of the total air mass flow rate from the cabinet evaporator outlet [5]. In such circumstances, the rest of the air flow would penetrate from

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Nomenclature

C_p, c	specific heat capacity (J/(kg K)
H, h	enthalpy (J/kg)
k	turbulent kinetic energy (m^2/s^2)
K	thermal conductivity (w/m k)
L	latent heat (J/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
Q	capacity (W)
q	specific heat source (W/m^3)
Q_{source}	heat source (W/m^3)
S_k	source term of k (kg/m s^3)
S_ε	source term of ε (kg/m s^4)
S	source term (W/m^3)
T	temperature (K)
t	time (s)
U, u	momentary velocity in x direction (m/s)
V, v	momentary velocity in y direction (m/s)
V	volume (m^3)
x	coordinate in x direction (m)
y	coordinate in y direction (m)

Greek symbols

μ	viscosity (Pa s)
α	thermal diffusivity (m^2/s)
Γ	diffusion coefficient
ε	turbulent kinetic energy (m^2/s^3)
β	liquid fraction
Δ	difference

Subscripts

evap	evaporator
l	liquid
ref	reference
S	*solid*
W,w	*with PCM*
Wo,wo	*without PCM*
a	*air*
airon	*evaporator air on*
airoff	evaporator air off
k	turbulent kinetic energy (m^2/s^2)

the back flow channel into the cabinet through a perforated back panel. The interaction between air flows surrounding the cabinet will significantly affect cabinet performance and food storage; however, this could be evaluated by using validated CFD modelling technology and thus optimising the designs [6,7]. A validated cabinet model could be an efficient tool to examine cabinet performance, conduct optimal designs and most importantly, imitate actual cabinet operation. Accordingly, a compete cabinet model was developed by integrating two parts of cabinet sub-models in which a CFD model was utilised to predict the air flow dynamics surrounding the cabinet from the evaporator outlet to the inlet while a detailed model was developed for the evaporator [8]. Such a complete model is believed more practical since unnecessary assumptions of boundary conditions at the evaporator inlet and outlet were disregarded.

On the other hand, the integrations of PCMs into refrigeration systems, and particularly refrigerated display cabinets, have attracted greater interest recently considering its potential energy savings and temperature uniformity control of food production storage [9,10]. A recent experimental investigation on an MDC with and without PCM integration revealed some benefits for the unit with PCM, including uniformity of food product temperatures, less compressor on/off frequencies and reduced power consumption [11]. The technology with PCM integration could be further improved by selecting and producing more appropriate PCMs in different refrigerated cabinets [12]. The applied PCMs were originally paraffin and water but when an additional agent (AgI) was added and mixed, the cabinet performance could be further improved in term of energy savings. In addition, further benefits were found experimentally when heat pipe technology was combined with PCM utilization in the cabinet [13], these being moderate food product temperature rises during the defrost period.

Although energy storage with PCMs can play an important role in the performance of refrigerated cabinets, much of the previous research in this area dealt with experiments with limited test conditions. To facilitate the application of PCMs in MDCs, detailed theoretical or modelling analyses need to be conducted so as to predict and evaluate the performance of cabinets with PCMs at larger-scale operating conditions. This will lead to optimal selections of PCMs, PCM heat exchangers and their installation. It is therefore the purpose of this paper to develop a detailed CFD model for the MDC with PCMs and validate the model with corresponding test results. The validated model then compares the performance with the same cabinet but without PCMs in terms of energy saving and food product temperature variations etc. Further development in this area will also be recommended. Regarding to the novelty of this paper, so far, to the authors' understanding there is not a validated simulation study on the integration of PCM with the refrigerated open-type display cabinets. In addition, this paper has firstly developed a complete dynamic CFD model for an open-type display cabinet with the integrations of PCM heat exchanger, thermostat control, defrost and cabinet evaporator and compressor. This dynamic model can therefore simulate and understand completely and accurately the actual cabinet operation and be used as an efficient tool to optimise the cabinet performance and PCM integration.

2. Experimental setup

An integral low-fronted multi-deck open display case was selected as an experimental prototype in this study (Fig. 1). The cabinet dimensions included 1.25 m × 0.85 m × 1.98 m (W × D × H), 3.15 m^2 refrigerated area and 1.5 m display opening height and was equipped with single air curtain situated from the top (base + 5shelves). The cabinet was loaded according to British standard (BS EN ISO, 23953-2: 2005) with test products used to simulate the thermal mass of food under real conditions. Those products were cooled by the low temperature air flow from the cabinet evaporator outlet which passed vertically in the back flow channel of the cabinet before reaching to the air curtain. Part of the air flow in the back channel emitted horizontally into the case inside through the perforated back panel and mixed into the air curtain and hence returned back to the evaporator inlet to be cooled again. The cabinet utilised off-cycle for defrost and required product temperature variation from 0 °C to +4 °C

The experiment design and setup had also been built according to the rules specified in BS EN ISO 23953-2: 2005 standard to measure air temperature and velocity and product temperature variation through the display cabinet. A series of preliminary experiments were prepared and carried out in order to find out the optimum operating setting and desirable air-off temperatures