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Modelling of Phase Change Material Implemented into Cold Storage Application

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ABSTRACT

Loss of electrical power for cold storage facilities leads to an increase in temperature and can result in the loss in quality and value of stored products. This paper proposes the use of a passive system integrated into the walls of the cold storage facility to limit the rise in temperature due to power loss. Experimental application of PCM into a domestic freezer has shown that the temperature rise during loss of power is limited. With PCM, the air temperature is kept constant at -8°C for 7 hours, compared to without PCM where the air temperature rises continuously and rises above -8°C in just 1 hour. Computational fluid dynamics (CFD) results show a reasonable match with experimental results. The CFD model is then extended to model a larger cold storage facility to show that PCM can have the same limiting effect on a larger scale application.

1. INTRODUCTION

It is important to maintain regular temperatures inside cold storage facilities and cold transport vehicles. Most frozen and chilled foods are sensitive to temperature fluctuations. For example, Russell et al (1999) state that for ice cream to have a smooth texture, one of the major requirements is to have small ice crystals. Studies by Flores and Goff (1999) and Donhowe and Hartel (1996) concluded that the size of ice crystals in ice cream is larger in samples stored in fluctuating temperature conditions.

A major contribution to the heat loadings for a cold store comes from heat penetrating the walls. The refrigeration system removes this heat load, but if there is a power failure, cooling is not provided to the stored product. Loss of electrical power could occur due to accidents, or could be due to implementation of demand side management schemes (DSM) to shift power usage to avoid high loads by the electricity supplier, or by the user to shift their electricity usage to off-peak pricing periods (electrical load shifting).

Phase change material (PCM) melts within a narrow temperature range (Farid et al, 2004), and absorbs a large amount of energy while in the transition state, thus minimizing the rise in the environment temperature (Khudair and Farid, 2004). PCM with a suitable melting temperature may be used to provide thermal capacity to maintain suitable internal temperature during power failure. PCM may also be used in load shedding applications to shift electricity usage to an optimum time.

Modelling of air flow and temperature distribution inside cold storage facilities based on Computational Fluid Dynamics (CFD) has been attempted. Moureh et al (2002) and Moureh and Flick (2004) modelled airflow pattern and temperature distribution in a refrigerated truck. Xie et al (2006) used a CFD package to simulate the velocity and temperature field in a 2D plane through a cold store. Hoang et al (2000) constructed a 3D model of a cold store using a commercial CFD package and modelled the air flow in the cold store. These models were constructed for steady state operation with constant cold air inlets to the cold storage areas. Nahor et al (2005) used a commercial CFD package to model the temperature change inside a cold store during cooling from ambient temperature. Tso et al (2002) used Fluent to solve for the temperature change with time during door opening in a refrigerated truck. Azzouz et al (2008) did not use CFD, but constructed a transient model for a refrigerator containing a PCM slab placed against its evaporator. Wang et al (2007) also described a transient model for a refrigeration circuit utilizing PCM heat exchangers in positions such as on the refrigerant line between the compressor and the condenser.

This paper aims to combine transient modelling of a 3D cold store using CFD with the inclusion of PCM panels in its walls. The effect on the change in air temperature during loss of electrical power (and thus loss of cooling) is investigated and validated for a domestic freezer and then extended to predict the transient performance of a typical cold store.

2. EXPERIMENTAL SETUP

For easier validation of the idea of using PCM to improve temperature stability in cold store, an Elba E150 vertical freezer (Fisher & Paykel, New Zealand) with dimensions 1207 mm H x 525 mm W x 575 mm D and a storage volume of 153 L was used. Anodized aluminium panels filled with PCM were placed against the walls of the freezer in the arrangement shown in Figure 1. A eutectic solution with a melting point of -15°C was used as the PCM. The freezer was allowed to reach a quasi steady state condition before the electrical power was stopped. This was done for the freezer with and without PCM panels.

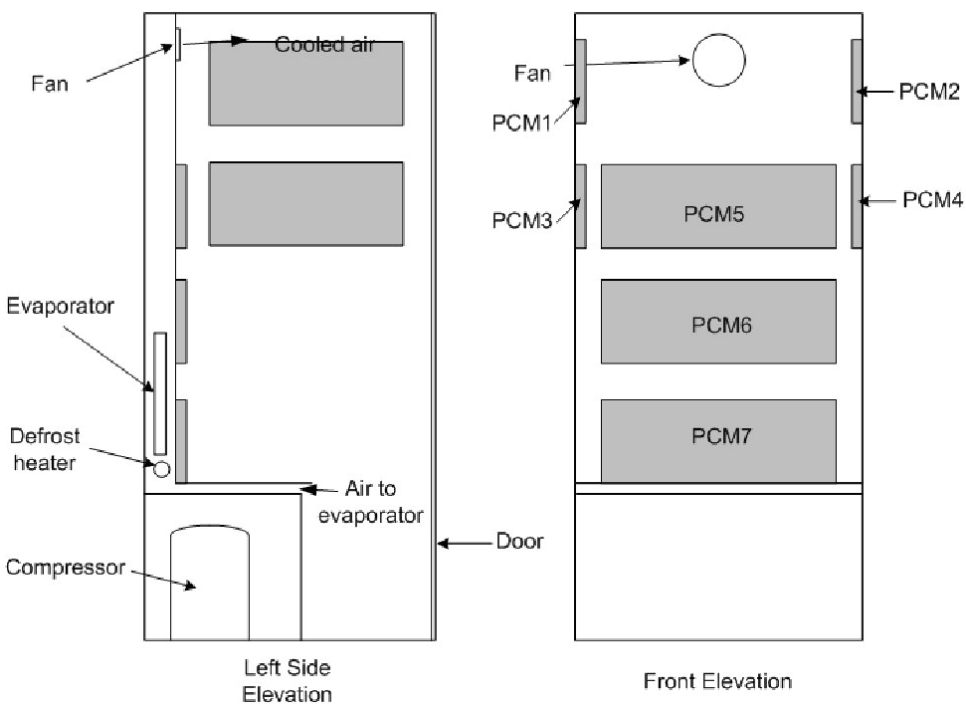

Figure 1: Front and side elevations of the freezer showing positions of the PCM panels

3. MODELLING DETAILS

Ansys CFX 11.0 (Ansys Inc, Pennsylvania, USA) was used for 3D CFD modelling.

3.1 Governing equations

The fundamental equations governing conservation of mass, momentum and energy are used in solving for the air flow and temperature changes occurring in the modelled systems.

For a stationary control volume, the rate of change of stored mass is equal to the flow of mass inwards through the volume's boundaries. The partial differential equation representing the conservation of mass is given in equation (1).

$$\frac{\partial \rho}{\partial t} + \nabla . \rho v = 0 \tag{1}$$

For momentum, the time rate of change of momentum of a material region is equal to the sum of the forces on the region. For a stationary control volume this is described by equation 2.

$$\int_v \rho \frac{Dv}{Dt} dv = \sum F \tag{2}$$

The partial differential form of the conservation equation when applied to an infinitesimal volume which is allowed to shrink to zero is described by equation 3.

$$\rho C_P \frac{\partial T}{\partial t} = \nabla . \left(k \nabla T \right) \tag{3}$$

3.2 Incorporation of PCM

A simplified effective heat capacity (EHC) approach developed by Farid et al (1998) was employed to model the phase change effect. This was done to avoid the need to model phase change using a two phase approach. The EHC method is described in full in the above-mentioned reference. The PCM was assumed to have a melting range from -16.4 to -14.4°C and a latent heat of 285,000 $J.kg^{-1}.K^{-1}$. This latent heat was assumed to spread over the 2°C melting range shown in Figure 2.

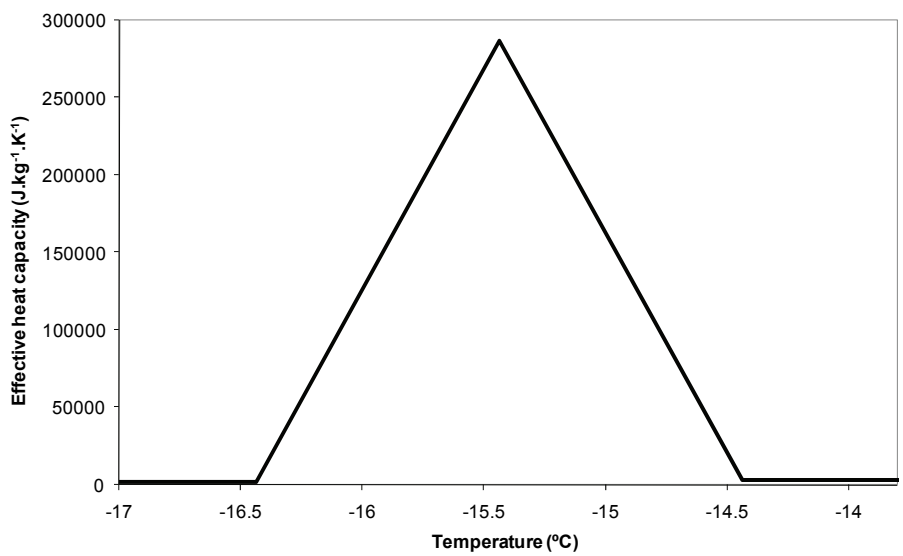

Figure 2: Latent heat expressed as an effective heat capacity as a function of temperature

3.3 Modelling of Freezer

The modelled geometry (shown in Figure 3) utilized a symmetry plane to halve the number of computations required and was done for the freezer with and without PCM. Initial conditions for the air in the freezer were set at -22°C while the PCM temperature was set to -20°C (measured experimentally). The modelled geometries consisted of the internal freezer air, PCM, and metal walls of the freezer. The insulation of the walls was not included as a modelled geometry; instead it was incorporated into the boundary conditions. The boundary conditions are described as:

- Symmetry at the walls, PCM and air domains for modelling half the geometry
- Solid/fluid interface between the walls and the air
- Solid/fluid interface between the PCM panels and the air
- Solid/solid interface between the PCM and the walls
- Heat transfer coefficient and external temperature at the external wall boundaries:
  - $h = 0.45\ W.m^{-2}.K^{-1}$, based on external free convection heat transfer coefficient of $10\ W.m^{-2}.K^{-1}$ and insulation thermal conductivity of $0.019\ W.m^{-1}.K^{-1}$ having thickness = 4 cm.
  - $T_{amb} = 19°C$

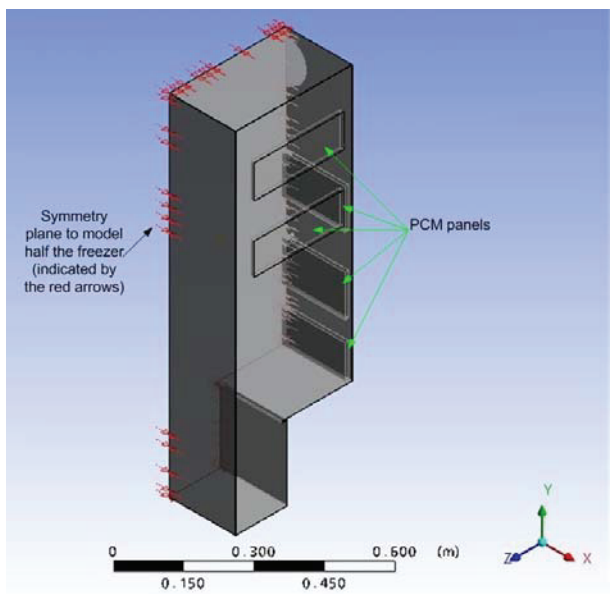

Figure 3: 3D geometry of the freezer constructed for the CFD model

3.4 Modelling of Cold Store

The geometry of the cold store is shown in Figure 4, which shows that only half the cold store was modelled due to symmetry. The model was run with and without PCM. The modelled geometries consisted of the internal air, thin metal wall, PCM and insulation. The model was first run at steady state with an air inlet at the fan operating at -18°C and walls at initially -20°C. This was then used as the initial conditions for the transient power loss model. The boundary conditions are described as:

- Symmetry at the walls, PCM and air domains for modelling half the geometry
- Solid/fluid interface between the walls and the air
- Solid/fluid interface between the PCM panels and the air
- Solid/solid interface between the PCM and the walls
- Heat transfer coefficient and external temperature at the external wall boundaries:
  - $h = 10\ W.m^{-2}.K^{-1}$
  - $T_{amb} = 19°C$

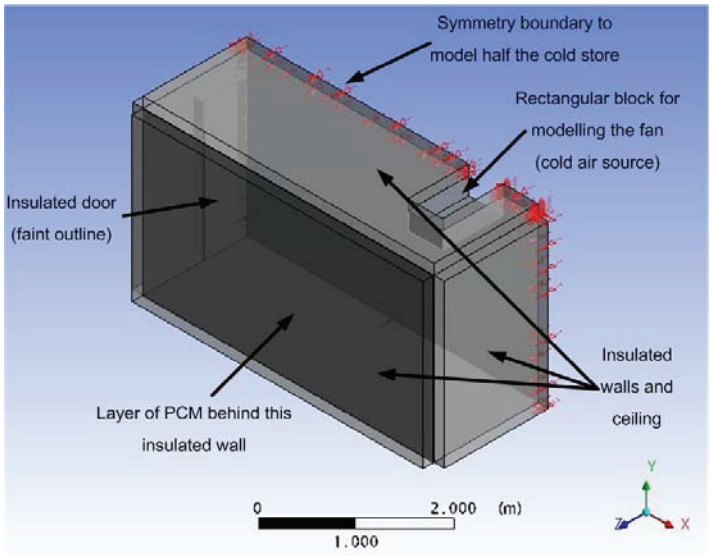

Figure 4: 3D geometry of the cold store constructed for the CFD model

4. RESULTS AND DISCUSSION

4.1 Modelling of Freezer

The measured and CFD predicted change in air temperature in the freezer without PCM can be seen in Figure 5. An average of five thermocouple measurements was obtained from the experimental setup, whereas the average of the air domain for the CFD model was calculated from the temperature distribution. The results show reasonable agreement between the experimental and simulation results. There is a deviation between experimental and simulated results where the experimental air temperature flattens at 5°C. This flattening in temperature is likely due to frost inside the freezer. As the temperature increases, the frost melts and results in the air temperature flattening while the ice phase change is occurring, thus leading to the deviation between the experimental and simulated results.

PCM panels were then placed into the freezer and implemented into the model. The results again show reasonable agreement between the average air temperatures as seen in Figure 6. With the implementation of PCM into the freezer, the rise in temperature during loss of electrical power is limited. The air temperature is kept at a constant temperature of -8°C for 7 hours, whereas without PCM (Figure 5), the air temperature rises continuously to above -8°C in 1 hour.

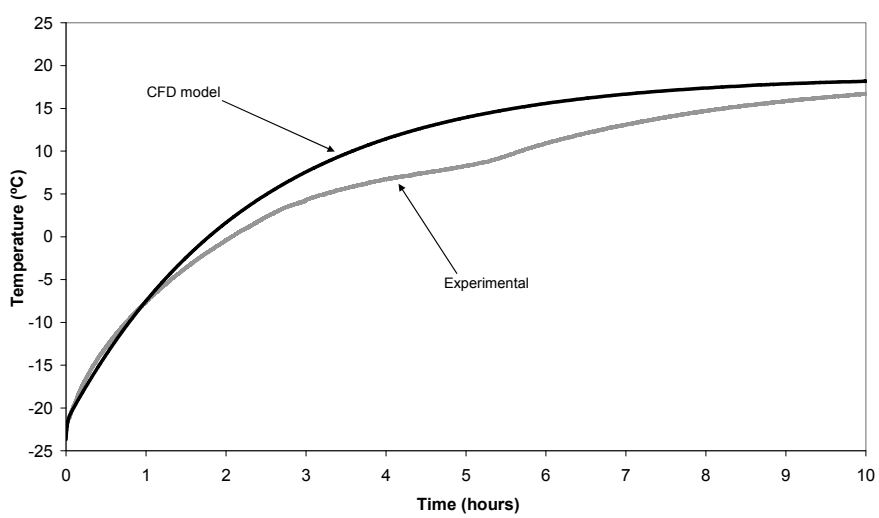

Figure 5: Experimental and simulated results for the change in average freezer air temperature without PCM

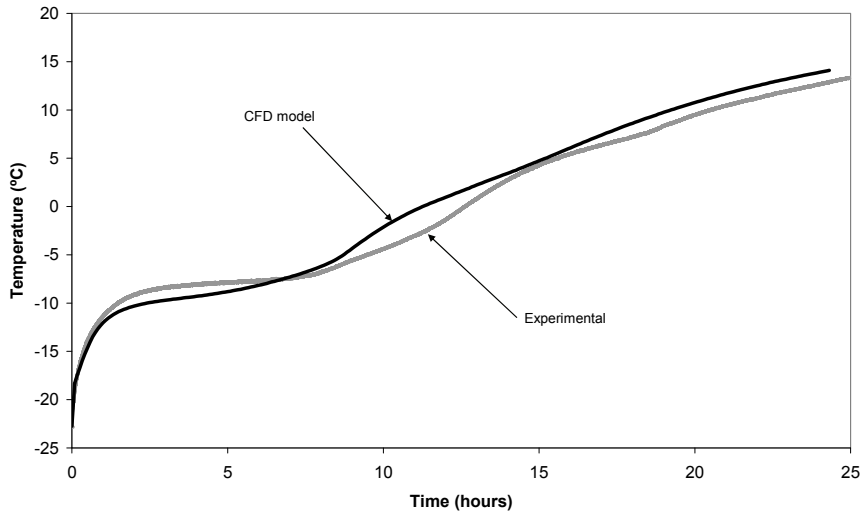

Figure 6: Experimental and simulated results for the change in average freezer air temperature with PCM panels

Thermocouples placed in the geometric centre of the panels were used to monitor the change in PCM temperature and these are shown along with those found through the simulation as shown in Figure 7. The shape of the simulated PCM curves shows the behaviour of the PCM melting over the specified melting range and resembles the curves from the experimental measurements. The melting times of the simulated PCM panels are longer than measured experimentally. However, it can be noted that for one of the experimental measurements, there is a second melting plateau close to 0°C (as indicated in Figure 7). The length of this melting time added to that at the PCM melting point (-16°C) extends the total melting time of the PCM panel and brings it to match the simulated melting time. The second melting could be due to separation in the PCM sample or a change in composition of the PCM. When the PCM composition deviates from the eutectic composition, the PCM melts over a larger temperature range with two distinct melting points.

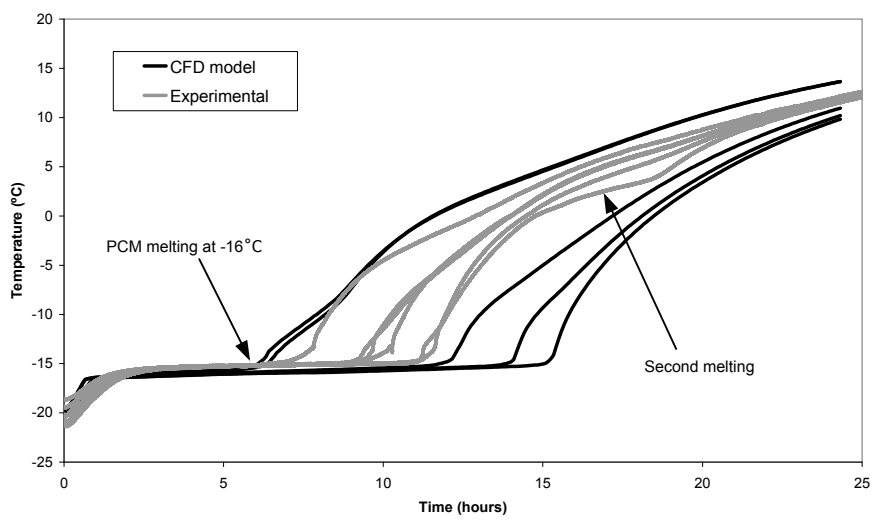

Figure 7: Experimental and simulated results for the change in PCM panel temperatures

In conclusion, the PCM behaviour has been modelled successfully using the EHC method incorporated into the CFD model of the freezer. This shows that CFD can be used to predict the transient behaviour in a freezer containing PCM panels during power loss.

4.2 Modelling of Cold Store

Following the success of modelling the domestic freezer, a 3D model of a cold store was constructed for the geometry shown in Figure 4. Figure 8 shows a comparison of the temperature change due to loss of electrical power with and without PCM in the cold store. As found with the domestic freezer, the PCM limits the rise in air temperature inside the cold store. Without PCM, the air temperature rises steadily. In comparison, the air temperature in the cold store with PCM reaches -7°C and remains constant for 60 hours. The PCM temperature rises slowly as the PCM melts over this 60 hour period. Once the PCM has finished melting, the air and PCM temperature rises steeply. This model shows that PCM can be useful in limiting the temperature rise during loss of power to cold stores. Increasing the available surface area of the PCM through the use finned surfaces will reduce the cold store temperature further and make it closer to PCM temperature.

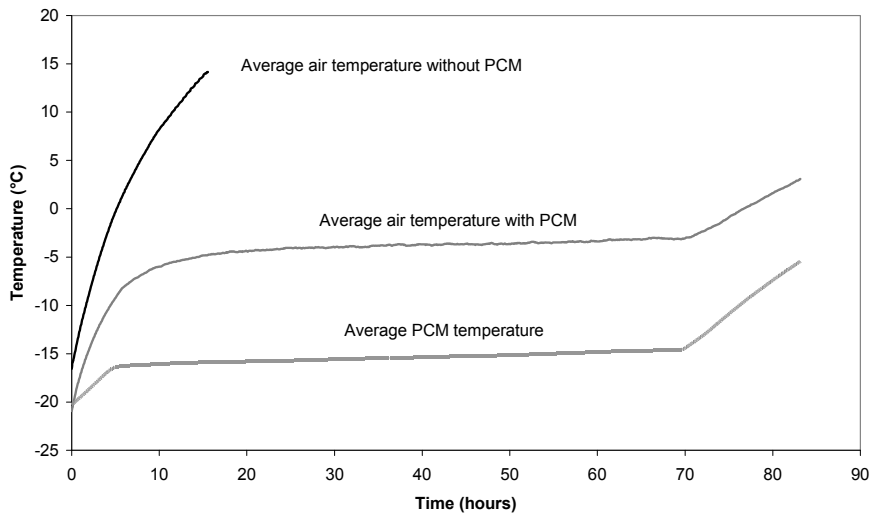

Figure 8: Simulated results for the change in average cold store air temperature with and without PCM panels along with the change in average PCM temperature

5. CONCLUSIONS

This paper has shown that use of PCM in the walls of a freezer and cold store can limit the rise in air temperature inside the cold storage facility during loss of electricity. As the PCM melts, it absorbs the thermal load that enters the cold storage space, thus limiting the rise in the cold store temperature. These results show that PCM could be utilised to limit temperature rises during loss of electrical power, which may occur due to an accidental power loss or done purposely to achieve electrical load shifting. CFD modelling can be used to predict the temperature change during power loss and the results show a reasonable match with experimental results conducted on a domestic freezer. The modelling was extended to predict the temperature changes in a large cold store and the results also indicate that PCM can limit the rise in air temperature. This modelling work can be extended to investigate the effects of increasing the surface area, use of fins and positioning of PCM panels in different way.

NOMENCLATURE

ρ	density	($kg.m^{-3}$)	**Subscripts**
t	time	(s)	amb ambient
v			
F	force	(N)	

T	temperature	(K)
C_P	specific heat capacity	($J.kg^{-1}.K^{-1}$)
k	thermal conductivity	($W.m^{-1}.K^{-1}$)
Δx	thickness	(m)
h	heat transfer coefficient	($W.m^{-2}.K^{-1}$)

REFERENCES

Azzouz, K., Leducq, D., Gobin, D., 2008, Performance enhancement of a household refrigerator by addition of latent heat storage, *Int. J. Refrig*., vol. 31, no. 5: p. 892-901.

Donhowe, D.P., Hartel, R.W., 1996, Recrystallization of ice during bulk storage of ice cream, *Int. Dairy J*., vol. 6, no. 11-12: p. 1209-1221.

Farid, M.M., Khudhair, A.M., Siddique, A.K.R., Said, A., 2004, A review on phase change energy storage: materials and applications, *Energy. Covers. Manage*., vol. 45, no. 9-10: p. 1597-1615.

Flores, A.A., Goff, H.D., 1999, Recrystallization in ice cream after constant and cycling temperature storage conditions as affected by stabilizers, *J. Dairy Sci*., vol. 82, no. 7: p. 1408-1415.

Hoang, M.L., Verboven, P., De Baerdemaeker, J., Nicolaï, B.M., 2000, Analysis of the air flow in a cold store by means of computational fluid dynamics, *Int. J. Refrig*., vol. 23, no. 2: p. 127-140.

Khudhair, A.M., Farid, M., 2004, A review on energy conservation in building applications with thermal storage by latent heat using phase change materials, *Energy Convers. Manage*., vol. 45, no. 2: p. 263-275.

Moureh, J., Flick, D., 2004, Airflow pattern and temperature distribution in a typical refrigerated truck configuration loaded with pallets, *Int. J. Refrig*., vol. 27, no. 5: p. 464-474.

Moureh, J., Menia, N., Flick, D., 2002, Numerical and experimental study of airflow in a typical refrigerated truck configuration loaded with pallets, *Comput. Electron. Agric*., vol. 34, no. 1-3: p. 25-42.

Nahor, H.B., Hoang, M.L., Verboven, P., Baelmas, M., Nicolaï, B.M., 2005, CFD model of the airflow, heat and mass transfer in cool stores, *Int. J. Refrig*., vol. 28, no. 3: p. 368-380.

Russell, A.B., Cheney, P.E., Wantling, S.D., 1999, Influence of freezing conditions on ice crystallization in ice cream, *J. Food Eng*., vol. 39, no. 2: p. 179-191.

Tso, C.P., Yu, S.C.M., Poh, H.J., Jolly, P,G., 2002, Experimental study on the heat and mass transfer characteristics in a refrigerated truck, *Int. J. Refrig*., vol. 285, no. 3: p. 340-350.

Wang, F., Maidment, G., Missenden, J., Tozer, R., 2007, The novel use of phase change materials in refrigeration plant. Part2: Dynamic simulation model for the combined system, *Appl. Therm. Eng*., vol. 27, no. 17-18: p. 2905-2910.

Xie, J., Qu, X.H., Shi, J.Y., Sun, D.W., 2006, Effects of design parameters on flow and temperature field of a cold store by CFD simulation, *J. Food Eng*., vol. 77, no. 2: p. 355-363.