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Experimental analysis of a cold store integrated with phase change material: a case study

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Thermal energy storage systems provide the potential to attain energy savings and reduce the environmental impact related to energy use. In this respect, phase change materials (PCMs) work as ''latent heat storage units'' which store or release large amounts of thermal energy. The aim of the presented study is to determine the function of PCM in an actively operating cold store at -18ºC during an operational failure or electricity shortage. The indoor temperature of the cold store, PCM temperature in the macrocapsules and ambient temperature are the continuously monitored parameters in this research. The results indicate that PCM macrocapsules, which cover 10% of the total heat transfer surface area, provide significant temperature maintenance under all ambient conditions and prominently extend the time to break the cold chain.

Keywords: cold store, phase change material (PCM), frozen storage, thermal energy storage, temperature maintenance

INTRODUCTION

In the refrigeration and heating systems, latent heat storage is frequently used due to its high energy saving potential and high system efficiency. Since it requires a smaller volume per unit of stored energy and has a narrow temperature range for heat transfer via phase change, latent heat storage systems have attracted the interest of many researchers and many studies have been conducted on this subject [1-7]. Phase Change Materials (PCMs) are used to store energy and balance temperature changes in different fields, including electronic devices, automotive industry, buildings and heat storage systems [8-10]. In recent years, PCMs have also become a widespread solution as an alternative cooling and heating method in applications [11-13].

In frozen storage applications, aqueous salt solutions are one of the basic PCMs. However, adjusting their chemical composition to obtain desired thermal properties, subcooling, corrosion and thermal stability are some of the main difficulties [14]. Using a convenient PCM combination and encapsulation tool may lead to major benefits without the need for extra design changes in refrigeration systems or enclosures. Among these benefits, longer-term autonomy of the refrigerator, optimization of the compressor operating time, maintaining homogeneous temperature distribution in the refrigerator in case of a breakdown and coefficient of performance (COP) increase can be mentioned [15-17]. As the PCM increases the COP by 25%, PCM macrocapsule thickness of 5 and 10 mm show the same effect due to partial freezing of the material [18,19]. In this sense, determination of the PCM thickness in relation to thermal load is an important parameter. For instance, the usage of PCM plates thinner than 5 mm is recommended for household refrigerators [20].

The aim of this study is to monitor the indoor temperature changes of an actively operating cold store under frozen storage condition at -18ºC in the presence and absence of PCM load to present the useful function of PCM during an operational failure or electricity shortage. Besides, the effect of different ambient air temperatures on temperature changes insurfaces. the cold store is also discussed in detail.

MATERIALS AND METHOD

The internal dimensions, i.e. the length, width and height (LxWxH) of the store are 212x113x218 cm, respectively. Within the cabin, the presented geometry in Fig.1a is established to circulate the air sweeping over the capsule surfaces. The side walls, ceiling and floor of the cabin contain polyurethane rigid foam blocks of 80 mm as main insulating material. Macrocapsules with PCM are mounted on the ceiling and the walls of the cabin and they cover about 10% of the total heat transfer surface area.

Fig.1b and Fig.1c show the positions of the sensors recording data and outer view of the cold store in the laboratory. The parameters measured by

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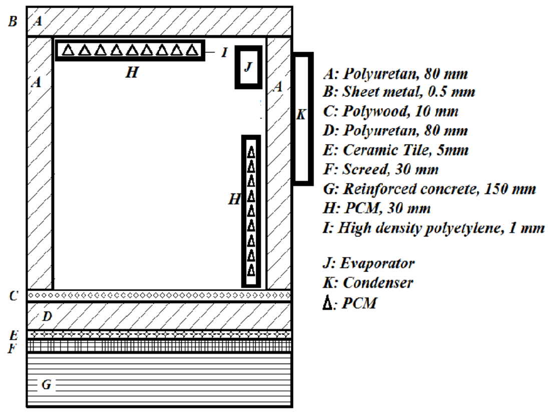
the sensors include the indoor temperature, PCM temperature in high-density polyethylene (HDPE) macrocapsules and ambient temperature. In this research, these three parameters are recorded with 10-second intervals.



(a)

(b)

(c)

Fig.1. The cold store cabin: (a) Cross-sectional details, (b) inner view and (c) outer view

The PCM used in the study as heat storage medium is a commercial eutectic mixture. The thermophysical properties of the mixture are given in Table 1. In the experiments, 62 HDPE macrocapsules containing approximately 62 kg PCM were used and the the total surface area integrated with macrocapsules containing PCM was about 2.5 m2. Each experiment was repeated twice to observe the reproducibility of the data and the mean values have been reported.

Prior to monitor the indoor temperature changes under different conditions, the cold store was operated for 24 h to reach -18°C and equilibrated between -16°C and -18°C.

In data evaluation, -4°C has been taken as boundary value since it is the critical temperature for safety of some perishable goods."

Table 1. Thermophysical properties of the PCM used in the study

Melting onset and peak temperatures, °C	-14.7/-10.7
Viscosity, kg/m.s (25°C)	0.0055
Density, kg/m^3 (25°C)	1.04 g/cm^3
Enthalpy, kJ/kg	274.3

RESULTS

In this research, the temperature changes in the PCM loaded cold store have been monitored at three different ambient air temperatures: (i) 24°C, (ii) 20°C and (iii) 13°C, whereas the thermal behavior of the cold store in the absence of PCM has been monitored at 24°C ambient air temperature as reference.

The repeated measurements indicate that the observed thermal changes are reproducible after equilibration of the cold store for 24 h between -16°C and -18°C and the observed fluctuations of the ambient temperature are ≤ ±2°C in the laboratory.

As it is given in Fig.2, the indoor temperature reaches -4°C in 5520 s (1.53 h) in the absence of PCM and breaks the frozen storage conditions when the ambient temperature is 24°C. It is relatively a short period of time in case of an operational failure.

The conducted runs with empty HDPE macrocapsules to observe the additional insulation effect of the macrocapsule material showed that the required time to reach -4oC was identical to the reference case, i.e. no significant additional insulation effect of the macrocapsule material. Therefore, it can be stated that the PCM load in the cold store cabin has a direct effect on indoor temperature maintenance. Although heat gain of the store changes with different ambient conditions, the PCM layer works both as an insulating layer and a latent heat storage volume. The resistance of PCM against heat transfer into the cold store functions in sensible heat form in solid and liquid phases and also, in latent heat form during phase change.

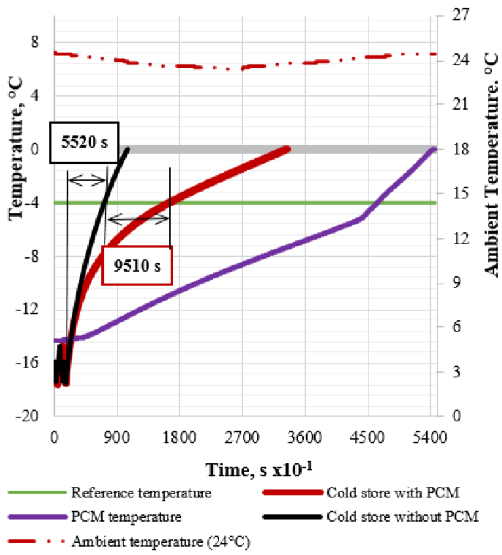


Fig.2. Cold store temperature changes with/ without PCM at 24°C ambient temperature

In the presence of PCM, the time period to reach -4°C shifts up to 15030 s (4.18 h), 21750 s (6.04 h) and 33210 s (9.23 h) at ambient temperatures of 24°C, 20°C and 13°C, respectively. Compared to the case without PCM load at 24°C in Fig. 2, the time period to break the cold chain is 9510 s (172%) longer in the presence of PCM macrocapsules, which cover about 10% of the total heat transfer surface area in the cold store.

The tabulated data in Table 2 indicate that in the case of lower ambient temperature levels, the PCM load provides longer temperature maintenance as a result of lower heat gain of the cold store from surrounding. Compared to the heat gain at 24°C, the time periods required to break the cold chain are 45% and 121% longer under 20°C and 13°C ambient conditions, respectively. The differences in temperature change curves in the cold store at different ambient temperatures are clearly seen in Fig.3.

Table 2. Changes in time to reach -4°C in cold store and PCM macrocapsules under different ambient conditions

	24°C	24°C	20°C	13°C
Cold store	5520 s	15030 s	21750 s	33210 s
% change in time	-	172%*	45%**	121%**
PCM	-	44790 s	45930 s	76140 s
% change in time	-	-	2.55% **	70%**

* longer than the reference case at 24°C without PCM
** longer than the case at 24°C with PCM

As PCM layer functions as an insulating layer with its sensible heat and latent heat storage ability, the temperature changes in the PCM macrocapsules are also meaningful to monitor under different ambient temperature conditions. Although the cold chain is broken after -4°C, the PCM load continues to work as a temperature regulator and delays the time of indoor temperature to reach 0°C (Fig.3). Besides, the PCM itself reaches in 44790 s (12.44 h), 45930 s (12.75 h) and 76140 s (21.51 h) to -4°C at different ambient temperatures, which are long enough to provide sufficient thermal load for temperature maintenance in the cold store. The thermal behavior of the PCM is illustrated in Fig.4.

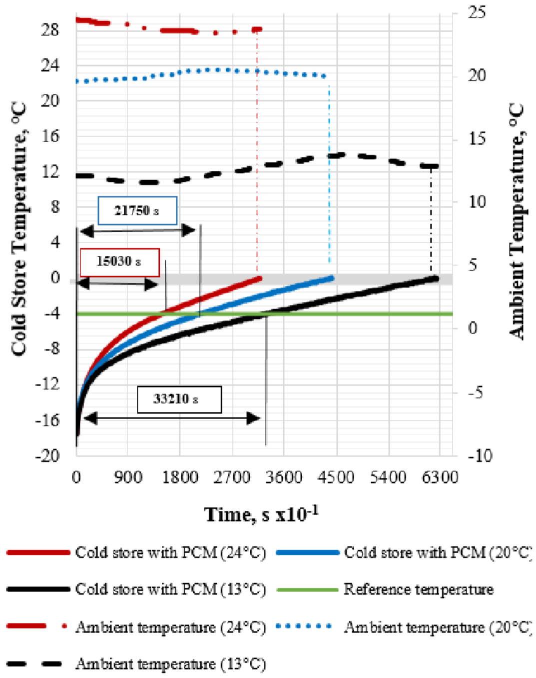


Fig.3. Cold store temperature changes with PCM under different ambient conditions

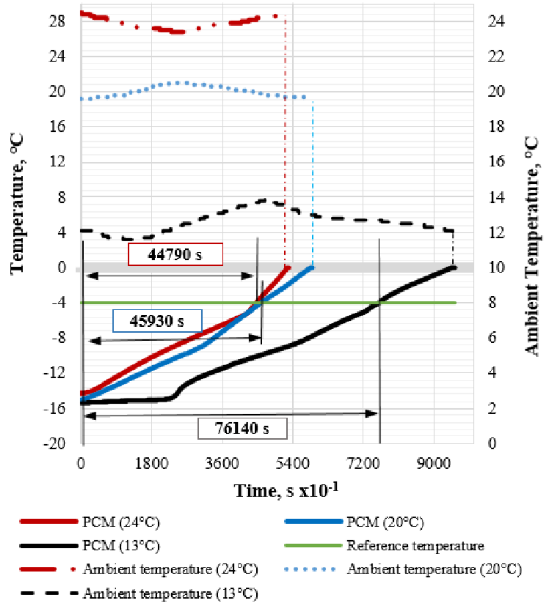


Fig.4. Temperature changes in PCM macrocapsules under different ambient conditions

CONCLUSIONS

In this research, a cold store operating under frozen storage condition at -18ºC has been investigated to determine the useful function of the PCM load during an operational failure or electricity shortage. The indoor temperature change has been continuously monitored and the time required to reach -4°C, at which the frozen storage condition is broken, has been determined under different ambient conditions.

The results indicate that PCM load covering 10% of the total heat transfer surface area provides significant temperature maintenance under all ambient conditions and prominently extend the time to reach -4°C.

In the case of highest heat gain from surrounding at 24°C ambient temperature, the PCM load ensures 172% longer temperature maintenance period than the conventional cold store. At 13°C ambient temperature, the thermal function of the PCM is much more effective and 9.23 h are needed to break the cold chain.

Since frozen storage conditions are very important for safety of the stored perishable goods, the presented research provides valuable data not only for cold stores, but also for refrigerated vehicles which are used for long-distance transportation. PCM macrocapsules might ensure lower fuel consumption related to continuous refrigeration, higher temperature stability with lower heat gain from surrounding and more flexible logistics planning.

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