Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 142 (2017) 3546–3552

Energy Procedia

www.elsevier.com/locate/procedia

9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Study on the application of latent heat cold storage in a refrigerated warehouse

Tianrun Yang, Changjiang Wang, Qie Sun*, Ronald Wennersten

Institute of Thermal Science and Technology, Shandong University, Jingshi Road No. 17923, Jinan and 250061, China

Abstract

Integrating latent heat cold storage (LHCS) system with refrigerated warehouses benefits both energy and operation cost savings, especially under a peak-valley price mechanism. This paper presented a feasible scheme with an operation strategy. Besides, a detailed three-dimensional CFD model was developed in ANSYS to test the temperature distribution in the refrigerated warehouse with phase change material (PCM) plates in order to validate the feasibility of the system. In addition, an economic analysis was also carried out to calculate the operation benefit and the payback period of the new scheme.

Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy.

Keywords: Cold storage; Refrigerated warehouse; Phase change material; CFD; Economic analysis

1. Introduction

Refrigerated warehouses are the place of processing and storing products. Broadly speaking, it is a storage building keeping a specified temperature with artificial refrigeration methods. China, one of the world's major agricultural countries, requires a large demand for refrigerated warehouses and, as a result, a huge amount of electric energy is consumed every year. With the growing requirements on energy conservation, the peak-valley price mechanism has been conducted in every province in China. This is a substantial disadvantage to the traditional refrigerated warehouses, for the coincidence of peak-valley load and peak-valley price.

To shift the cooling load from the peak period to the valley, applying latent heat cold storage (LHCS) in the cold storage industry as a technology to store low temperature energy temporarily for later use has attracted a considerable

* Corresponding author. Tel.: +86-(0)531-88399000-2306.
E-mail address: qie@sdu.edu.cn

1876-6102
Peer-review under responsibility of the scientific committee of the 9th International Conference on Applied Energy.
10.1016/j.egypro.2017.12.243

amount of attention these years[1,2]. A recent experiment analysed the effectiveness, the reacted fraction and the total heat transfer of a versatile latent heat storage tank capable of working with organic phase change materials [3]. An experimental investigation into a tube-in-tank design filled with phase change materials (PCMs) for cold storage applications developed a function of the measured average NTU [4]. The cold storage technology with PCM integration could be further improved by selecting and producing more appropriate PCMs in different refrigerated warehouses [5,6]. It is noted that there are two main schemes becoming recent research hotspots. One is to build a cold storage tank beside the refrigerated warehouse, which can cool the air cycle between the tank and the refrigerated warehouse. The other is to install solid-state PCM plates in refrigerated warehouses or vehicles directly, but they need to be dismantled for recharging after use. This paper aims at the application of latent heat cold storage in a high temperature refrigerated warehouse (0-5 °C). To achieve this aim, the paper first presents a scheme that is to install PCM plates with coils connected to the compressor inside on the inner side of the refrigerated warehouse walls and then develops a three-dimensional CFD model to validate the feasibility of the system. In addition, an economic analysis is also carried out to calculate the operation benefit and the payback period of the scheme.

2. Methodology

2.1. System structure

The refrigerated warehouse with PCMs is to attach PCM plates to the insulation walls in order to shift the cooling load from the peak period to the valley, which can help reduce the electricity cost under the peak-valley price mechanism. Fig. 1 presents the schematic diagram of applying latent heat cold storage in a refrigerated warehouse. The system is composed of two parts: the refrigeration system and the refrigerated warehouse. The refrigeration system comprises of a compressor, a condenser, a gas-liquid separator, an oil-liquid separator and several throttle valves. The refrigeration system provides cold energy to PCM plates directly and the product in the refrigerated warehouse through an evaporator, respectively.

2.2. Operation strategy

To cooperate with China’s peak-valley price mechanism, the refrigeration system provides cold energy to both the evaporator and the PCM plates at the valley period (23:00-7:00). PCM plates reserves a large amount of latent heat through the solidification process during this period. And the product absorbs the cold energy released from the PCM plates during the melting process at daytime, while the refrigeration system is off.

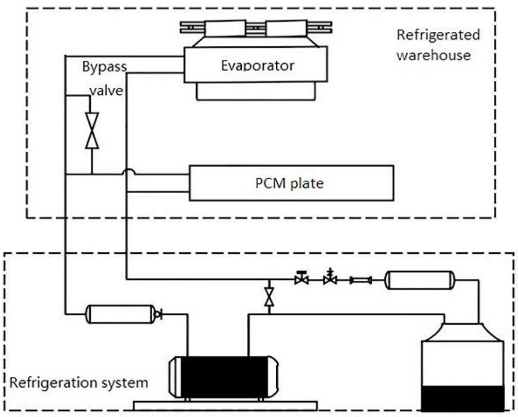

Fig. 1. Schematic diagram of applying latent heat cold storage in a refrigerated warehouse

2.3. Assumptions

The key assumptions used to develop the model are summarized below:

(1) The PCM is pure, isotropic, and has no qualitative exchange with the outside world during the melting process.

(2) The air inside the refrigerated warehouse is regarded as the incompressible Newton fluid, and the density change only affects the buoyancy force.

(3) The air inside the refrigerated warehouse obeys the Boussinesq hypothesis; namely, the viscous dissipation is neglected. The impact of temperature change on the fluid density is considered, but the impact on pressure change is ignored.

(4) The temperature of the PCM in each plate is uniform and the thermophysical properties of the PCM are assumed as constant.

(5) The refrigerated warehouse has a good air tightness, ignoring the impact of leakage.

2.4. Model description

In this study, the refrigerated warehouse was constructed with polyurethane, and PCM plates were made of the aluminum encapsulation with water in it. It is important to select optimal materials in experimental and industrial applications considering both costs and operations. Polyurethane and water are the most widespread materials for isolated walls and PCMs respectively because of their stability, availability, and superb thermal properties [7]. And the thermophysical properties of the PCM, the product and the construction materials are summarized in Table 1.

Table 1. Thermophysical properties of the PCM, the product and the construction materials.

Parameters	PCM	Product	Construction materials	
	Water	Potatoes	Aluminium	Polyurethane
Density (kg/m^3)	998.2	1000	2719	35
Specific heat (J/kg K)	4182	3500	871	1380
Thermal conductivity (W/m K)	0.6	0.5	202.4	0.024
Dynamic viscosity (Pa s)	0.001003	-	-	-
Pure solvent melting heat (J/kg)	333146	-	-	-
Melting point (K)	273.15	-	-	-

In this study, a compressor was used along with the refrigerated warehouse. The cooling capacity and the motor input, according to the compressor specification, are 2770 and 885 W respectively, accounting for a coefficient of performance (COP) of 3.13. The power consumption of the compressor measured by a power meter is 2.22 kW h per day; namely, the cooling load of the refrigerated warehouse is 6.95 kW h per day. A margin of 60% is engaged in the cooling load, as suggested by the supplier, to make up the cooling load of the product respiration and the personnel operation, which are not able to measure in the experiment. According to the application and the temperature range of the refrigerated warehouse, water was chosen as the PCM in this study.

The inside dimensions of the refrigerated warehouse are listed in Table 2. In this study, PCM plates were constructed as part of the encapsulation inside the polyurethane with a laying area of 14.8 m^2. The thickness of the PCM plates, therefore, is 0.009 m.

Table 2. Inside dimensions of the refrigerated warehouse.

Walls	Length (m)	Width (m)	Laying area (m^2)
Sidewall1, 3	2.2	1.4	3.08
Sidewall2, 4	1.2	1.4	1.68
Floor, roof	2.2	1.2	2.64

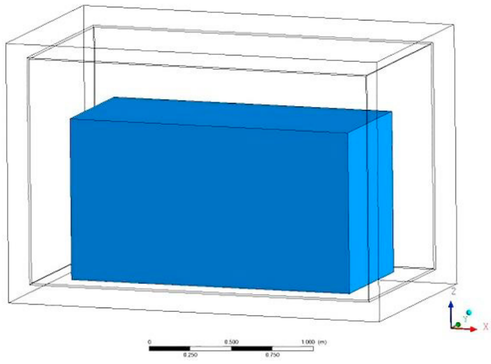

Fig. 2. Layout of the refrigerated warehouse.

A detailed three-dimensional CFD model was developed in ANSYS to test the temperature distribution in the refrigerated warehouse with PCM plates in order to validate the feasibility of the system. Fig. 2 shows the layout of the refrigerated warehouse. The outermost layer is the polyurethane with the thickness of 0.1 m, and there is a layer of ice, 0.009 m thick attached with the inner side of the polyurethane. The central part stands for the product with the dimensions of $1.8 \times 1 \times 0.8$ m^3. In addition, the polyurethane and the product are taken as solid materials.

2.5. Initial conditions and boundary conditions

In order to figure out the temperature distribution during the PCM melting process, a transient analysis was carried out. And the grid size of 714420 cells and the time step size of 1 s were chosen in the simulation after the independence verification. Designed conditions were implemented for the simulation, where the floor was assumed as a constant temperature of 298.15 K and the sidewalls and roof were set in a natural convection environment with the temperature of 298.15 K and the heat transfer coefficient of 5 W/m^2 K. And the temperatures of the product and the PCM were set as 276.15 and 272.15 K at the initial time.

According to China's peak-valley price policy, the valley period is always 23:00-7:00, while the peak period varies with different cities, e.g. the peak period is 8:30-11:30, 16:00-21:00 in Jinan and 10:00-15:00, 16:00-17:00, 18:00-21:00 in Beijing. Therefore, this study implemented the simulation for 16 hours in a single day.

3. Results and discussion

3.1. Simulation result

Fig. 3 indicates the average temperature variations of the air and the product inside the refrigerated warehouse. It is noted that the temperature of the air rises sharply during the first 7500 s, reaching a maximum of 274.12 K, and then experiences a slight decrease until the end. While the temperature of the product drops considerably in the first 10000 s, and then the downward trend slows down till the end. Because of the huge temperature difference at the initial time, a strong heat exchange occurs between the product and the air, resulting in a significant change in the temperature of both parts. As the temperature difference becomes smaller, the heat transfer also decreases and both the changes in temperature and heat transfer are mild. In addition, with the falling temperature of the product, the heat transfer between the product and the air decreases, and that becomes less than the heat transfer between the air and the ice layer eventually after 10000 s. So it is expected that the average temperature of the air which is used as cooling fluid also decreases slightly with time.

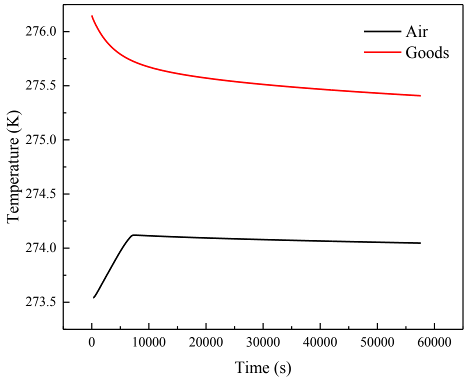

Fig. 3. Average temperature variations of the air and the product.

Fig. 4 presents the temperature contours of the YZ side at X=1.2 and the XZ side at Y=0.7 at 57600 s. It can be observed that the cold energy released from the surrounding ice layers is well-distributed in the refrigerated warehouse. The lowest temperature of the air appears at the zone near the ice layer, which is close to the melting point of ice. And the temperature of the center section of the product is 277 K, which causes a temperature gradient of 3.5 K/m in the X direction, 6.4 K/m in the Y direction and 5.5 K/m in the Z direction. Besides, it is obvious that the lower part of the product has lower temperature than the upper, because the method that the product absorbs cold energy comprises of the conduction from the floor ice layer and the convection from the side ice layer.

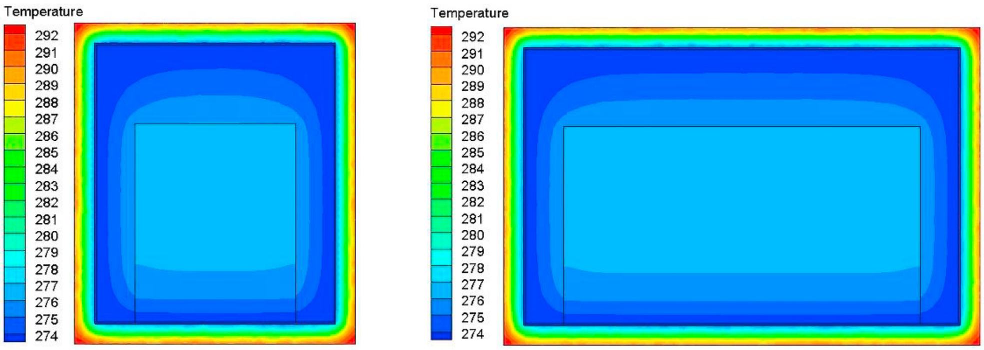

Fig. 4. Temperature contours of (a) the YZ side at X=1.2; and (b) the XZ side at Y=0.7 at 57600 s.

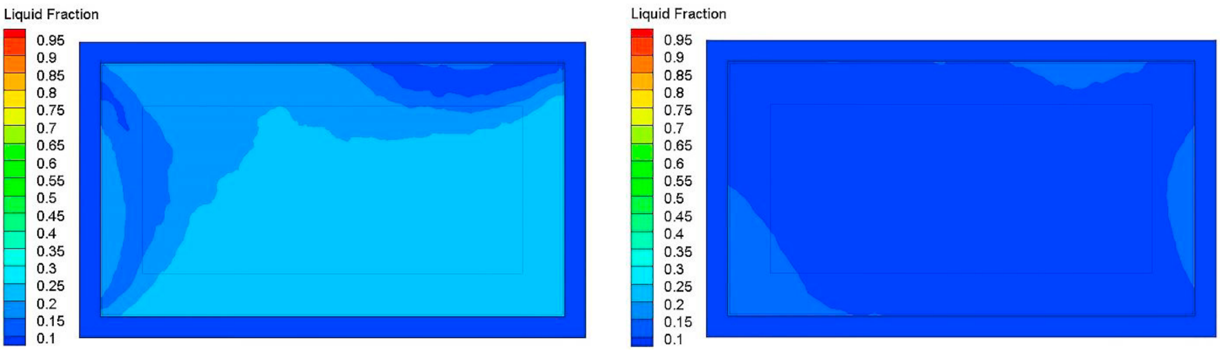

Fig. 5. Liquid fraction contours of (a) the floor PCM plate; and (b) the roof PCM plate at 57600 s.

Fig. 5 shows the liquid fraction contours of the XY side at Z=0.105 and 1.495 at 57600 s, standing for the floor and the roof ice layer, respectively. It is noted that the floor ice layer melts much more quickly than the roof, because of the direct contact with the product. It also explains the phenomenon of Fig. 4, where the lower part of the product has lower temperature than the upper.

3.2. Economic analysis

The refrigerated warehouse is taken as an example to evaluate whether the system has obvious economic benefits. Table 3 lists the refit costs of the latent heat cold storage refrigerated warehouse. The initial investment of the latent heat cold storage refrigerated warehouse is 822.6 CNY more than that of a traditional one.

Table 3. Refit costs of the latent heat cold storage refrigerated warehouse.

Equipment	Units	Quantity	Unit price	Total price
Cold accumulator encapsulation	pcs	6	91	546
Coils	pcs	6	46	276
Cold storage medium	m^3	0.13	4.2	0.6
Aggregate	-	-	-	822.6

According to the peak-valley price policy in Jinan, as shown in Fig. 6, the daily operation cost of a traditional refrigerated warehouse and a latent heat cold storage refrigerated warehouse can be calculated by:

$$C_1 = 1.1982 \times \frac{E}{3} + 0.7988 \times \frac{E}{3} + 0.3994 \times \frac{E}{3} \quad (1)$$

$$C_2 = 0.3994 \times E \quad (2)$$

where E is the daily power consumption.

And the payback period of the latent heat cold storage refrigerated warehouse can be calculated by:

$$P = \frac{R}{(C_1 - C_2) \times 365} \quad (3)$$

where R is the refit costs.

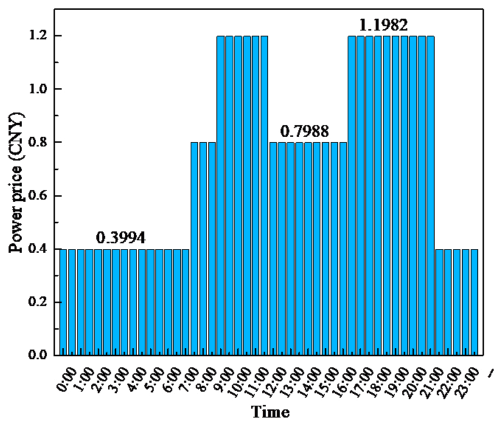

Fig. 6. Peak-valley price policy in Jinan, China.

Stated thus, the payback period is 2 years and 7 months. And after that, the latent heat cold storage refrigerated warehouse can benefit 323.6 CNY every year.

4. Conclusions

In this study, a feasible scheme and an operation strategy of a refrigerated warehouse integrated with the latent heat cold storage system is presented. Besides, an experimental refrigerated warehouse is built, and the daily power consumption is measured by experiment. Calculations are carried out to design a latent heat cold storage refrigerated warehouse based on that. To validate the feasibility of the system, a detailed three-dimensional CFD model is developed in ANSYS, and the temperature distribution and heat transfer characteristics in the refrigerated warehouse are simulated and analyzed. In addition, an economic analysis is carried out in this study to show the operation benefit and the payback period. The results show that integrating the latent heat cold storage system with refrigerated warehouses benefits both energy and operation cost savings, especially under China's peak-valley price mechanism. The simulation and economic results achieved from this work could be used to predict and optimize the temperature system performance of refrigerated warehouses in different sizes and uses, by changing various parameters.

Acknowledgements

The financial support from the National Key Basic Research Program of China (No. 2013CB228305) and the Natural Science Foundation of Shandong Province, China (No. ZR2014EEM025) is gratefully acknowledged.

References

[1] Diaconu BM, Varga S, Oliveira AC. Experimental assessment of heat storage properties and heat transfer characteristics of a phase change material slurry for air conditioning applications. Applied Energy. 2010; 87(2):620-8.
[2] Liu M, Saman W, Bruno F. Development of a novel refrigeration system for refrigerated trucks incorporating phase change material. Applied Energy. 2012; 92:336-42.
[3] López-Navarro A, Biosca-Taronger J, Corberán JM, Peñalosa C, Lázaro A, Dolado P, Payá J. Performance characterization of a PCM storage tank. Applied Energy. 2014; 119:151-62.
[4] Tay NHS, Belusko M, Bruno F. Experimental investigation of tubes in a phase change thermal energy storage system. Applied Energy. 2012; 90(1):288-97.
[5] Fan L, Yao X, Wang X, Wu Y, Liu X, Xu X, Yu Z. Non-isothermal crystallization of aqueous nanofluids with high aspect-ratio carbon nano-additives for cold thermal energy storage. Applied Energy. 2015; 138:193-201.
[6] Melone L, Altomare L, Cigada A, De Nardo L. Phase change material cellulosic composites for the cold storage of perishable products: From material preparation to computational evaluation. Applied Energy. 2012; 89(1):339-46.
[7] Oro E, de Gracia A, Castell A, Farid MM, Cabeza LF. Review on phase change materials (PCMs) for cold thermal energy storage applications. Applied Energy. 2012; 99:513-33.