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Cold storage condensation heat recovery system with a novel composite phase change material

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HIGHLIGHTS

- Cold storage condensation heat recovery system using PCM was proposed.
- CW with a phase change temperature of nearly 80 °C was selected as the potential PCM.
- The optimal mass ratio between the CW and EG was 10:1.
- The thermal and physical performances of the CW/EG were investigated.
- The thermal reliability was demonstrated by 1000 cycles.

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ABSTRACT

Using condensation heat from cold storage refrigeration systems to provide heat for domestic hot water preparation and industrial hot water supply promotes energy conservation. However, few studies have investigated cold storage condensation heat recovery using phase change materials (PCMs). In this study, a cold storage condensation heat recovery system that uses PCMs has been designed and analysed. According to the principle of energy cascade recycling, different operation modes could be effectively switched to recycle condensation heat. Furthermore, a novel and suitable phase change composite material is developed for cold storage condensation heat recovery, which has a relatively large latent heat, high thermal conductivity, and an appropriate phase change temperature (i.e. 80 °C). With carnauba wax (CW) as the PCM and expanded graphite (EG) as the additive, a composite was developed with an optimal mass ratio of CW:EG = 10:1. The thermal and physical properties and the interior structure of the composite were then investigated using a scanning electron microscope (SEM), thermal constants analyser (Hot Disk), differential scanning calorimeter (DSC), and Fourier transform infrared spectrometer (FT-IR). Furthermore, experiments on the melting and solidification processes and accelerated thermal cycling were also conducted. It was found that at the optimal mass ratio of 10:1, the temperatures of the CW/EG composite in the melting and solidification processes were 81.98 °C and 80.43 °C, respectively, while the corresponding latent heats were 150.9 J/g and 142.6 J/g, respectively. During both processes, CW could retain its original worm-like structure after being completely adsorbed by EG. Compared to only CW, the melting and solidification time of the CW/EG composite were reduced by 81.7% and 55.3%, respectively, while its thermal conductivity was 16.4 times higher. After 1000 runs of accelerated thermal cycling, the endothermic/exothermic phase change temperatures of CW and the CW/EG composite increased by only 0.42%/0.42% and 0.23%/0.27%, respectively, while their endothermic/exothermic latent heats decreased by 4.96%/4.78% and 2.05%/3.44%, respectively. These results indicate that both CW and the CW/EG composite have excellent thermal reliability, while the CW/EG composite exhibits a slightly better performance. Finally, the experiments show that the CW/EG composite has desirable thermal and physical properties such as high thermal conductivity and reliability; Hence, it has good potential as a material for facilitating condensation heat recovery from cold storage refrigeration systems.

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1. Introduction

Large amounts of condensation heat emitted by cold storage refrigeration systems and discharged directly into the atmosphere can not only lead to increased energy consumption but also result in environmental pollution and global warming. Consequently, there is growing interest in utilising low-grade waste heat from cold storage to provide heat for domestic hot water preparation and industrial hot water supply in order to reduce global energy consumption and protect the environment. Thus far, the major studies in this field continue to focus on economic analysis and cold storage refrigeration system design [1–3]. Moreover, the application of phase change materials (PCMs) as a prospective technique for residual or stored energy recovery is expected to play a significant role in enhancing condensation heat recovery from cold storage refrigeration systems in the future. Therefore, the present paper focuses on the design of a cold storage condensation heat recovery system using a newly developed PCM, the preparation of which is also described. Several tests were performed to demonstrate the effectiveness of heat recovery from the cold storage refrigeration system using the PCM.

Owing to the large latent heat potential and isothermal character during phase change, PCM-based heat recovery systems are smaller and allow for more stable operation as compared to conventional systems [4,5]. Thus, PCM-based heat recovery systems have been widely investigated. Pandiyarajan et al. [6] investigated a shell and finned tube heat exchanger integrated with an internal combustion (IC) engine setup to extract heat from the exhaust gas, with a thermal energy storage tank used to store the excess energy available. The exhaust gas from an IC engine carries away around 30% of the heat of combustion. The results showed that nearly 10–15% of the total heat (that would otherwise be wasted) was recovered by this system. The maximum heat extracted using the heat exchanger under full load condition was around 3.6 kW. Vasiliev et al. [7] investigated a heat storage system for preheating a petrol engine operated under real conditions in cold weather. Subramanian et al. [8] experimentally investigated waste heat recovery from diesel engine exhaust, and they showed the advantages of a combined sensible and latent heat storage system. Maruoka and Akiyama [9] proposed a new thermal energy recovery process for recovering the hot gas exhausted from a steelmaking converter by utilising not only the latent heat but also the endothermic heat of reaction. The results showed that their system has the potential to produce a large amount of methanol, corresponding to 20% of the total demand in Japan, with only 28% of the exergy consumption of the conventional method. Sun et al. [10] developed a technology that combines PCMs with a natural cold source to reduce the space-cooling energy of telecommunications base stations (TBSs). Takeda et al. [11] designed a ventilation system for residential buildings by using PCMs. Their results showed that the maximum benefit of such a system could be realised by reduction of the ventilation load by as much as 62.8% during summer in a humid subtropical climate.

The use of PCMs for condensation heat recovery in conventional air conditioning systems has been well established in the literature [12–14]. Jia and Lee [12] designed a prototype storage-enhanced heat recovery room air-conditioner (SEHRAC) integrated with an expanded graphite (EG)/paraffin composite PCM. They conducted two identical sets of experiments with and without the PCM (wPCM and woPCM scenarios) under a range of outdoor temperature conditions. Gu et al. [13] designed a heat recovery system consisting of two different PCM accumulators installed in series before the condenser of an air conditioning device in order to store the exhaust heat released by the condenser. Zhang et al. [14] also proposed a heat recovery system for air conditioning using a PCM; Placed before the condenser, the PCM storage tank was designed for daily hot water preparation.

PCMs are the key components of PCM-based condensation heat recovery systems for air conditioning. Many researchers have investigated various types of composite PCMs. Fang et al. [15] developed a stearic acid (SA)/EG composite material with various mass ratios by using SA as the PCM and EG as the supporting material. They found that an SA/EG mass ratio of 5:1 could not only prevent liquid leakage under the melting condition of SA but also impart preferable values of latent heat and thermal conductivity to the composite. Yuan et al. [16–18] devoted considerable effort to the investigation of organic PCMs such as fatty acids and fatty acid/EG composite; They showed that the latter has a large latent heat capacity, stable chemical properties, high thermal conductivity, and low degree of undercooling.

However, few studies have investigated condensation heat recovery from cold storage refrigeration systems using PCMs. A comparison between air conditioning systems and cold storage systems shows that differences exist not only in the operation modes and system components but also in the condensation temperature. Further, the PCM is the key component of the condensation heat recovery system. Owing to the different operation modes and outlet temperatures of the compressor (65–85 °C vs. 90–150 °C), different materials are selected. Thus, how to develop a new material with an appropriate phase change temperature, thermal and physical properties for cold storage refrigeration systems has attracted considerable attention in recent years.

This paper is divided into two parts. The first part discusses the components, working principle, and operation modes of a cold storage condensation heat recovery system. The second part focuses on the development and characterisation of a new PCM composite.

2. Cold storage condensation heat recovery system with PCMs

2.1. Components of cold storage condensation heat recovery system

As shown in Fig. 1, a conventional cold storage refrigeration system consists of a gas–liquid separator (11), a compressor (1), an oil separator (2), a condenser (4), a liquid receiver (5), a filter (6), sight glasses (7), a solenoid valve (8), an expansion valve (9), an evaporator (10), a low-pressure gauge (P1), a high-pressure gauge (P2), other valves, etc. An additional PCM heat recovery unit (3) is incorporated in systems that achieve cold storage condensation heat recovery using the PCM.

However, whether the PCM heat recovery unit (3) is attached to or separated from the system depends on the switch control of the relevant bypass valve K2. The PCM heat recovery unit (3) is connected with the oil separator (2) by switching on the A and B sides and switching off the C side of valve K2. The cold water from the water tank (12) is transferred to the PCM heat recovery unit (3) by switching on valve K4 or by switching on valve K3 and the F side of valve K5. Further, the flow rate of the cold water from the water tank (12) entering the condenser and the PCM heat recovery unit can be regulated by the switching range control of valve K4 and valve K3, which could influence the temperature, flow rate, and total yield of hot water through outlets 402 and 304.

To increase the temperature of hot water flowing through outlet 304, it is feasible to preheat the cold water from the water tank (12) flowing through inlet 303 by switching on valve K3 and the F side of valve K5. The cold water that flows through valve K4 can be mixed with the low-temperature hot water obtained after heat exchange between the refrigerant and the cold water that flows into the condenser (4) through inlet 401. Thus, the cold water can be preheated.