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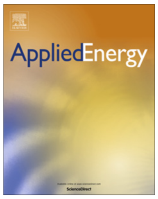

Industrial waste heat recovery using an enhanced conductivity latent heat thermal energy storage

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HIGHLIGHTS

- A latent heat thermal energy storage is designed for industrial waste heat recovery.
- An expanded natural graphite matrix is used to increase the thermal conductivity.
- A performance investigation of the storage is performed in various configurations.
- Differences on heat transfer coefficients appeared between heating and cooling phases.
- An economically sound industrial application of the thermal storage is highlighted.

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ABSTRACT

The aim of this work is to present the experimental performance of a latent heat thermal energy storage. A demonstrator devoted to recover waste heat in food processing industry is investigated. The storage is composed of an expanded natural graphite matrix impregnated with paraffin wax. This kind of composite material has been studied in previous works and appears to be one of the best solutions for the applications requiring a high heat transfer density, defined as the ratio of requested thermal power and stored energy. An investigation of the thermal performance of the storage during cooling and heating phases is presented. The results show that the storage is able to save 6 kW·h, which represents 15% of the energy of the process and delivers a thermal power larger than 100 kW, as planned during the design phase. Differences appear between the performances in heating and cooling. Some assumptions on the causes of this phenomenon are proposed, such as the change of viscosity of the heat transfer fluid, the heat losses through the external casing, or the variation of the thermal contact resistance within the heat exchanger containing the storage material. Finally, an economical approach is performed, showing a manufacturing cost of 260 €/kW·h and a payback period within 500 days for this application.

1. Introduction

Waste heat recovery and storage of the thermal energy present a major challenge in fundamental and technological research. The use of renewable energy requires storage to meet the intermittent needs of many applications. In addition, waste heat recovery is a challenge to improve energy efficiency. The latent heat storage, based on Phase Change Materials (PCMs), is a widely studied technique, particularly for energy storage applications of solar origin [1–12] or in the field of building [13–22]. The low number of cycles of these applications - usually one per day - increases the payback period of the storage solution. The present application focuses on the storage of heat for industrial processes with a significant number of cycles per day and a high ratio power on energy. In all cases it is related to a batch system and not to continuous industrial processes. Owing to both considerations of product safety/quality and power demand, most of such batch processes use a set temperature in the form of a ramp during the heating and cooling phases. Working with ramps and a PCM-based thermal storage differs from publications using fixed set temperatures. It is also closer to the applications of the industrial sector.

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Nomenclature

Cp	specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
h	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
$\dot{m}_{fluid}$	mass flow rate of the HTF ($kg \cdot m^{-3}$)
Q	energy (J)
S	heat exchange surface (m^2)
T	temperature (K)
ΔH	enthalpy variation ($J \cdot kg^{-1}$)
ΔT	temperature difference (K)
ΔT_{LM}	logarithmic mean temperature difference (K)
Δt	period (s)
η	efficiency coefficient (–)
Φ	thermal power (W)

Abbreviations

DSC	Differential Scanning Calorimetry
ENG	Expanded Natural Graphite
LHTES	Latent Heat Thermal Energy Storage
PCM	phase change material
PBP	payback period

However, PCMs have low thermal conductivities which reduce significantly the heat transfer rates for industrial applications. The improvement of the heat exchange surface or the thermal conductivity of the PCM is then necessary. The increase of heat exchange surface can be achieved through the use of various heat exchanger geometries. Several works use tubular heat exchangers with the PCM in the annular part and a heat transfer fluid circulating inside the tube [23–25]. Velraj et al. [10] evaluated the performances of a longitudinal finned heat exchanger. Medrano et al. [26] compared a radial finned heat exchanger to other configurations, such as plate heat exchanger. Multitube systems are studied by Agyenim et al. [27] and Xiao and Zhang [28]. The investigation of a metallic honeycomb is carried out by Hasse et al. [17]. The improvement of the heat exchange surface with a heat transfer fluid can be performed by the encapsulation of the PCM. The shells can be of metal or polymers materials, depending on the application, the nature of the PCM and the heat transfer fluid. The size of the shells can also differ according to the publications, with macro-encapsulation [29–32] or micro/nano-encapsulation [33–35]. A few works focuses on the study of a direct contact between the PCM and the heat transfer fluid, such as Wang et al. [36].

Another way to obtain higher heat transfer rates within the PCM is to increase its thermal conductivity. The use of conductive additives is widely studied in the literature [37–39]. The nature of the additives can be of different kind, such as metallic [2,10] or graphite origin [40]. One of the most frequent additive is graphite, in its expanded form, denoted Expanded Natural Graphite (ENG) [3,18,28,41–52]. The preparation process of ENG, from expandable graphite powder, is detailed by [41–43,53]. Albouchi et al. [45] investigated the influence of the preparation method of ENG/PCM composites on the thermal conductivity. Two methods are studied: dispersion of ENG particles in molten PCM during stirring and cold uniaxial compression of mixed PCM powder and ENG particles. The results show better values in case of dispersion, with equivalent mass fractions of ENG. These composites are then compared to the use of graphite in other forms: fibers, fins and foam.

The use of a conductive network to increase the thermal conductivity of the PCM is a promising technique. The nature of the material can be metallic [54–59], carbon [60] or ENG [1,4,13,26,53,61–66]. Medrano et al. [26] showed that the use of an expanded natural graphite matrix provides better performances in comparison to other configurations, such as tubular/finned/plate heat exchangers. This enhancement method was also highlighted by Mehling et al. [61], showing that the heat transfer coefficient between this ENG/PCM composite material and a wall (electric heater) can reach values up to 3–5 $kW \cdot m^{-2} \cdot K^{-1}$, resulting in a decrease of the melting time (between 10 and 30 times faster) compared to the PCM alone. The thermal conductivity of the obtained composite material is also increased by a factor of 100, with values between 20 and 25 $W \cdot m^{-1} \cdot K^{-1}$, for an ENG volume fraction of 10%. The thermal conductivity improvement of such a material was also investigated by Py et al. [62], as a function of the density of the ENG used. Tamme et al. [6] compared various composites, including compression of PCM/graphite powder, infiltration of graphite fills and infiltration of a graphite matrix.

A few publications focus on Latent Heat Thermal Energy Storages (LHTES) for industrial applications including short-term cycles and high thermal power demand. The aim of this paper is to present the experimental performances of a demonstrator devoted to waste heat recovery in food processing industry. The storage system has been designed to store 6 kW·h of energy and to deliver a thermal power higher than 100 kW. A previous comparative study of various latent heat thermal exchangers has been carried out [67], and has shown that a composite material using an ENG matrix with a density of about 200 $kg \cdot m^{-3}$ infiltrated with a paraffin is suitable to short-term applications. The thermal characterization of this material indicated an increase of thermal conductivity by a factor of 100 (22 $W \cdot m^{-1} \cdot K^{-1}$) compared to the PCM alone with an ENG mass fraction of 20%, which is in agreement with the values found in the literature, such as Py et al. [62]. The calculated heat transfer coefficients between the heat transfer fluid and the PCM exceeds 3000 $W \cdot m^{-2} \cdot K^{-1}$. Based on these results, an industrial storage demonstrator has been built and implemented on an existing industrial lab-scale installation: a sterilizer from STERIFLOW®. The thermal performance of this storage system is investigated for various conditions: change of the fluid flow circulation, the maximum temperature of the process or the load inside the sterilizer. In each case, the thermal power, the heat transfer coefficient and the thermal efficiency are calculated and analyzed, both during charging and discharging processes. Finally, an upscaling of this demonstrator is operated to predict the performance and suitability of a 1.2 MW–90 kW·h storage system, devoted to a larger sterilizer.

2. Materials and methods

2.1. Description of the industrial application

STERIFLOW® is a French industrial company and world leader in batch sterilizers for food industry. Such sterilizers have a 3–6 m^3 internal capacity, involving a significant energy consumption per cycle (150–300 kW·h), depending on the load and temperature set points. Furthermore, the sterilizing cycle lasts about one hour, implying a number of cycles up to 10 per day. A smaller unit of 1 m^3, working on the same principle, is used at STERIFLOW's laboratory. The Sterilizer model Microflow 902S has been chosen for the storage implementation. The cycle description of the thermal cycle of this sterilizer is illustrated in Fig. 1. This cycle can be divided in three major phases: heating, sterilization and cooling.