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Bio-Based Latent Thermal Energy Storage for Air Conditioning

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Abstract

Future smart and efficient energy management systems for space cooling and heating in building applications call for novel solutions to store heat in order to decouple the energy demand and the availability of renewable energy sources. Latent thermal energy storages represent one of the most promising solutions; however, their cost-effective implementation in terms of energy and cost savings, payback time needs to be verified case-by-case. This work is meant to present the experimental behavior of a novel 18 kWh latent thermal energy storage which uses the roll-bond technology to efficiently store and release cold energy exploiting the solid/liquid phase change process of 300 kg of a bio-based phase change material having a melting temperature of 9 °C. The effects of inlet water temperature and flow rate are studied to understand how the performance varies and to identify possible control strategies.

Keywords: PCM, Latent Thermal Energy Storage, Air Conditioning, Roll-Bond Technology, Modelling

1. Introduction

According to IEA report [1], about 37 Gton CO2 were estimated having been released in the atmosphere during 2019. A similar value was obtained for 2020. It is absolutely essential to reduce this figure, calling the researchers to focus on finding and developing innovative solutions. A huge amount of the energy is used for space heating and cooling and, in the last decades, energy management and indoor thermal comfort have become challenging issues. Gagliano et al. [2] reported that in the European Countries the total cooled floor area is destined to grow up to 2 billion m2 in 2020 (it was 1000 million m2 in 2012). Therefore, more than 100 TWh year-1 will be required for building cooling only.

In a recent critical review work, Cabeza and Chafer [3] reported the passive and active strategies needed to achieve zero energy buildings. Among other solutions, the presence of energy storages has been recommended. Thermal Energy Storage (TES) can be considered an enabling technology to promote a great, more efficient adoption of renewable sources which are one of the solutions to reduce the GHG emissions. The TES technologies can be classified into four types: sensible, latent, thermochemical, and mechanical-thermal. Compared to other types of TES, Latent Thermal Energy Storages (LTESs) equipped with Phase Change Materials (PCMs) exhibit many advantages. In fact, as described by Colla et al. [4], by virtue of the latent heat of fusion, the LTESs energy storage density capability is remarkably higher as compared to sensible-only TES systems. Considering the same temperature range, when using LTESs, from 5 to 14 times the energy of a sensible thermal energy storage system can be stored in the same volume; in addition, the phase change process can be considered almost isothermal [4]. These characteristics permit to maximize both the storing capabilities and the heat transfer process. It is also important to note that the use of PCMs allows for the decoupling between energy demand and availability; this point is of fundamental interest for the effective integration of renewable sources, that are intermittent by definition.

One of the most interesting applications of this technology is in the air conditioning (i.e. space cooling) field, in which the possibility of a direct integration of the LTES with an air/water or water/water heat pump powered by photovoltaics (PVs) can lead to huge energy savings by matching the energy source availability with the cooling demand, which are commonly mismatched. This is particularly true especially in hot and humid climates. In general, there is the lack of understanding if the data collected in small scale prototypes can be used to anticipate the performance of the systems at larger scale; moreover, it is also not clear so far if the models developed and validated on the basis of these results are representative to simulate the behavior of LTES at system or building level.

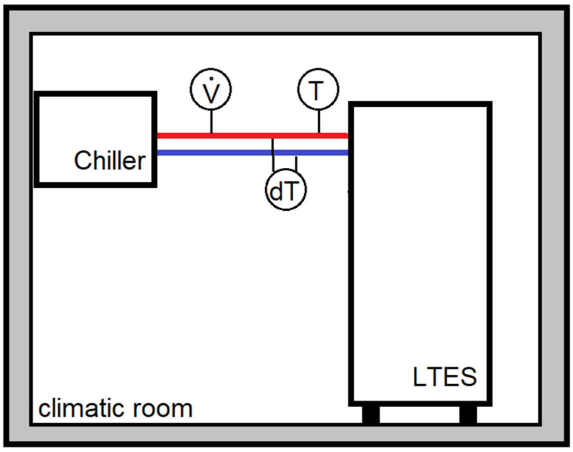
Only few papers deal with large amount of PCM. Among those, Atalay and Cankurtaran [6] experimentally tested an industrial solar dryer for strawberries coupled to a latent energy storage made by 300 kg of paraffin wax which allowed the drying process to continue during the absence of sunshine. Wu et al. [7] studied a 96 kWh storage tank made of 2442 encapsulated ice/water nodules to be coupled with a heat pump while Liu et al. [8] tested the thermal behavior of a refrigerated truck when a LTES was added to maintain the refrigerated truck at a temperature of -18 °C. In this application, 136.8 kg PCM having a melting temperature of -26.7 °C were subdivided in 19 parallel flat slabs to store cold energy generated by a refrigeration unit located off the vehicle when stationary.

This work aims at presenting a novel 18 kWh LTES especially designed for space cooling, which uses the roll-bond technology to efficiently store and release the energy exploiting the solid/liquid phase change process of a commercially available bio-based PCM, CRODATHERM9.5. This PCM, it is a water insoluble organic PCM derived from plant-based feedstocks and has the form of a crystalline wax or oily liquid (depending on temperature). This material is completely bio-compatible and biodegradable. Besides, the roll-bond heat exchanger is a simple, almost inexpensive cold (hot) plate, which can be easily used in any type of LTES due to its versatility. It can be produced in different sizes and it allows for a direct scalability of both capacity and heat transfer capabilities of the LTESs. The LTES is fully experimentally characterized as a function of the main operating conditions, trying to identify the optimum set of parameters which maximizes the performance of the LTES.

2. Experimental setup

A specific setup was built to run the experimental characterization of the LTES under study. Figure 1 shows a schematic of the experimental apparatus. It consists of an off-the-shelf storage tank with internal dimensions of 1400 mm x 710 mm x 650 mm. The wall contains 50 mm of insulation to limit heat losses to the surroundings, covered with an aluminum sheet.

The tank is filled with 300 kg of a commercially available bio-based PCM, named CRODATHERM9.5 supplied by CRODA. Its main thermophysical properties are listed in Table 1. The phase change temperature peak is at around 9 °C and the latent heat is 220 kJ/kg.



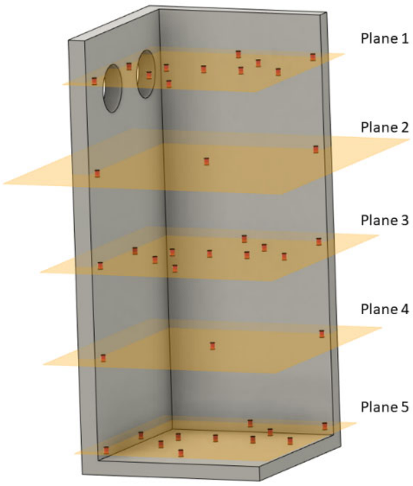


Figure 1. Experimental set up scheme.

Figure 2. Thermocouples positioning inside the tank

Inside the tank there are 16 roll-bond heat exchangers made of aluminum having dimensions 1170 mm x 570 mm x 1.5 mm. The heat exchanger pitch is 31 mm and it is filled by PCM. The roll-bonds allow the passage of hot and cold water and, thanks to the presence of their continuous aluminum plate, they promote the heat transfer within the PCM that has a relatively low thermal conductivity, similarly to the large majority of PCMs. The roll-bond heat exchangers are fed in pairs in parallel by two manifolds located on the top of the tank. The water flowing inside the inlet manifold is supplied by an external thermostatic bath that can independently regulate the flow rate and the inlet temperature. The volumetric flow rate is measured by an Endress + Houser Promag H electromagnetic flow meter with an accuracy of ±0.5% of the full scale (full scale 40 l min^{-1}). The inlet water temperature is measured with a calibrated T-type thermocouple (copper-constantan) with uncertainty (coverage factor k=2) equal to ±0.1 K since it is connected to a Kaye K170 Ice Point Reference with stability of ±0.005 °C and accuracy of ±0.005 °C. A thermopile with uncertainty (coverage factor k=2) of ±0.05 K measures the temperature difference between water inlet and outlet. In addition, 39 calibrated T-type thermocouples (uncertainty ±0.1 K) were immersed inside the PCM. They were located using 11 stainless steel rods at 5 different heights as depicted in Figure 2. In this way it was possible to analyze the temperature field during the experimental tests. All data were acquired by means of a Keysight 34970A acquisition system with a sampling rate of 1 Hz. The data are then processed using LabView software. The tank was placed inside a climatic room whose temperature was maintained during all the tests at 9.0±0.2 °C to avoid heat losses from the tank to the environment.

3. Results

The (cold) energy charging test started when the LTES had an average temperature of 14°C. Cold water flowed through the roll-bond heat exchangers at an inlet temperature of 2 °C and a flow rate of 17 l min-1, which are the reference rating conditions. The test ended when all the thermocouples inside the PCM recorded a temperature of 7 °C, i.e. 2 K lower than the PCM phase change temperature. The (cold) energy discharging test began immediately thereafter; the average temperature of the PCM under these conditions was 6 °C. An equal water flow rate (17 l min^{-1}) at a temperature of 16 °C flowed inside the heat exchangers until the PCM reached an average temperature of 14 °C, 2 K lower than the water temperature. During this test the climatic chamber was set at 9°C to limit as much as possible the heat loss to the surroundings. Figure 3 reports the complete charging and discharging cycle collected at constant water flow rate of 17 l min^{-1} and inlet water temperature equal to 2°C and 14°C during the charging and discharging phases, respectively.