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Experimental testing of a hybrid sensible-latent heat storage system for domestic hot water applications

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HIGHLIGHTS

- Experimental characterization a small scale heat storage for domestic applications.
- The heat storage is based on the hybrid "sensible + latent" configuration.
- Two different PCMs were compared, namely, a commercial paraffin and a hydrate salt mixture prepared in lab.
- A heat storage density increasing up to 13% has been highlighted.
- A new ESP-r component has been developed and validated thanks to the experimental outcomes.

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ABSTRACT

Aim of this work is to present the results of the testing of a small scale hybrid sensible/latent storage system (nominal volume 48.6 dm^3), consisting of water in which macro-encapsulated phase change materials (PCMs) are added. Two different PCMs were macro-encapsulated, a commercial paraffin and a hydrate salts mixture prepared in the CNR ITAE lab, and loaded inside the tank in order to be tested. Different volume ratios between the PCM and the water were tested. The tests were conducted simulating different domestic hot water draw-off profiles.

The resulting data showed an appreciable increase of heat storage capacity per unit of volume, even for limited fractions of PCM employed, reaching up to 10% of heat storage increasing by 1.3 dm^3 of hydrate salts mixture added. Finally, the experimental results were used to test a numerical method of a PCM enhanced tank for dynamic plant simulations in ESP-r environment.

1. Introduction

Currently, the development of innovative heat storage systems represents one of the main issues to be overcome, in order to promote the market penetration of renewable energies as well as to optimize the energy management, especially for application in residential buildings [1].

The state of the art of commercially available heat storages for domestic applications is dominated by sensible systems [2], based on water as heat storage medium. Actually, for applications at temperatures lower than 100 °C, the sensible/water system seems to be the best option thanks to its availability, its low cost, and sufficiently high specific heat [3]. Nevertheless, it suffers of the intrinsic limit related to the heat losses to the ambient that causes reduction of energy stored during the stand-by periods. This leads to the necessity of careful insulation of the vessels, thus reducing the overall volumetric heat storage density of the systems.

During last years, application of Phase Change Materials (PCMs) as heat storage mediums has been proposed in order to increase the heat storage density as well as to guarantee an optimization of the performance achievable by systems exploiting renewable energy sources [4,5]. To this aim, initially, many efforts have been dedicated to the development of advanced materials with increased heat storage capacity, good heat transfer properties and excellent cycling stability [6]. Actually, these research activities have led to excellent results, which are confirmed by the growth of new companies commercializing PCMs for heat storage applications [7,8].

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Nomenclature

Cp	specific heat [kJ/(kg K)]
E	energy [kJ]
$\dot{m}$	flow rate [kg/s]
t	time [s]
T	temperature [°C]
u(*P*)	uncertainty on power calculation [kW]
V	volume [m^3]
ρ	density [kg/m^3]

Subscripts

disch	discharge
nom	nominal
tap	tap water
user	user
w	water

Recently, more attention has been paid to the realization of advanced heat storage concepts, based on the employment of PCMs [9]. In case of heat storage for domestic applications, two main approaches have been followed namely, the integration of macro-capsules inside a water heat storage container [10,11] and the realization of full scale heat storages based on PCM embedded inside efficient heat exchangers [12–14]. Despite the higher storage volumetric density achievable by the latter one, the low delivered thermal power during discharging phase represents its main limit [15]. This is mainly due to the slow kinetic of phase transition as well as the poor thermal conductivity of PCMs [11]. In order to overcome this limit, different approaches have been proposed in literature, like the addition of carbon powders [16] or the embedding of PCM inside open-cell metal foams [17], to increase the overall thermal conductivity of the material. Although the obtained results seem encouraging, these approaches are limited by the high cost of the employed materials as well as the complicated preparation procedure. Another possible solution recently proposed for thermal energy storage for domestic applications, is to exploit supercooled state of particular PCMs, such as Sodium Acetate Trihydrate, to increase heat storage capacity limiting the heat losses through the environment. Recent experimental results [18] demonstrate the interesting achievable performance of this innovative concept. Nevertheless, some issues like material stability and reliability of the supercooling process need to be carefully investigated to make this approach more attractive.

In such a background, the approach based on the inclusion of certain quantities of macro-encapsulated PCMs inside a water tank, despite the lower increasing in thermal storage density, is not affected by limitations in discharging power, since water is the primary heat transfer medium [10]. Moreover, it results to be a more cost effective solution. Some examples have been proposed within the activities of IEA Task 32 "Advanced storage concepts for solar and low energy buildings" [19]. In that case, configurations employing metallic bottles filled with organic as well as inorganic PCMs, whose thermal conductivity was increased by means of graphite filler, were experimentally investigated. The results confirmed the possibility of increasing heat storage density, compared to water. Nevertheless, the low heat transfer surface to volume ratio of the employed macro-capsules limited the achievable charging/discharging rate. Castell et al. [20] have reported similar results.

Accordingly, such a kind of configuration needs to be optimized in order to exploit as much as possible the benefit deriving from the PCMs implementation.

Furthermore, numerical analysis carried out by means of software for energy systems simulation, like ESP-r, can be a useful tool to analyze application of PCM in buildings. By analyzing literature, only few examples are available due to the lack of validated components. For instance, in [21] analysis of PCM embedded in the gypsum panels to store solar energy thus reducing the thermal load in buildings has been carried out thanks to the implementation of a dedicated component model in ESP-r. More recently, Padovan and Manzan [22] have optimized a hybrid sensible/latent heat storage in ESP-r environment, but no experimental validation has been reported so far.

Accordingly, aim of the present paper is the experimental analysis of a domestic small-scale heat storage based on the hybrid "sensible + latent" configuration properly sized for space heating and DHW delivering. Sensible configuration has been experimentally compared to the hybrid ones. Two different PCMs, never investigated in literature under relevant operating conditions, have been integrated inside the heat storage by macro-encapsulating them in sealed parallelepiped polymeric capsules. In particular, the employed PCMs are a commercial paraffin and a hydrate salt mixture prepared at the CNR ITAE lab. The effect of varying volume of PCM inside the heat storage has been experimentally analyzed by means of a properly designed and realized test rig, able to simulate the daily hot water withdrawal profiles. Finally, a new ESP-r component, able to simulate the behavior of a hybrid heat storage, has been defined, implemented and validated by means of the obtained experimental data. This will cover the lack of available components to simulate the behavior of PCM-based heat storage for system simulation.

2. Tested heat storage and test rig

With the aim to evaluate the performance of a hybrid "sensible + latent" heat storage for domestic application, a cylindrical vertical tank has been realized. It is a fully mixed system (without internal heat exchangers) made of stainless steel, and its main geometrical characteristics are reported in the following Table 1.

It has been realized with the idea to get a tank as flexible as possible in order to vary different testing parameters like typology, amount and position of PCM material and to monitor temperatures of several points within the tank and inside PCM macro-capsules.

Fig. 1 shows the realized cylindrical storage, in which the different available hydraulic connections and the thermocouples feedthroughs can be recognized. Furthermore, the allocation of the six thermocouples inside the tank (T0–T5), the thermocouple for PCM (T7), the position of the PCM module and the inlet and outlet water connections are reported. They allow the monitoring of the temperature evolutions along the vertical axis of the tested

Table 1
Main geometrical characteristics of the tank.

Nominal volume [dm^3]	48.6
Height [m]	0.85
Diameter [m]	0.27
Weight [kg]	35.6