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PCM-Cold Storage System: an Innovative Technology for Air Conditioning Energy Saving

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An innovative solution to store cold energy by means of the solidification latent heat of PCMs is presented. The cold storage system is suitable for domestic application (typical in/out primary circuit temperature = 7-12°C) since it stores cold energy at 5.5°C. The innovative heat exchanger system implemented in the storage unit allows the increase of energy charge/release dynamics and, therefore, leads to high power both in charge and release phases.
The 5 kWh prototype developed and tested is illustrated, together with some experimental results, demonstrating the technology application potentialities.

1. Introduction

Due to the increasing use of air conditioning (AC) in residential and office buildings, the Italian daily electrical load curve shows remarkably high peaks during summer months, leading to the shifting of the peak consumption from the winter to the summer.

Developing AC systems, able to flatten the load curve during the summer period and to improve the energy conversion efficiency, is crucial to reduce the electricity consumption and the consequent pollutants and GHGs emissions, and to protect the electrical grid from overloads. This can be achieved by shifting the power consumption needed by the air conditioning units towards off peak hours, integrating thermal storage systems. At the moment, several solutions are adopted in large industrial applications, but not in residential air conditioning systems.

Operating in off-peak hours, which would certainly provide benefits at the level of national electrical energy distribution, can also increase the performance of air conditioning systems. In fact, during the night, the chiller's Coefficient of Performance (COP) increases due to the lower external temperatures. Moreover, thanks to the adoption of a storage system, the chiller can operate mostly at constant and optimal power (peak shaving concept) instead of following the user requirements profile, leading to a strong enhancement of energy efficiency and to a reduction of installed power. All these benefits lead to a potential reduction of electricity consumption of 20% and more.

Among the existing methods to store thermal energy, the ones using Phase Change Materials (PCM) are particularly interesting (Mehling, 2008; Regin, 2008; Zalba, 2013; Castell, 2011). These substances store the heat through their latent enthalpy, changing the phase from liquid to solid during charging and from solid to liquid during releasing. Several PCMs for storage applications have been developed and are available on the market at reasonable prices. Moreover, PCMs can offer a high value of heat stored per unit volume (approximately 42 kWh/m^3). This is 5 to 14 times more than for conventional sensible-heat storage materials such as water, masonry or rock. Another quality of PCMs is that they store and provide thermal energy maintaining the temperature in their melting range. Eutectic alloys do even maintain the temperature steady

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throughout the whole process. This allows the air conditioning system to run in a nearly steady-state and helps remarkably the designer in sizing the heat exchanger of the unit. Due to these benefits and due to the PCMs' environmental compatibility, storage systems using Phase Change Materials are the most suitable for residential applications.

In this paper, the possibility of integrating a PCM-based thermal storage unit in a residential air conditioning system is explored.

In Figure 1, the integration of the thermal storage unit in a chiller-users system is shown. The valves system allows the energy tank to work in three different configurations: charge, mixed release and pure release. While charging, the unit is in series with the chiller and the user is excluded from the circuit. All the cooling energy produced by the chiller is stored by the solidification of the PCM. Once the system is charged, the thermal energy stored can be released through the melting of the PCM, using two configurations: pure release and mixed release. In the first one, the users are supplied by the thermal energy released by the tank, while the chiller is turned off. Only a storage system which employs PCM can operate in this configuration while maintaining a nearly-steady state. In fact, the operating temperatures in the heat exchanger of the unit are constrained in a narrow domain determined by the melting range of the adopted phase-changing alloy. This allows to run the AC plant without showing sensible spreads in the inlet/outlet temperatures of the users. In the case of the mixed release configuration, the cold water flow is produced by both the chiller and the storage unit, working in parallel.

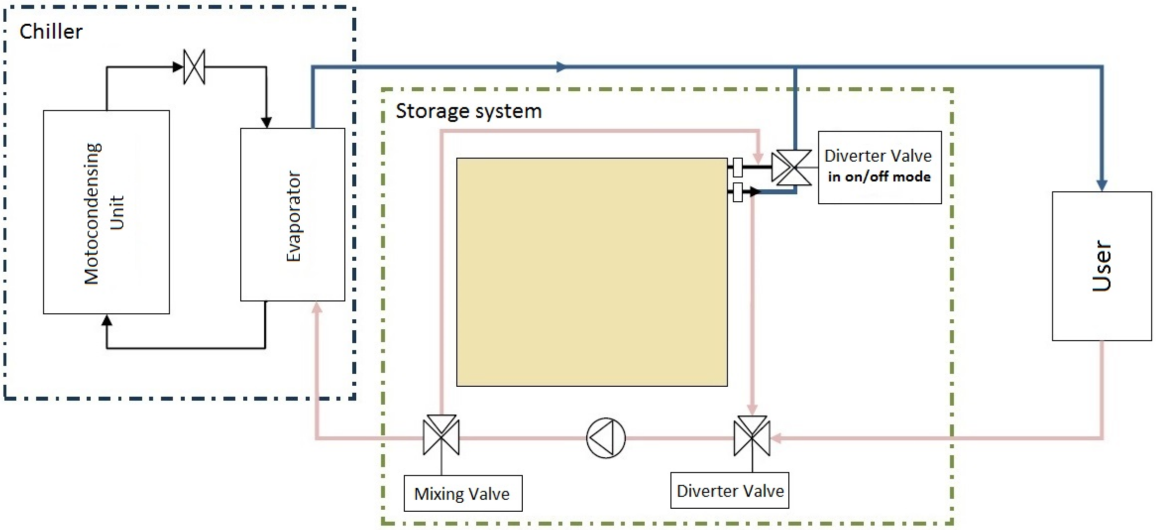

Figure 1: Plant scheme of a heat storage unit integrated in a chiller-users air conditioning system.

The technological solution for cold storage described in this work presents an innovative solution to optimize the heat exchange between the PCM and the water stream of the chiller circuit, as reported by De Falco (2014). The solution has been implemented in a 5 kWh_{cold} prototype (refer to Figure 2), described in the following and experimentally validated. Some experimental results, obtained during a first testing phase, are reported.

2. Prototype description

2.1 Analysis of the system operation

The cold storage unit presented in this work is composed by a tank that contains a heterogeneous mixture of distilled water and PCM in which a coaxial heat exchanger is immersed (refer to Figure 3). The functioning of the system is based on the natural separation between the two liquid substances in solution and, therefore, the PCM adopted has to be water-immiscible and must have a density lower than 1 kg/lt. The water available at the bottom of the tank is suctioned by a feed pump and sent in the inner tube of the coaxial heat exchanger, then it is fed at the top of the tank (secondary circuit) by nozzles and drops down for gravity (the density of the water is higher than the density of PCM). The external flow in the coil comes instead from the chiller-users circuit (primary circuit).

The total heat exchange is composed of two contributions. The first one consists of the thermal flow exchanged by the water drops generated by the nozzles and the PCM volume; the second one takes place outside the coaxial exchanger and it is due to the heat that flows between the external tube of the coil and the PCM volume in which is immersed. Such a technological solution allows to reduce the size of the heat exchanger, with a lower pressure loss and unit cost.

Figure 2 – 5 kWh_{cold} prototype for cold storage by means of PCM

2.2 Selection of the PCM

In order to meet the thermal requirements needed in the different configurations of the plant, the adopted PCM melting range is bound to respect the following limitations. During the charging phase of the system, the cooled water produced by the chiller enters in the external tube of the coil and then must have a lower temperature of the PCM-water mixture. Similarly, while releasing, the heterogeneous solution has to be colder than the warm water flow that comes from the users. Therefore, after choosing appropriate temperature gradients in the exchanger, the melting range of the PCM is subject to the following relation:

$$T_c + \Delta T_{app\_c} < \Delta T_m < T_h + \Delta T_{app\_h} \tag{1}$$

where:

T_c is the temperature of the cold water produced by the chiller in the charging phase;
T_h is the temperature of the water returning from the users in the releasing phase;
ΔT_{app_c} is the fixed temperature gradient of the heat exchanger in the charging phase;
ΔT_{app_h} is the fixed temperature gradient of the heat exchanger in the releasing phase;
ΔT_m is the melting range of the PCM.

Assuming approach temperatures of 4°C and inlet temperatures in the heat exchanger of 1°C during the charge and 12°C during the release, the melting range of the PCM has to be between 5°C and 8°C. The narrowness of this domain suggests to adopt a eutectic alloy as heat storage material. In the prototype, the PCM packed in the storage system has a constant melting temperature equal to 5.5°C.

3. Experimental results

During the experiments phase, the cold storage system had a capacity of 5 kWh_{cold}, referred to the cold stored by the latent enthalpy. Each test was conducted until reaching the full charge or release of the energy.

3.1 Charge test

For this test, the chiller is required to provide at 0°C the ethylene glycol based water solution that flows in the primary circuit. The storage system starts in condition of total discharge; the PCM is in a liquid phase and has a temperature higher than its melting point. In Figure 4, the dynamic trends of the thermal power exchanged by the water flows of the primary and secondary circuit are shown. In the first minutes of the test, the unit reaches the solidification conditions and the thermal power presents peak values due to the high temperature differences and high overall heat transfer coefficient. After the PCM starts changing phase, the heat transfer begins to decrease, due to the thermal resistance offered by the forming solid mass. However, the technological solution adopted in the prototype, which includes an inner circuit that increases the heat exchanger capacity, allows to partially overcome this drawback. In fact, at the end of the test, the thermal power exchanged between the primary and secondary circuits amounts to 75% of the total power absorbed by the storage unit.

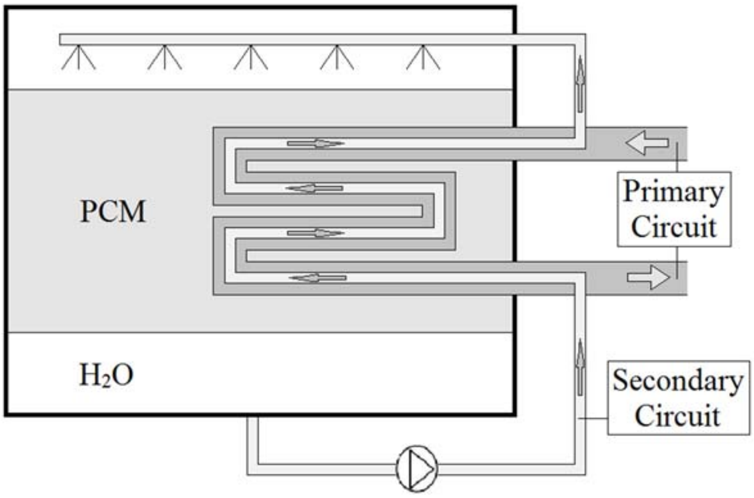

Figure 3: Layout of the thermal storage unit

In Figures 5 and 6, it is shown the inlet/outlet temperature trends over time of respectively the external and internal water flow of the coil. We observe temperatures slightly below the melting range of the PCM, due to a decreasing of the heat exchange between the PCM and the water fed to the tank. In fact, the forming solid mass obstructs the water from reaching some portion of the liquid heat storage material and, in this way, the stream leaving the heat exchanger will cool the same piece of matter over and over, resulting in the subcooling of the solidified PCM. Consequently, the water is in contact with a solid mass that has a temperature lower than the melting point, and therefore the heat exchange decreases due to the lower temperature difference between the substances. Nevertheless, this can be easily avoided adopting an appropriate method of water diffusion (e.g. dynamic nozzles).

Table 1: Mean values during solidification of plotted operating parameters

T_EST_IN	T_EST_OUT	T_INT_IN	T_INT_OUT	P_EST	P_INT
0.091°C	2.430°C	3.833°C	2.649°C	1.684 kW	1.086 kW

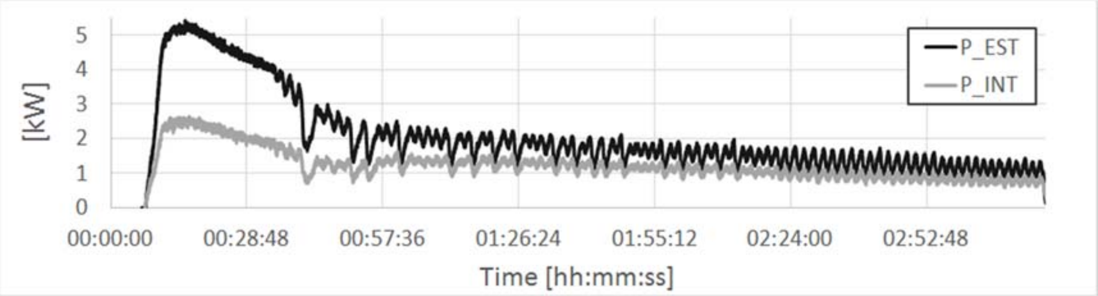

Figure 4: Trends over time of the thermal power exchanged by the primary (P_EST) and secondary (P_INT) circuit water flows.

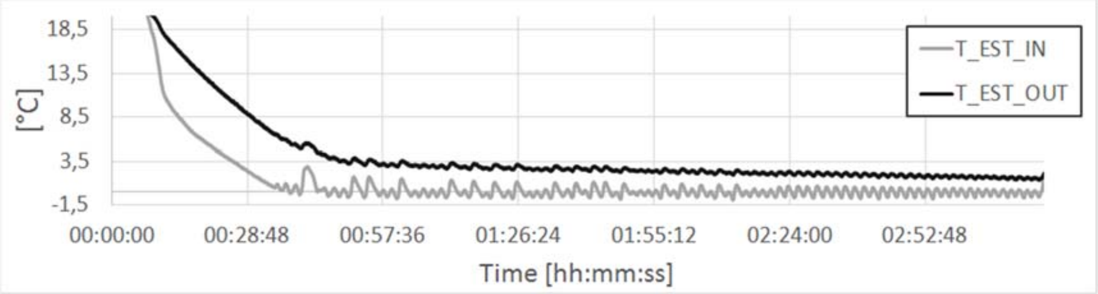

Figure 5: Inlet/outlet temperature trends over time of the external water flow of the coil.

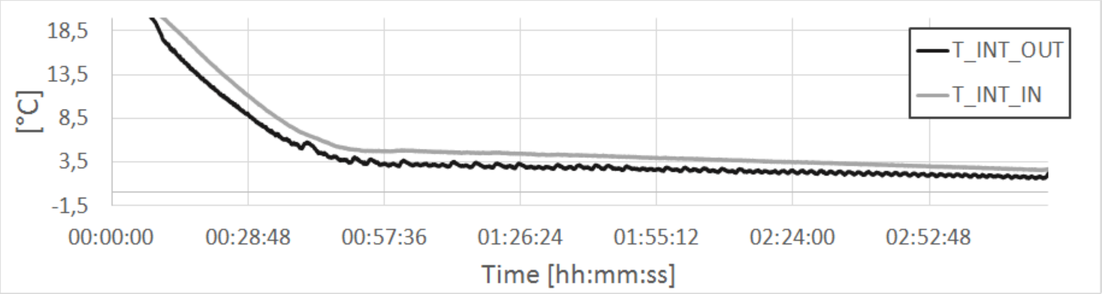

Figure 6: Inlet/outlet temperature trends over time of the inner water flow of the coil.

3.2 Release test

The results shown in Figures 7-9 concern a mixed release test conducted in environmental condition at 26°C. In Figure 7, it is plotted the trends over time of the cooling power released by the storage unit and consumed by the user. The gap between these two curves represents the power delivered by the chiller. We can see that the storage system provides a good part of the whole cooling power requirement: on average 28.7% of the total, with a peak of 54.2% at the beginning of the test. During the release we observe, similarly to the previous case, a slight reduction of the power delivered by the storage unit, due to the decrease of the temperature difference in the coaxial heat exchanger (Figure 8). This is a consequence of the inhomogeneity of melting in the PCM. As before, this drawback can be easily overcome adopting an appropriate method of water diffusion, capable of spreading evenly the water reinserted in the tank. For the sake of completeness, the inlet/outlet temperature profiles of the user are shown in Figure 9.

Table 2: Mean values during fusion of plotted operating parameters

T_COAX_IN	T_COAX_OUT	T_USER_IN	T_USER_OUT	P_COAX	P_USER
12.16°C	8.003°C	7.551°C	12.14°C	1.245 kW	4.337 kW

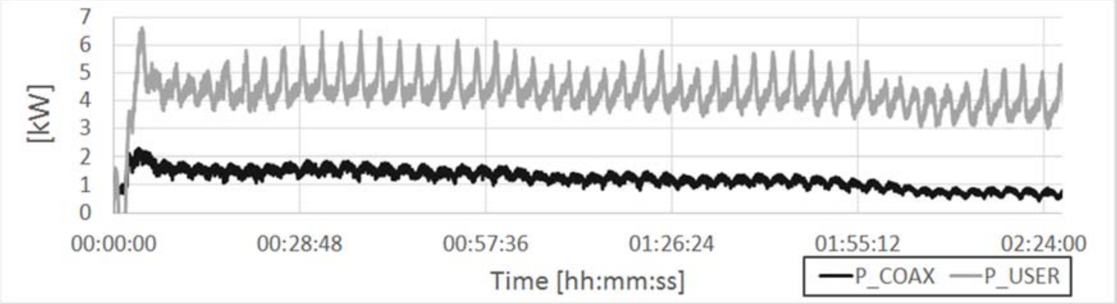

Figure 7: Trends over time of the cooling power delivered by the storage unit (P_COAX) and consumed by the user (P_USER).

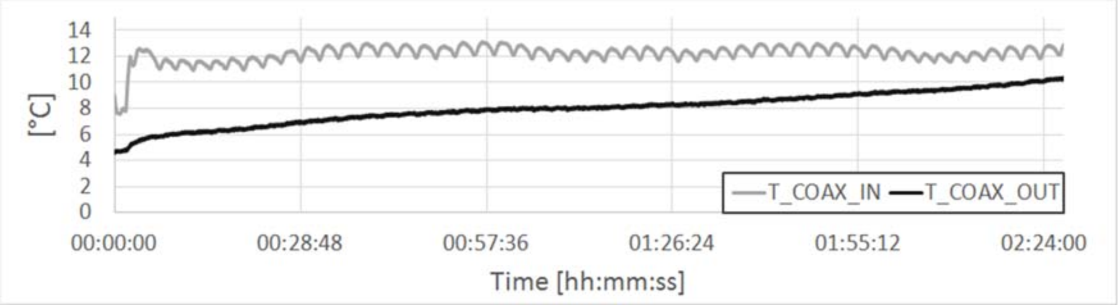

Figure 8: Inlet/outlet temperature profiles of the primary circuit in the coaxial heat exchanger.

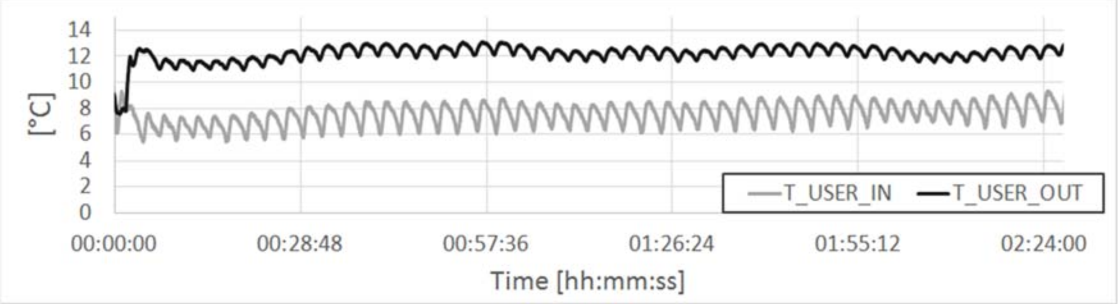

Figure 9: Inlet/outlet temperature profiles of the user.

4. Conclusions

An innovative solution to store cold energy by means of the solidification latent heat of PCMs is presented in this work. The cold storage system is suitable for domestic application (typical in/out primary circuit temperature = 7-12°C) since it is able to store cold energy at 5.5°C. The heat exchanger system implemented in the storage unit allows the increase of energy charge/release dynamics, exploiting the immiscibility between the PCM and a stream of water fed into the tank by means of nozzles, and the heat exchanging between the chiller primary circuit water stream and the secondary circuit water stream, suctioned by a pump from the tank, then sent to the heat exchanger and finally fed to the nozzles. By this technology, the charge/release phases are much quicker and, consequently, the charge/release thermal power is higher.

The test campaign performed on a 5 kWh_{cold} prototype has demonstrated the potentialities of the proposed solution, which is patent pending. A second design phase is required in order to improve the integration between the storage system and the chiller.

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