STUDY ON SEASONAL AND SHORT-TERM THERMAL ENERGY STORAGE USING A PHASE CHANGE MATERIAL EMULSION FOR DISTRICT HEATING APPLICATIONS

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Abstract

Thermal energy storage systems are necessary to increase the flexibility and the share of renewable energy sources in district heating systems. The use of latent heat storage materials (PCM) can reduce the volume of the storage and at the same time the storage temperature needed for a given heat storage. This work studies since a technical viewpoint the potential application of Thermal Energy Storage using “low cost” emulsion of latent heat storage material in district heating for: central heat storage in Solar District Heating systems (seasonal) and de-centralized heat storage (short-term). Results obtained for the seasonal application showed slight improvement achieved by the latent heat storage system using the selected “low-cost” PCM emulsion. On the other hand, the de-centralized TES unit using the PCM emulsions integrated into the DH grid increased the thermal performance and allowed the connection of additional buildings in a saturated grid.

Keywords: District Heating, thermal energy storage, latent heat, phase change materials emulsion, solar thermal.

1. Introduction

In the European Union (EU), buildings account for 40% of the total energy consumption (European Union, 2010), which suggests a great potential for energy savings. In this regard, the EU Directive on energy efficiency (European Union, 2012) recognizes district heating and cooling networks, as key elements for improving the energy efficiency. Thus, the 4th generation of district heating (DH) systems, i.e. low temperature district heating (LTDH), is being developed in order to accomplish the European goals as well as the target of fossil fuel free by 2050 established by some countries, e.g. Denmark. Lower distribution temperatures and more flexible elements of the network provide heat to low-energy buildings and allow the integration of low-temperature heat sources (Fevrier et al., 2012), as it is the case of solar thermal energy. In northern and central European countries, e.g. Denmark, Germany or Austria, new installations also supply heat for the space heating needs. The approach of central solar heating plants with seasonal storage (CSHPSS) is the storage of solar thermal energy from the period of higher offer (summer) to be consumed in the periods of higher demand (winter). These installations are integrated into district heating systems that supply heat for a large number of dwellings and reach a solar fraction about 50% or higher (Nielsen, 2014).

Thermal energy storage systems (TES) cover a central role in this scenario, increasing the efficiency of the energy systems in which they are integrated and the potential utilization of new renewable energies (RES). Although TES themselves do not save final energy, they are able to “move” heat and cold in space and time, correcting the mismatch between supply and demand allowing: a) energy conservation by exploiting new RES; b) peak shavings both in electric grids and DH grids; c) power conservation by reducing the required power of energy conversion machines; d) reduced GHG emissions (IEA, 2014)

The study of thermal energy storage systems (TES) has been a very intensive branch of research in the last decades. Even though the most commonly used method remains based on sensible heat, the latent heat storages, based on the employment of phase change materials (PCM), are an attractive solution, because they provide higher storage density and smaller temperature difference between the absorbed and the released heat than sensible heat storage. Recently, a new class of latent heat fluids, phase change slurries (PCMs), have been analyzed because of their promising role. The main advantage of PCMs is their applicability either as thermal storage medium and/or heat transfer fluid (HTF). They can be continually pumped in charging/discharging cycle, without the necessity of an additional fluid, reducing the losses and increasing the heat transfer thanks to

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the high ratio surface/volume. These slurries are two-phase fluids composed by a PCM dispersed phase in a carrier fluid, usually water. Based on the nature of the dispersed phase, among the PCMs are mentioned the PCM emulsion, ice slurries, microencapsulated PCM slurries (mPCM), clathrate slurries and shape-stabilized PCM slurries (Delgado et al., 2012).

This work studies the potential application of Thermal Energy Storage (TES) using a low-cost emulsion of latent heat storage material (PCM emulsion) in central solar heating plants with seasonal storage (CSHPSS). Furthermore the main outcomes of a second analysis on the application of PCM emulsions into short term de-centralized TES into low temperature district heating (LHTD) networks are presented. The study is made from a technical feasibility viewpoint, analysing the physical advantages and constraints. No economic feasibility analysis is presented due to the lack of appropriate economic information.

2. Thermal energy storage materials: PCM emulsions

The PCM emulsions are mixture of two immiscible fluids whose one forms the continuous phase in which the other part is dispersed in small droplets. They are dispersions with particle size distribution between 1-1000 nm thermodynamically unstable. Usually for energy applications the oil-in-water type, more precisely the paraffin-in-water, is selected because of its suitability given by lower viscosities and higher conductivities than the water-in-oil combination (Edelen, 2012). The properties of a paraffin emulsion depend on many factors like the preparation method, which influences the particle size distribution of the paraffin, and on the surfactants used. The emulsifiers are indispensable components of a PCM emulsion since they provide the kinetical and thermo-mechanical stability between the two phases. The addition of these organic molecules lowers the interfacial tension between the oil and the water and, consequently, lowers the energy required to manufacture the emulsion. Furthermore, the surfactants form a protective layer around the oil droplets preventing coalescence, particles breaking and other instability phenomena like creaming, flocculation and sedimentation. (Shao et al., 2015).

In the current study, two “low cost” paraffinic emulsions were considered. Emulsion 1 is a paraffinic emulsion produced by an oil company, as by-product of the petrochemical industry that has been chosen as test material. This PCM slurry is an anionic emulsion of paraffin with an oleic consistence, with a solid content of about 60% of paraffin, and white color. The thermophysical properties of the selected paraffinic emulsions have been experimentally characterized (Figs. 1-3) applying the methods shown in Table 1, available in the Thermophysical Properties Characterization Lab at the GITSE-I3A facilities in the University of Zaragoza. From the study with the DSC (heating process) and with the T-History (cooling process), the whole phase transition behavior of the Emulsion 1 has been characterized. The phase change occurs in the temperature range of 30 – 50 ºC. Such a wide melting range is due to its by-product nature which enables the cost reduction of the material. However, thermal and rheological properties are not optimal. The enthalpy-temperature curve has been determined (Fig. 1), obtaining a phase change enthalpy value of $h_{sl} \cong 140$ kJ/kg. Some hysteresis between the melting and solidification curves was observed, as well as a slight but not significant subcooling. The specific heat curve of the Emulsion 1 as a function of the temperature was also obtained as shown in Fig. 3. Its value outside the change of phase is about 3.2 kJ/(kg K), which is rather poor and lower than the water specific heat. The measured density range of the Emulsion 1 was 0.9372 kg/m^3 at 20 $^\circ$C - 0.8704 kg/m^3 at 60 $^\circ$C.

Table 1: Properties and equipment used for the characterization of the considered PCM emulsion (Delgado et al., 2015)

Property	Method	Accuracy	Sample size	Equipment
Enthalpy	T-history/DSC	< 10%	≈ 10 g	T-history / DSC 200F3 Maia (Netzsch)
Phase change ΔT	T-history	0.2 K	≈ 10 g	T-history
Specific heat	DSC/T-history	< 1%	≈ 20 mg – 10 g	DSC 200F3 Maia (Netzsch)
Viscosity	Reometer	0.1 nN·m	0.5 cm^3 – 30 cm^3	Reometer AR-G2 TA
Density	Densimeter	< 1%	> 1 cm3	Densimeter DM-40 (Mettler-Toledo)

Subsecuently, a second PCM emulsion, called Emulsion 2, has also been considered in this study for analyzing the applicability of PCM emulsions in Central Solar Heating Plants with Seasonal Storage (CSHPSS. Indeed the advantages obtained with the employment of a PCM usually derive from its utilization as close as possible to the phase transition. For this reason, the study of a second emulsion with a more convenient temperature range of the phase change has been evaluated to explore the potential utilization of PCM emulsions in this application.

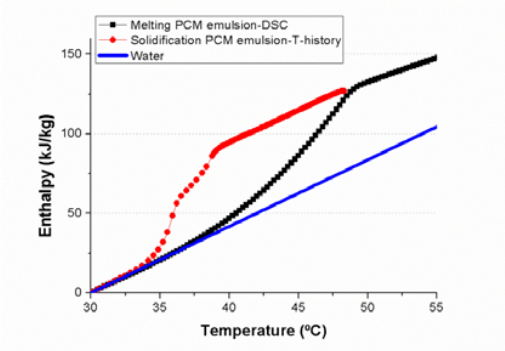

Fig. 1: Enthalpy vs temperature (Emulsion 1)

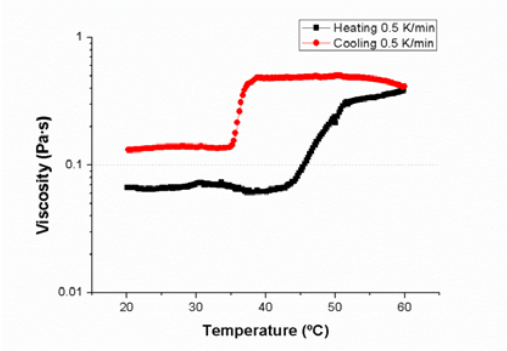

Fig. 2: Viscosity vs. temperature (Emulsion 1)

This Emulsion 2 is a hypothetical material with the same density, thermal conductivity and viscosity values than those experimentally measured for Emulsion 1, but with the curves c_p-T and h-T moved 10 ºC in order to get the phase change in the temperature range of 40 ºC to 60 ºC, as shown in Fig. 3.

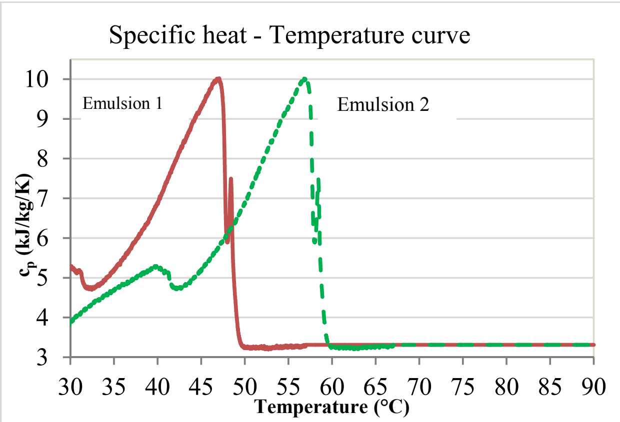

Fig. 3: Specific heat vs temperature curves for the emulsions considered (Emulsion 1 and Emulsion 2).

3. Mathematical model for the evaluation of Central Solar Heating Plants with Seasonal Storage using PCM emulsion as thermal energy storage

The model developed to evaluate the performance of Central Solar Heating Plants with Seasonal Storage (CSHPSS) using PCM emulsion as Thermal Energy Storage (TES) material in the seasonal storage is based on the *simple model* for the predesign of CSHPSS, built on the Engineering Equation Solver (EES, 2016) and developed by Guadalfajara et al. (2015). This model is based on an approximate calculation of the solar collector field production and of the capacity of the seasonal thermal energy storage on a monthly basis and using water as TES working fluid, to match production and demand, as well as to perform easily parametric analysis for the evaluation of CSHPSS. Fig. 4 shows the system scheme and identifies the main energy flows that appear in the system model.

The radiation received, Q_r, over the solar collector is harvested and the production of the solar field, Q_c, is calculated simulating its hourly operation during a representative day of the month. It is considered a complete mixture in the thermal energy storage, i.e. without stratification; so that it keeps uniform the seasonal storage (accumulator) temperature, T_{acu}, along the calculation period, which is a month in the proposed method. With this approach the considered temperature in the tank is lower than the top temperature and higher than the bottom temperature. This approach slightly underestimates the performance of the system, because the estimated temperature of the inlet water of the solar collector is higher than the real value, provoking a reduction of the solar collector efficiency. Nevertheless, the study developed by Braun et al. (1981) revealed that stratification effects have a negligible effect on the performance of CSHPSS. The solar collector performance and the heat losses, Q_l, of the seasonal storage are calculated considering the tank temperature at the beginning of the month.

In a seasonal storage tank, the premise of considering constant the water tank temperature along the month is reasonable due to its high thermal inertia (high volume). A monthly energy balance is used to calculate the temperature in the thermal energy storage at the end of the month. This temperature, water tank temperature at the end of the month, is used to calculate the solar collector performance in the next month.

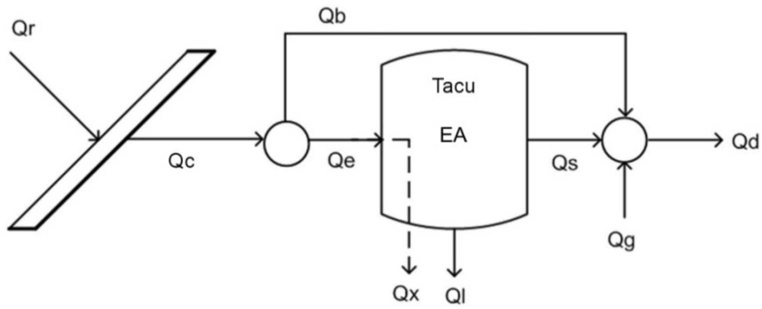

Fig. 4: Energy flow chart of the *simple model* of central solar heating plants with seasonal storage (Guadalfajara et al., 2015)

The monthly operation of the seasonal storage tank has two different operation modes during the year: i) charge and ii) discharge. The charge mode occurs when the production of the solar field, Q_c, is higher than the heat demand, Q_d. Consequently, part of the collected heat is used to attend the immediate demand, Q_b, and the surplus of the collected heat is sent to the seasonal storage for its later consumption, Q_e. In the discharge mode, the heat demand, Q_d, is higher than the production of the solar collector field, Q_c, and the seasonal storage tank is first discharged, Q_s. If it is not sufficient, the auxiliary system, Q_g, provides the required heat to cover the demand. The thermal energy storage operation is constrained by two temperature limits, T_{min} and T_{max}. When the limit of the minimum temperature is reached, the thermal energy storage cannot be discharged anymore and the auxiliary system provides the required heat, Q_g, to fulfill the demand. The thermal energy storage cannot be either charged over the maximum temperature. When it achieves this maximum temperature limit, part of the heat production is rejected, Q_x, to avoid overheating and equipment damage. As the thermal energy storage is warm, the heat losses to the environment, Q_l, are also calculated. The thermal energy accumulated in the storage tank is denoted by the variable EA, and its maximum value EA_{max} depends on the temperature limits. A complete description of this model as well as its validation can be found in Guadalfajara et al. (2015) and Guadalfajara (2016). Note, that this model is suitable for studying the employment of water as storage medium. Although the overall framework of the model has been maintained, several modifications have been required for testing the performance of a different material and especially when considering a PCM emulsion (Rinaldi, 2016).

Thus, replacing the current storage material (water) with the investigated PCM emulsions requires using their properties, obtained from the thermo-physical characterization of the PCM emulsions (Delgado et al., 2015), in the equations related to the storage and to the secondary circuit. While the density of the emulsions, $\rho_{em}(30°C)$ = 921.5 kg/m^3, and their conductivity, λ_{em} = 0.4 W/m/K, were assumed constant in all the analyzed cases, the viscosity depends on the shear stress. However, to minimize the pressure losses, the working fluid conditions have been created in order to attain the lowest viscosities of the curve (~0.05 Pa·s; see Fig. 2). Moreover, when a PCM emulsion is used as storage material, the latent heat of the phase transition is exploited for storing or discharging thermal energy, and it has been necessary to consider the enthalpy-temperature curves measured with the DSC and T-History (Fig. 1).

Additionally, a second modification was implemented. In the model developed by Guadalfajara et al. (2015) it was considered that the fluid circulating through the solar collector transfers the collected heat to the water of the seasonal storage through a heat exchanger with effectiveness, E_{ff} = 0.9. This value is used to calculate the heat exchanger inlet and outlet temperatures. Substituting the heat storage medium with a PCM emulsion, a heat transfer study was required due to the significant different properties of the secondary fluid affecting the efficiency of the process. Consequently, a specific flat-plate heat exchanger was modeled. For a detailed explanation see Rinaldi (2016).

3.1. Base case

The considered base case taken as a reference for the analysis presented in this paper is a CSHPSS, in which a water tank is a seasonal thermal energy storage system (sensible heat), located in Zaragoza, Spain (latitude 41.6º North) supplying heat for space heating and domestic hot water to a community of 1000 dwellings of 100 m^2 each. The input data required few public available data (Guadalfajara et al., 2015): annual demand of domestic hot water, Q_{DHW}, and space heating, Q_{SH}; latitude of the location of the plant; monthly average of daily global radiation on a horizontal surface, H (monthly data); monthly average of daily medium, minimum and maximum ambient temperatures, Ta_{ave}, Ta_{min} and Ta_{max} (monthly data); cold water temperature from the net, T_{net} (monthly data); ground temperature, T_{ter}; and ground reflectance, ρ_g.

The design data for the base case, which were selected based on manufacturers' catalogues, existing plants and bibliographic information, are presented in Table 2.

Table 2: Design parameters for the base case with water as storage material (Guadalfajara et al., 2015; Rinaldi, 2016).

	Parameter	Value		Parameter	Value
Solar Collector Field	RAD: ratio collector area / demand	0.6 m^2/(MWh/yr)	Seasonal Storage	RVA: ratio volume / area	6 m^3/m^2
	A: area of solar collectors	3210 m^2		V: volume of seasonal storage	19,260 m^3
	η_0: optical efficiency	0.816		T_{min}: minimum storage temperature	30ºC
	k_1: 1st order heat loss coefficient	2.235 W/(m^2·K)		T_{max}: maximum storage temperature	90ºC
	k_2: 2nd order heat loss coefficient	0.0135 W/(m^2·K^2)		RHD: ratio height / diameter	0.6 m/m
	β: tilt	45º		U_{acu}: heat transfer coefficient	0.12 W/(m^2·K)
	γ: orientation	0º		A_{acu}: heat transfer area	4101 m^2
	m_s: solar field flow rate	20 kg/(h·m^2)		$\rho \cdot c_p$: heat capacity	4.18 MJ/(m^3·K)
				EA_{max}: storage capacity	1342 MWh
Flat Plate Heat Exchanger	E_{ff}: heat exchanger effectiveness	0.90		Φ: corrugation factor	1.22
	A_{ht}: total heat exchange area	73.78 m^2		N_{pl}: number of plates	42
Annual Heating Demand	Q_{SH}: annual space heating demand	4060 MWh/year	District Heating	T_{sup}: supply temperature	50ºC
	Q_{DHW}: annual DHW demand	1290 MWh/year		T_{ret}: return temperature	30ºC
	Q_d: annual demand	5350 MWh/year		T_{DHW}: DHW temperature	50ºC

Primary design variables considered in the model are: solar collector's area, A (or RAD, which is the ratio of the area of the solar field, m^2, divided by the annual demand in MWh/year), and the volume of the seasonal storage tank, V (or RVA, which is the ratio of the volume of the seasonal storage tank, m^3, divided by the area of the solar field in m^2). The RAD and RVA values for the base case were selected to obtain a significant solar fraction, higher than 50%, avoiding stagnation and heat rejection during the summer period.

Secondary design variables are: the efficiency curve parameters (η_0, k_1, k_2) taken from a manufacturer's catalog (Arcon, 2013) of large solar collectors employed in CSHPSS; tilt, β, and orientation, γ, of the solar collectors, which values were defined considering the geographical coordinates of the plant location; the specific mass flow rate of the working fluid circulating through the solar collectors, m_s, based on the low-flow model (Peuser at al., 2010), characterized by a nominal flow rate of 12-20 l/(h·m^2), and suitable for larger solar thermal installations, since it favors a higher temperature spread between outlet and inlet in the solar collector and pumping savings in the solar field; the temperature of the water supplied to the district heating network, T_{sup} and the temperature of the water returning from the district heating network, T_{ret}, which values were selected considering a high efficiency district heating network (Nielsen, 2014); the minimum and maximum temperatures allowed in the storage tank, T_{min} and T_{max}, and its global heat transfer coefficient for the calculation of the heat losses, U_{acu}. The seasonal storage has been modeled considering a global heat transfer coefficient value of 0.12 W/(m^2·K), in agreement with the specialized literature (Raab et al., 2003; Raab et al. 2005). The seasonal storage is assumed as an underground cylindrical tank with a shape ratio RHD = 0.6 (height divided by diameter). Once the volume is known, the other dimensions can be calculated. The flat plate heat exchanger, consisting of N_{pl} = 42 thin corrugated plates, was modeled following technical specification of manufacturers (ALFA LAVAL, 2015; SWEP, 2015) and recommendations of specialized bibliography (Marin and Guillen, 2013). It has been sized considering the maximum energy flow which has to be handled (in the considered base case location the maximum solar heat production occurred in July 1st at 13 hours), the corresponding inlet and outlet temperatures, the same water mass flow rate in both sides, an effectiveness E_{ff} = 0.90, and a corrugation factor Φ with a typical value of Φ = 1.22.

(i) Comparison of CSHPSS base case behavior: water vs. PCM emulsions

Once the model of the flat plate heat exchanger was implemented in the *simple model*, it was possible to analyze the heat transfer phenomenon when operating with PCM emulsions. Table 3 shows the comparison of the plate heat exchanger working with water in both sides (water-water) or with the investigated PCM emulsions in the secondary side (water-emulsion)

Table 3. Heat transfer study results and comparison of plate heat exchanger performance: water-water vs. water-emulsions.

$\dot{m}_{sto}$= 20.5 kg/s	Water	Emulsion 1	Emulsion 2
v_{sto} (m/s)	0.5362	0.5793	0.5793
Re_{sto}	2633	42.01	42.01
Pr_{sto}	5.53	551.6	551.6
α_{sto} (W/(m^{2}K))	14047	2890	2939
U (W/(m²K))	6346	2313	2344
E_{ff}	0.9067	0.7382	0.7505
Δp_{distr} (Pa)	131317	403012	403012

The results indicate a relevant decrement in the heat exchanger effectiveness when working with the PCM emulsions, caused by the drop of the Reynolds number and, consequently, of the global heat transfer coefficient.

This phenomenon is due to the high viscosity (0.05 Pa·s) of the investigated material compared to the water. The significant rise of the Prandtl number highlights that the momentum diffusivity dominates the heat transfer in the PCM emulsions, while the pure conduction diffusivity in the fluid is low. Choi et al. (1994) reported that the local convective heat transfer coefficient varies slightly in forced convection heat transfer with phase-change-material slurries. However, the lack of experimental study and literature about test of PCM emulsions in plate heat exchangers does not permit to consider this factor. Consequently, the heat convective coefficient of the emulsion and the overall heat transfer performance of the plate heat exchanger experience a significant reduction. This phenomenon affects the operation of the global CSHPSS plant since the solar collected heat is not well discharged and utilized. Another important aspect, related to the utilization of the PCM emulsion in the secondary circuit, is the pressure losses. Just analyzing the distributed pressure drop (Δp_{distr}) that occurs in the heat exchanger, they result almost four times higher than those generated by the water circulation in the same circumstances. The high viscosity of the studied PCM emulsion arises to be one of the critical factors on which it is necessary to work for achieving a satisfactory behavior.

Table 4. TES comparison: water vs. PCM emulsions (Annual results. Base case, T_{max}= 90°C, V= 19260 m^3, A= 3210 m^2).

	Water	Emulsion 1	Emulsion 2	*Annual energy flows*	Water	Emulsion 1	Emulsion 2
PHE E_{ff}	0.9067	0.7504	0.7641	Q_x (MWh/y)	0	0	0
$EA_{max,calc}$ (MWh)	1153	1167	1180	Q_l (MWh/y)	148.8	140.2	138.5
Solar fration and efficiencies				Q_{aux} (MWh/y)	2359	2368	2342
SF	0.5591	0.5574	0.5622	Q_c (MWh/y)	3140	3122	3146
η_{coll}	0.5706	0.5673	0.5717	Q_e (MWh/y)	1244	1252	1263
η_{sto}	0.8803	0.8880	0.8904	Q_s (MWh/y)	1095	1111	1125
η_{sys}	0.5435	0.5419	0.5466	Q_b (MWh/y)	1896	1870	1883

Table 4 illustrates the results obtained from the annual calculation of the CSHPSS. As can be observed, in these circumstances the substitution of the water with the PCM slurry in the storage does not represent any significant benefit. The storage temperature along the year with both water and emulsion does not reach the maximum fixed constrain (T_{max}= 90°C) and it remains below 82°C in all the cases, for water and for both PCM emulsions. In terms of solar fraction, SF, and global efficiencies, Emulsion 2 presents a slightly improved performance while Emulsion 1 is even slightly worse than water. Even though the solar heat transferred to the secondary circuit Q_c diminishes in the case of Emulsion 1 compared to the case of water-water, surprisingly the calculated energy accumulated in the storage ($EA_{max,calc}$) is higher. This was mainly due to two factors: the decrease of the heat losses in the storage (Q_l), due to the lower temperatures in the seasonal storage tank when using PCM emulsions as TES, and the change in the collector efficiency curve along the year (Rinaldi, 2016). Although the yearly solar collector field efficiency (η_{coll}) is reduced and, consequently, the yearly solar heat collected (Q_c), the solar field presents a greater performance in the summer months, when a significant share of energy is stored, due to the lower temperature in the seasonal storage when operating with PCM emulsions. The critical feature that was recognized in the utilization of the PCM emulsion in this particular case is the large operating temperature range. Indeed, the advantages obtained with the employment of a PCM usually derive from the utilization of the material always close to the phase transition. The chart of the cp_{em} of the PCM emulsions as the function of temperature (Fig. 3) shows that the cp_{em} outside the change of phase is about 3.2 kJ/(kg K), which is a rather poor value and lower than the water specific heat. Accordingly, the benefits linked to handling PCM materials are limited by the running conditions of this application since it has to operate mostly out of the melting-solidification stages.

(ii) Sensitivity analysis of CSHPSS operation with PCM emulsions

From the first two steps of the calculation procedure, the results highlight that two are the main obstacles which make difficult the exploitation of the real PCM emulsion as seasonal storage material: a) the high viscosity and b) the incompatibility between the phase change temperature and the operating conditions of the storage. Thus, a sensitive analysis was performed based on the base case design, decreasing only the seasonal storage upper limit (T_{max}) and varying this parameter from T_{max}= 80°C until the minimum allowed temperature, T_{max}= 60°C, for discharging heat to the DH grid.

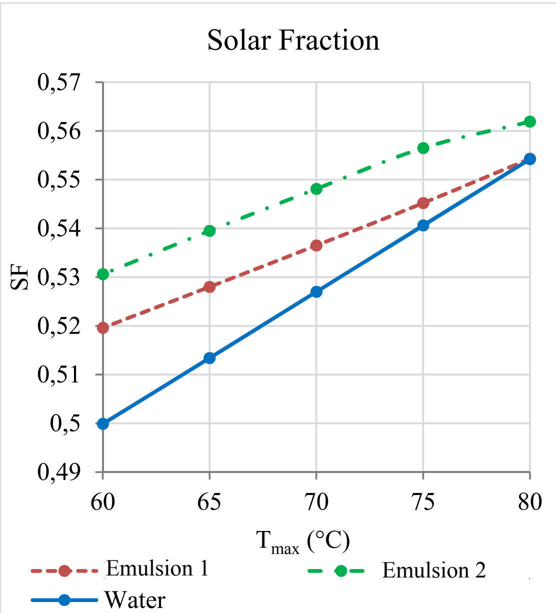

Fig. 5. Base case: Solar fraction (SF) versus T_{max} of TES.

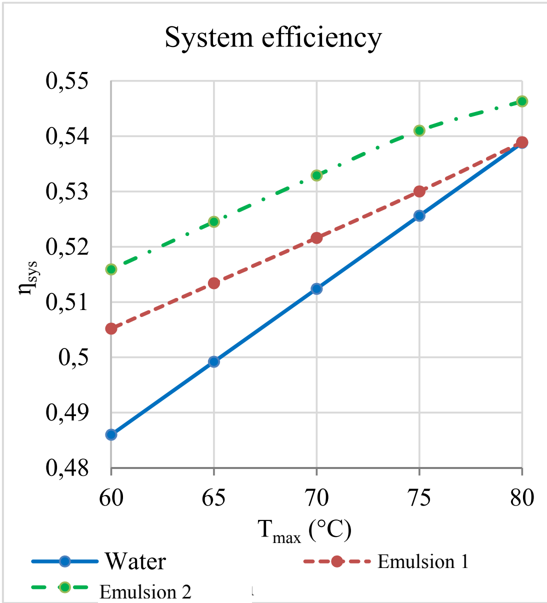

Fig. 6. Base case: System efficiency, η_{sys}, versus T_{max} of TES.

As shown in Figs. 5 and 6, the benefit coupled with the replacement of water with the studied emulsions grows moving T_{max} towards values closer to the phase transition. This benefit is particularly interesting in the case of Emulsion 2, in which enables to achieve a 6% higher of solar fraction with respect to the water as TES material thanks to the increased efficiency of the system. The growing heat capacity of the PCM emulsions working closer to the phase transition permits to accumulate more thermal energy in the same volume (see Table 5). Nevertheless, from results shown in Table 5 it is possible to note that when the maximum allowed temperature in the seasonal storage is T_{max}= 60°C, some solar heat is rejected. However, this phenomenon is significantly lower when PCM emulsions are employed and particularly operating with Emulsion 2, generates a reduction of about 40% in heat rejection compared with the water case. In order to avoid heat rejection when working with the Emulsion 2 and T_{max}= 60°C, the volume of the seasonal storage tank should be increased about 8540 m^3, requiring a seasonal storage tank of 27,800 m^3 (Rinaldi, 2016). However, in this later case 305 MWh/y would be still rejected if the seasonal storage tank were operating with water. An additional volume of about 8740 m^3, reaching a tank volume larger than 36,500 m^3, would be required in order to avoid heat rejection when water is used as storage medium and T_{max}= 60°C. In these conditions, the volume of the seasonal storage with Emulsion

2 would be about 25% smaller than when operating with water. Additionally, note in Table 5 that the heat transfer in the flat plate heat exchanger operating with PCM emulsions, being worse than operating with water (Table 3), increases due to the higher specific heat values, since the operation temperature range is more favorable and closer to the phase change.

Table 5. TES comparison: water vs. PCM emulsions when T_{max}= 60°C (Annual results, Zaragoza, V= 19260 m^3, A= 3210 m^2).

	Water	Emulsion 1	Emulsion 2	*Annual energy flows*	Water	Emulsion 1	Emulsion 2
PHE Eff	0.9067	0.7907	0.8073	Q_x (MWh/y)	567.9	421.5	343.2
$EA_{max,calc}$ (MWh)	668	815.4	884	Q_l (MWh/y)	120	118	121.4
Solar fration and efficiencies				Q_{aux} (MWh/y)	2676	2570	2511
SF	0.4999	0.5196	0.5306	Q_c (MWh/y)	3362	3319	3303
η_{coll}	0.6110	0.6032	0.6003	Q_e (MWh/y)	1318	1315	1307
η_{sto}	0.9089	0.9103	0.9071	Q_s (MWh/y)	629.9	776	842.3
η_{sys}	0.4860	0.5052	0.5159	Q_b (MWh/y)	2044	2004	1996

3.2. Geographic analysis of CSHPSS operation with PCM emulsions

Since the CSHPSS performance is strongly related to the climate conditions as well as to the heat demand characteristics, the assessment of a plant situated in a different European climatic zone, as it is the case of Oslo (Norway), was also analyzed. The location of the CSHPSS highly influences the design process and parameters of the whole system. Considering a colder area than the south of Europe, the heat demand rises because of the higher space heating requirements, caused by the more severe winters, as well as its distribution (SH demand) along the year. Moreover, the solar radiation decreases and consequently, the solar energy production per area of solar collector falls down making necessary the installation of a larger solar field surface per MWh of heat demanded (i.e. increase of RAD). Furthermore, the lower average environmental temperature along the year reduces the collector efficiency because of the higher heat losses with the surroundings. In regard to the seasonal storage, colder climates need relative smaller storage per unit area of solar collector (i.e. smaller RVA ratio). Warmer locations, present higher accumulation requirements per area of solar collector because of the shorter heating period and of the larger solar energy yielded in summer (Guadalfajara, 2016). Thus, the CSHPSS placed in Oslo (latitude 59.93º North), sized according to the criteria previously adopted for the plant in Zaragoza (1000 dwellings of 100 m^2 each, T_{max}= 90°C, SF~0.5, no heat rejection), owns the specific design parameters listed in Table 6. The rest of the parameters are the same shown in Table 2.

Table 6: Design parameters for the CSHPSS in Oslo with water as seasonal TES material (1000 dwellings of 100 m^2 each, T_{max}= 90°C, SF~0.5, no heat rejection) (Rinaldi, 2016).

***CSHPSS Oslo* (latitude 59.93º North)**							
Solar collector field		*Seasonal storage*		*Flat plate heat exchanger*		*Annual heating demand*	
RAD	1.39 m^2/MWh	RVA	1.75 m^3/m^2	E_{ff}	0.9	Q_{SH}	6427 MWh/y
A	11,383 m^2	V	19,920 m^3	A_{ht}	342.47 m^2	Q_{DHW}	1769 MWh/y
β	60°	A_{acu}	4196 m^2	N_{pl}	116	Q_d	8197 MWh/y
γ	0°	Ea_{max}	1389 MWh				

The heat transfer problems occurring when operating with PCM emulsion in the seasonal TES already explained in subsection 3.1 were also observed in this case. Indeed, the change of the equipment dimensions does not vary the worsening heat transfer performance utilizing the PCM emulsions instead of water. As already noticed, the heat exchanger effectiveness working with the Emulsion 2 appears improved respect to the Emulsion 1 because of its higher average specific heat in the working temperature range (Rinaldi, 2016). A comparison of the behavior of the CSHPSS located in Oslo operating with different seasonal storage materials (water and PCM emulsions) are shown in Table 7. As occurred in the base case analysis, the Emulsion 1 does not provide any enhancement of the overall system efficiencies. Additionally, the seasonal storage with this PCM emulsion as storage material has a lower heat storage capacity than with water. Consequently, the main benefit linked to the employment of a PCM is lost as well as the possibility of the application of this solution in the studied conditions (large temperature range). In contrast, interesting outcomes have arisen from the CSHPSS calculations using the Emulsion 2. From a first look to Table 7, there is a slight increase of the overall plant performance as well as of the component performances coupled with the higher maximum storage capacity of the seasonal TES (EA_{max}). Thus, it is observed an appreciable rise of the solar production Q_c (+74 MWh/y) and the decrease of the tank losses Q_l (-6.4 MWh), obtaining as a consequence some heat rejection (Q_x= 28.2 MWh).

Table 7. TES comparison: water vs. PCM emulsions (Annual results. Oslo, T_{max}= 90°C, V= 19,920 m^3, A= 11,383 m^2).

	Water	Emulsion 1	Emulsion 2	*Annual energy flows*	Water	Emulsion 1	Emulsion 2
PHE E_{ff}	0.8951	0.7525	0.7600	Q_x (MWh/y)	0	0	28.2
$EA_{max,calc}$ (MWh)	1372	1350	1419	Q_l (MWh/y)	194.1	187.8	187.7
Solar fration and efficiencies				Q_{aux} (MWh/y)	4129	4148	4077
SF	0.4958	0.4935	0.5021	Q_c (MWh/y)	4254	4282	4328
η_{coll}	0.3755	0.3780	0.3820	Q_e (MWh/y)	1468	1495	1538
η_{sto}	0.8678	0.8744	0.8779	Q_s (MWh/y)	1274	1255	1322
η_{sys}	0.3584	0.3567	0.3630	Q_b (MWh/y)	2786	2787	2790

The explanation to these effects can be found evaluating the seasonal storage temperature (T_{acu}) along the year (Fig. 7). Indeed, the higher specific heat of the PCM emulsion during the phase change generates lower storage temperatures. This fact reduces the heat losses of the tank, which are larger in a cold climate. Furthermore, since the storage temperature affects the solar field efficiency, its decrement leads to higher collector performances despite the worse solar heat transfer through the PHE, thanks to the lower temperature of the working fluid when the PCM emulsion is used. The most profitable solution in order to avoid the heat rejection is the reduction of the solar field area. Since the collector production is more effective, a smaller surface area of solar collectors can be installed for generating the same amount of solar heat avoiding heat rejection. The value obtained was 11,040 m^2, which is 335 m^2 smaller than the required for satisfying the heat demand employing water in the Seasonal TES. Despite the smaller solar field, the whole plant operation with the Emulsion 2 is even slightly more efficient than operating with water, reaching very similar values to those shown in Table 7.

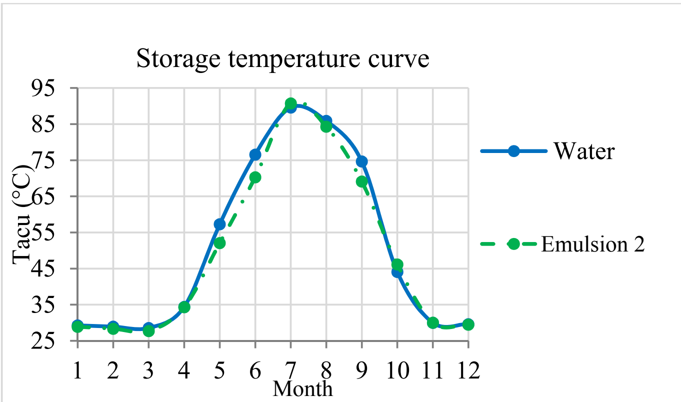

Fig. 7. Monthly temperatures of the water and Emulsion 2 in the seasonal TES

From the conclusions achieved studying the base case, working with temperatures closer to the phase transition of the emulsion would allow to accomplish more relevant advantages. Consequently, a sensitivity analysis lowering T_{max} of the Oslo seasonal TES has been carried out in order to create a more favorable state for the PCM emulsion operation.

As shown in Figs. 8 and 9, and similarly to the base case, the performance of the yearly plant operation continually gets worse with the decrease of the seasonal TES maximum temperature, T_{max}. Indeed, the volume of the seasonal TES is kept unchanged (V= 19,920 m^3). It has been sized to be appropriate for reaching T_{max} = 90 ºC. Thus, when limiting T_{max} to a lower value, the seasonal TES is not able of storing all the collected solar energy and there is heat rejection, reducing the solar fraction and the system efficiency. However, Figs. 8 and 9 show that this decay is smaller for the PCM emulsions, particularly for the Emulsion 2. Note that the lower is T_{max}, the better is the paraffinic emulsions performance and, consequently, the lower is the reduction of SF and η_{sys} compared to the water case. Further, note that the whole SF and η_{sys} variations along the sensitivity study are less significant in the Oslo case in comparison with the sensitivity analysis of the base case (Figs. 5 and 6). These observations show that in cold climate the variation of T_{max} has a less important impact on the overall efficiencies, due to the improvement of the solar collector efficiency when lowering the seasonal TES temperature, which provokes an increased solar production. The reduction of the storage temperature can be performed substituting the water with the PCM emulsion or by lowering $T_{max.}$

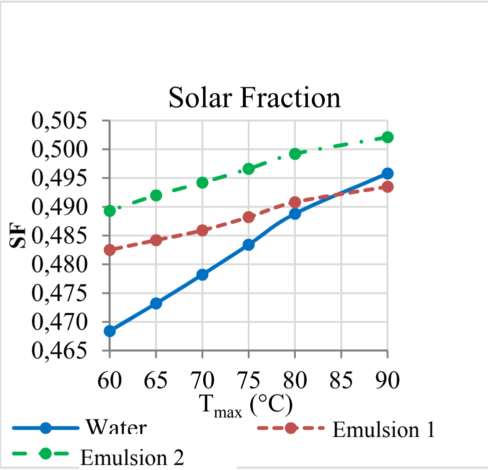

Fig. 8. Oslo case: Solar fraction (SF) versus Tmax of TES.

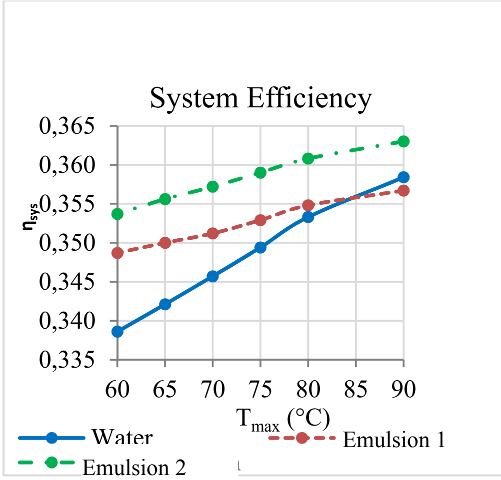

Fig. 9. Oslo case: System efficiency, ηsys, versus Tmax of TES.

In the Oslo case, the required collectors surface area, for a seasonal TES using Emulsion 2 as storage material with T_{max}= 60°C, avoiding heat rejection (Q_x= 0 MWh/y), and maintaining unchanged the volume of the seasonal TES (V = 19,920 m^3), is A = 7270 m^2. This represents a reduction of the solar collector area of about 36%, in comparison with the design value at T_{max} = 90°C (Table 6). As a consequence, the obtained solar fraction is obviously lower, SF = 0.4192, when T_{max}= 60°C. If the storage material employed in these operating conditions and with these last design values were water instead of Emulsion 2, there would be a significant heat rejection (Q_x = 192.8 MWh/y) requiring a seasonal TES 28% larger, i.e. with a volume of 25,450 m^3. These results show that significant reductions in seasonal TES volume could be achieved when using PCM emulsions with appropriate properties. The narrower is the temperature range of the seasonal TES the better is the behavior of the PCM emulsion thanks to the longer period working at the phase transition.

4. Integration of de-centralized TES with PCM emulsion into LTDH

This section presents the results of a research carried out on the improvement that a utility of Low Temperature District Heating (LTDH) can undergo when a tank of thermal energy storage is integrated into its network. The performance of two different cases, with water and with a PCM emulsion, have been analyzed and compared within a set of 40 residential buildings consisting of twenty-five apartments each, i.e. 500 dwellings, located in Zaragoza (Spain). A detailed heat transfer model of the storage tank was established to determine the actual behavior of a system TES-DH in de-centralized storage application. The chosen configuration is a typical cylindrical tank with internal coils through which the DH water flows to carry out the charge and discharge processes. The outcomes show the benefit of the operation with either water or PCM emulsion as storage materials, with a noticeable advantage for the PCM emulsion. See Rinaldi (2016) for further details of the model and the analysis.

The results obtained show that a de-centralized TES unit integrated into the DH grid is able to curtail the peak demand and, consequently, to reduce the mass flow that the network has to handle. This solution allows the connection of additional buildings in a saturated grid.

Concerning the additional new area that could be connected to the district heating (DH) network thanks to the de-centralized TES unit, it has been possible to maintain a regular nominal power supplied by the DH without raising the production during the peak hours. Furthermore, this solution permits to move the heat production to the night where the electricity costs and requirements are lower. Additionally to the potential economic benefits, the installation of de-centralized storages allows to the power unit to operate more regularly and provide the peak energy that otherwise should be supplied by auxiliary units (e.g. boilers).

In respect to the PCM emulsions as storage medium, it has been shown that their use provides remarkable benefits in relation to the conventional use of water. These positive effects are due to the favorable working conditions due to the phase change of the PCM. According to the priority of the system design and to the main objective pursued, the particular advantages are: 1) Accumulation of a greater amount of thermal energy than water in the same configuration of the system, generating a smoother operation with less abrupt changes in the mass flow circulating in different hours. Thus, higher TES temperature during the discharge hours guarantees an easier control of mass flows variation. Additionally, the flat-plate heat exchanger in the customers substation works better thanks to the greater temperature at the heat exchanger inlet, $T_{HE,in,}$ also when part of the heat is delivered by the TES. 2) Reduction of the storage volume and, consequently, of the investment costs in order to achieve the same system operation than that attained using water. 3) Reduction of the nominal monthly DH power and, therefore, the additional mass flow rate that the existing DH pipes have to handle with the connection of the new area. Fig. 10 shows an example of the results obtained (Rinaldi, 2016).

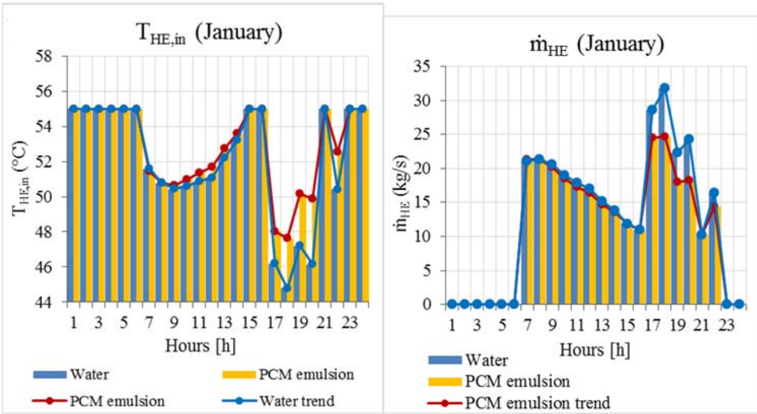

Fig. 10 Example of the results obtained in the case of Vsto,eff=180 m^3 in Zaragoza (Spain)

5. Conclusions

The potential application of Thermal Energy Storage using a low-cost emulsion of latent heat storage material (PCM emulsion) in two different District Heating applications has been studied from a technical viewpoint. It has not been presented an economic analysis due to the lack of appropriate economic information.

The analysis of the behavior of CSHPSS operating with two different PCM emulsions has been performed for several scenarios in different climates (Zaragoza, Spain and Oslo, Norway). The study revealed that the wide temperature working range of this application makes non-optimal the operation with the analyzed PCM emulsions, particularly with Emulsion 1. The operation of the CSHPSS operating with the improved Emulsion 2 has shown some advantages. The temperature stabilization produced by the phase change, especially along the charging process, improved the solar field production and, consequently, the overall system performance and the solar fraction, as well as the storage efficiency. Thus, the material properties enhancements that are necessary to seek for the application of PCM emulsions in CSHPSS are: i) higher density; ii) lower viscosity; and iii) more suitable h-T and c_p-T curves: all the phase transition temperature range has to be included in the working interval of the STES, higher c_p values outside solidification-melting window, higher c_p peak, reduced phase transition range for a more relevant temperature stabilization.

The connection of de-centralized TES units has demonstrated to be a valuable solution for the peak shaving of the thermal demand and for the decrement in the DH mass flow permitting additional connections. The usage of the analysed PCM emulsion improved the overall system operation thanks to the temperature stabilization generated by the change of phase, and to the greater thermal storage capacity of the TES. The hydraulic transients resulted less abrupt and the mass flow changes smoother. This suggested an easier regulation of the DH-TES connection and more regular working conditions, allowing higher efficiencies of the components.

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