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OPTIMIZATION MODEL OF SOLAR COOLING SYSTEM WITH LATENT HEAT STORAGE

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Abstract. Today, the fastest growing end-use in the buildings sector is cooling demand, notes the International Energy Agency (IEA). In the last few years, the interest in solar cooling systems has been growing globally. Solar cooling systems are the next solution to meet the growing demand for air conditioning. The literature analysis shows that solar cooling systems mainly use single-stage absorption chillers, with water as the working fluid, and only a small fraction of them use phase change materials to improve heat storage. Based on previous studies on solar-assisted cooling systems, the use of phase change materials for thermal storage should be investigated.

The paper will present a study of a solar cooling system with the optimized PCM thermal storage, with the aim of stabilizing the operation of heat storage, taking into account the volatility of solar energy, the impact of short-term operations and peak hours on the amount of heat produced. This means that the amount of electricity consumed to heat up the accumulation tank will be significantly reduced. The optimization model in simulation software will be performed to test solar cooling system with latent heat storage, with aim to investigate the efficiency of the developed latent energy storage and provide technical guidance for the implementation of such system in the practice. All indicators, including environmental impact and economic calculations, will be identified in order to determinate the specific systems for foresight market uptake.

Keywords: Solar cooling, thermal energy storage, phase change materials.

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1. Introduction

The indoor climate in buildings has a major impact on occupant productivity, especially during the hot summer period when large amounts of energy are used to cool rooms. In 2020, global demand for space cooling continued to grow, in part due to greater home cooling with more people spending more time at home. Space cooling accounted for almost 16 % of the final electricity consumption of the building sector in 2020 (approximately 1 885 TWh) [1]. As solar cooling systems (SCS) use solar thermal energy as a source of energy, they have the potential to substantially reduce the proportion of conventional energy used to cool rooms and the negative impacts they generate. However, there is a fundamental shortcoming of solar energy, a mismatch between available energy and consumption, which makes it necessary to store the energy. Phase change materials (PCMs) are effective for storing heat in thermal energy storage because they can store not only thermal energy beyond temperature change as sensible heat storage but also through melting and solidification, as latent heat storage, which occurs over a narrow temperature range allowing 5 to 14 times more thermal energy to be stored than sensible thermal energy storage of the same size [2]. Latent heat storage uses the phase change of matter between different aggregate states – gas/liquid, solid/gas, solid/liquid and solid/solid [3].

Based on a literature analysis [4, 5], the SCS working in a temperature range of 60–120 °C were determined to be most efficient, depending on the thermal heat supplier used in the chiller and the capacity of the cooler. It is therefore necessary to look in depth at the possibility of integrating the various PCMs into the energy storage to stabilize its functioning, thereby increasing the COP (Coefficient of performance) of solar thermal driven air-conditioning system.

2. Methods

2.1. Solar Thermal Cooling systems

In solar cooling systems a mixture of ammonia, lithium bromide (LiBr) and water can be used in the absorption cycle [6]. A solar assisted absorption cooling system using a mixture of 60 % LiBr and 40 % water has been investigated and the performance of the system has been optimized using various thermodynamic analysis methods. Among other sorption cooling systems, absorption cooling circuits are the mainstream in the context of high COP, in particular at temperatures above 80 °C [7]. However, when comparing absorption cycle COP (0.5 to 0.8) to traditional cooling systems with COP up to 3.0, the absorption cycle efficiency optimization becomes significant [8]. The generator of the chiller is warmed up using heat from solar thermal panels. The heat is collected and stored in a thermal storage tank, after which the required amount of heat is supplied to the generator. It is

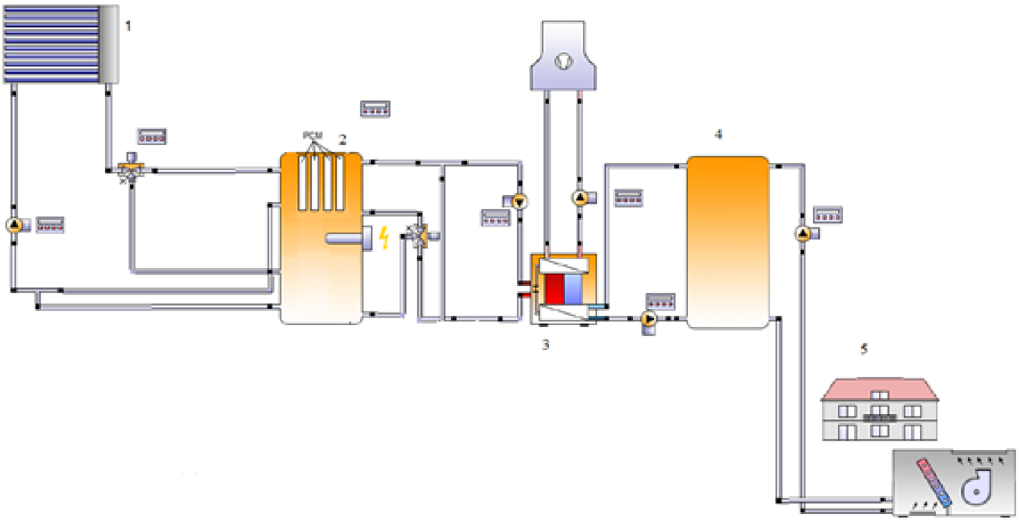

FIGURE 1. Scheme of solar cooling system.

estimated that the system heat carrier could reach 85–90 °C using the solar thermal panels [9]. The heat supplied to the generator will be used to evaporate the water from the LiBr-water solution mixture returning from the absorber.

The simulation Model of Solar Cooling System was developed with absorption chiller nominal power −8 kW and maximal cooling capacity of 11 kW. Heat is mainly produced by solar collectors and used for thermal driving chiller. In the presented case, heat output of solar thermal system is 15 kW [10]. The solar thermal system includes one cubic meter thermal energy storage tank with an additional 8 kW electric heater.

Solar thermal cooling system model has the following parts: 1 – solar collectors, 2 – thermal storage tank with integrated PCM encapsulate tubes and auxiliary heater, 3 – chiller (evaporator, condenser) with cooling tower, 4 – cold storage and 5 – consumer part. Basic configuration of solar thermal absorption cooling system technologies is shown in Figure 1. A simulation model was developed and validated to assess the impact of the PCM on the operation parameters of the solar assisted cooling system.

During the day solar available energy is volatile. It also has impact on the temperature in the thermal storage. This is shown in the case study where an experimental solar pilot plant was developed to verify the PCM behavior under realistic conditions, in which following stratification, the PCM modules were integrated at the top of the hot water storage tank. In addition, PCM module is designed to use multiple cylinders, notes Luisa F. Cabeza et al. [11]. The scientist concludes that the introduction of the PCM module into thermal water storage tanks for DHW supply is highly prospective technology. This will allow hot water to be supplied for a longer period, even without an auxiliary source, or use smaller tanks for the same application. As shown in Maher Shehadi et al. study [9], stable temperature for heating the generator has great importance in order to raise absorption cooling systems at COP. It can be seen in the Figure 2.

The Additional COP of solar cooling system shall be determined as follows:

$$COP_{thermal} = \frac{\text{Useful Power [kW]}}{\text{Input Power [kW]}}. \tag{1}$$

When using PCM in a thermal energy storage tank, the additional useful energy will be the energy of the PCM storage. The COP with additional energy from hot water heating will be calculated by following equation:

$$COP_{thermal,modified} = \frac{\text{CO} + \text{SHO} + \text{WHO} + \text{UpfPCMs}}{\text{ASPfC}}, \tag{2}$$

where

CO	Chiller Output [kW],
SHO	Space Heating Output [kW],
WHO	Water Heating Output [kW],
UpfPCMs	Usefull power from PCM store,
ASPfC	Available Solar Power from Collector [kW].

2.2. PCM SELECTION CRITERIA

In selecting PCMs to be applied as LHTES materials for thermal storage, there are some important aspects to consider. The main criteria [12] for selecting PCMs are:

- Thermophysical properties: PCM, within the required temperature range, has high latent heat of fusion, high conductivity, high specific heat, cyclic stability, high density, low phase transition volume change, low vapor pressure at operating temperature, and consistent melting.
- Kinetic properties: high nucleation rate and high crystal growth rate (achieving optimal recovery from storage system).

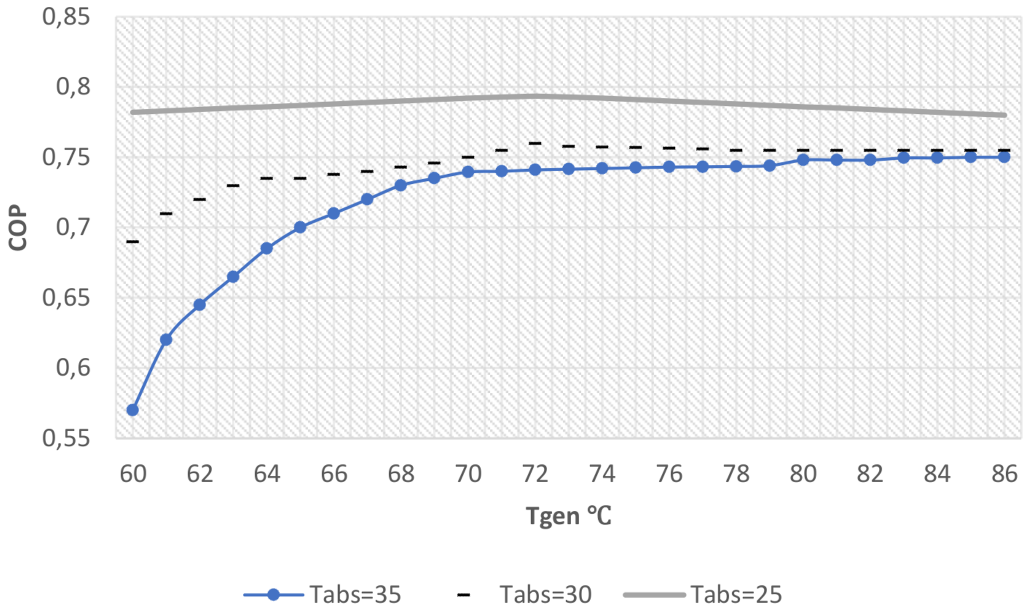

Figure 2. COP of the absorption cycle depending on the generator temperature, accounting for various absorber temperatures [9].

PCM/parameter	$MgCl_2 \cdot 6H_2O$	RT100	Erythritol
PCM melting point, Tm [°C]	116.7	99	117.7
PCM heat of fusion, l_{PCM} [$\mathrm{kJ\,kg^{-1}}$]	168.6	168	339.8
Specific heat of PCM, liquid, $C_{p,l}$ [$\mathrm{J\,kg^{-1}°C^{-1}}$]	2.6 (120 °C)	2.4	2.8
Specific heat of PCM, solid, $C_{p,s}$ [$\mathrm{J\,kg^{-1}°C^{-1}}$]	1.4 (20 °C)	1.8	1.4
Thermal conductivity of PCM, liquid, k_l [$\mathrm{W\,m^{-1}°C^{-1}}$]	0.6 (120 °C)	0.2	0.3 (140 °C)
Thermal conductivity of PCM, solid, k_s [$\mathrm{W\,m^{-1}°C^{-1}}$]	0.7 (20 °C)	0.2	07 (20 °C)
Density of PCM, liquid, r_l [$\mathrm{kg\,m^{-3}}$]	1450 (120 °C)	770 (130 °C)	1300 (140 °C)
Density of PCM, solid, r_s [$\mathrm{kg\,m^{-3}}$]	1570 (20 °C)	940 (20 °C)	1480 (20 °C)

Table 1. Main parameters of the selected PCM.

- Chemical properties: fully reversible cycle, chemically stable without deterioration after multiple freeze/melt cycles, chemically compatible with encapsulating materials, non-corrosive, non-toxic, non-explosive, non-flammable.
- Economical characteristics: cost effectiveness and commercial availability for large-scale practice.
- Environmental characteristics: environmentally friendly, non-polluting over a lifetime, and has the possibility of recycling.

Based on the above criteria, PCM – $MgCl_2 \cdot 6H_2O$, paraffin RT100 and Erythritol to enhance the efficiency of a LiBr-H_2O solar cooling system was selected. Similar findings are also in place for other researchers [13]. Their main parameters of selected PCM [14–16] are summarized in the Table 1.

Highest energy density for a specified mass of all PCMs was calculated using following equation:

$$Q = m[C_{p,l}(T - T_m) + \lambda + C_{p,s}(T_m - T_{ref})], \quad (3)$$

where m [kg] is the mass of material, C_p [$\mathrm{J\,kg^{-1}°C^{-1}}$] is a specific heat of material, L [kW] is the latent heat, and T [°C] is the temperature. The thermal conductivity λ is calculated from the measured thermal diffusivity a, density r and heat capacity c_p.

2.3. STORAGE TANK DESIGN

For most latent heat applications, methods to improve heat transfer are required, as majority of phase change materials have inappropriately low thermal conductivity [17, 18] resulting in slow charging and discharging rates. Series of methods have been used to optimize the heat transfer properties of PCM. Among the most widely used methods are the finned tubes [19], rings and bubble mixing techniques [20], the application of carbon fibre and multitubes [21]. Most of the studies report significant improvements in the thermal conductivity of phase change materials but have not compared them to other improvement techniques. From this it can be concluded that the design of the thermal storage tank is in charge of efficiently charging/discharging the PCM as needed. Shell-and-tube heat exchangers are the most widely used type of storage technique, with PCM on the shell side. For example, Francis Agyenim [22] conducted a study on a variety of PCM tube configurations, where the heat transfer improvement for three different modifications – circular fins, longitudinal fins and multitube systems was compared. The findings indicate that the use of a heat transfer mechanism increases the amount of the charge/discharge energy. The quantity of charged/discharged energy depends on the effectiveness of the heat transfer technique used in the PCM modules. Equally important is that the multi-tube system has the highest stored energy, followed by the longitudinal and circular finned systems in that order. The longitudinally finned system with the highest discharge efficiency, followed by the multi-tube circular finned systems. As the author [22] points out, the multi-tube system was most effective for charging, but exhibited significant subcooling during discharging process. Multitube systems will require a minimum container size, followed by a system with vertical and circular fins. The combination of longitudinal fins and multitubes in each configuration is the optimal combination to boost the PCM charge and discharge efficiency. Cylindrical geometries are said to be the best performing storage systems with high efficiency and cylindrical containers with minimal dimensions [23].

Based on effective heat capacity method, heat capacity is considered to be a function of temperature due to phase changes in the temperature interval between melting and solidification, so the calculations are done on PCM, using both – temperature and latent energy. When charging (PCM melting) – the hot water from the solar collector exchanges heat with the solid PCM and the melting of PCM starts. Whereas when discharging (PCM solidification) – the cold heat carrier flows in the inner tube and the PCM modules exchange heat with it to initiate the solidifying process.

Based on the mentioned above, two experimental configurations of PCM modules were studied. In the first experiment, PCM is filled in the copper shell tube with an inner diameter of 146 mm and the heat carrier flows into the embedded 54 mm tube without a heat increase. This served as a starting point for evaluating the efficiency of the other advanced configurations. In the second experiment, circular fins were welded in the surface of the heat transfer tube.

The amount of cumulative energy charged and discharged, heat lost to the environment and storage efficiency were calculated using mathematical model [22] which contains the following equations:

- Cumulative energy charged/discharged Q_{Char} [J]:

$$Q_{Char} = \sum_{0}^{t} \dot{m} C_{p,h} (\Delta T) \Delta t, \tag{4}$$

where

$\Delta T = T_0 - T_i$ for charged energy,

$\Delta T = T_i - T_0$ for discharged energy,

$\dot{m}$ mass flow rate [kg/s],

Δt change in time [s],

ΔT change in temperature [°C],

$C_{p,h}$ specific heat capacity of heat carrier [kJ/kg°C].

- Cumulative energy heat lost Q_{loss} [J]:

$$Q_{loss} = \sum_{0}^{t} \frac{T_{i,ins} - T_{o,ins}}{\frac{ln(r_{o,ins}/r_{i,ins})}{2rk_{ins}L} + \frac{1}{h_0 A_0}} \Delta t, \tag{5}$$

where

$r_{i,ins}$ inner radius [m],

$r_{o,ins}$ outer radius [m],

h_0 heat transfer coefficient [W/(m^2 °C)],

A_0 area [m^2],

L length [m],

k_{ins} thermal conductivity of material [W/m°C],

$T_{i,ins}$ inner temperature [°C],

$T_{o,ins}$ outer temperature [°C].

- Charging efficiency η_{Char}:

$$\eta_{Char} = \frac{Q_{Char} - Q_{loss}}{Q_{Char}}. \tag{6}$$

- Discharging efficiency $\eta_{Dischar}$:

$$\eta_{Dischar} = \frac{Q_{Dischar}}{Q_{Char} - Q_{loss}}. \tag{7}$$

- Storage efficiency based on energy charged:

$$\eta_{store,input} = \eta_{Char} \times \eta_{Dischar}. \tag{8}$$

The efficiency of the heat transfer mechanism used in the PCM determines the cumulative amount of energy charged/discharged.

3. RESULTS

After Equation (3), it is calculated that the energy storage capacity using Erythritol is the highest. Erythritol results are 20 % higher than magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$), moreover 32 % higher than RT100. This coincides with other studies [13]. In addition, pure $MgCl_2 \cdot 6H_2O$ shows supercooling about 37 K, thus the study will continue and seek appropriate modifications. Therefore, in the experiment Erythritol was used for filling in tubes.

The results of two experimental configurations of copper tubes filled with Erythritol are shown in Figure 3.

The temperature curve produced by the experiment shows the temperature spread over the three different phases during the charge/discharge process of experimental tube filled with Erythritol. In the first phase the energy was accumulated by the PCM and was used to raise the temperature of the Erythritol till it nearly reached melting point temperature 117.7 °C. The temperature increased almost linearly with time. In the

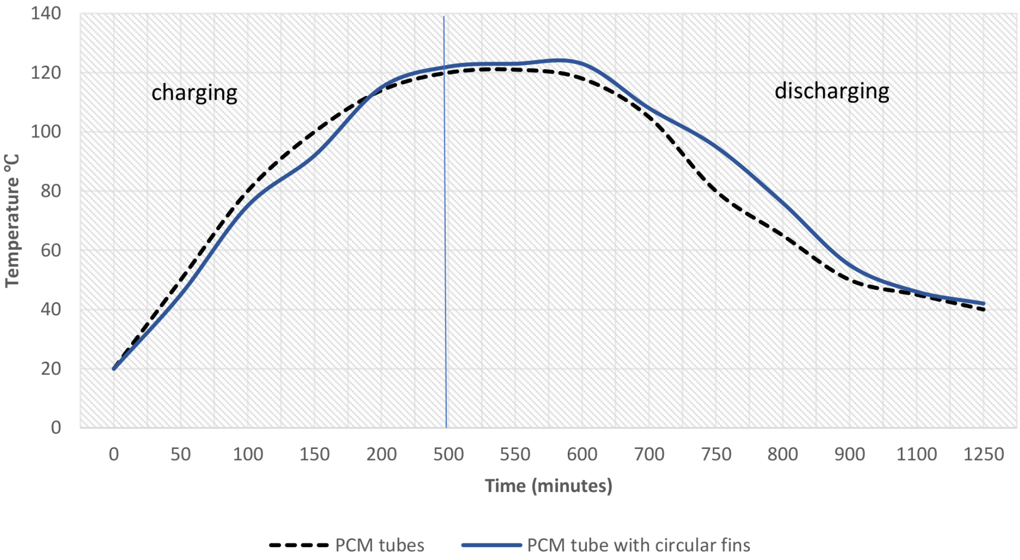

Figure 3. Temperature curves of two experimental tube configurations melting/solidification.

next phase temperature curves tended to asymptote due to a rapid change of phases. In the third phase the energy was absorbed in the form of sensible heat and the temperature increased once again, only then the temperature curve started to fall. Due to the solidification a subcooling process effect was observed.

The circular finned system improved the temperature curve a little during the charging phase of sensible heat addition when conduction controlled the heat transfer, despite the increase in surface area of the circular finned system over the tube without a fin system. In the discharge phase, the tube with fins shows slightly better results, but this difference does not appear to be significant.

The cumulative amounts of energy charged and discharged were calculated using Equations (4)–(8) and summarized in Table 2.

The overall coefficient of performance of real solar cooling systems was calculated by Equations (1) and (2), the $COP_{thermal}$ close to 0.78, but $COP_{thermal,modified}$ 0.81 throughout the year.

3.1. Energy and Economic Analysis of the system

Based on the simulation results, it was concluded that the modified thermal storage tank maintains the temperature of the heat carrier required for the operation of the SCS operation for a long period of time, so using the latent storage tank significantly reduces the energy generated by the auxiliary heater.

Given that, the excess heat is used for DHW needs. It should be added that the modified storage tank simulation results show substantial outcome for providing stable operation of the solar collector system and compensating for short-term variations in available solar energy (eg. for example, cloudy hours) [24].

With the PCM modified storage tank, the COP increased by an average of about 4 % compared to the COP of the SCS non-modified storage tank. In addition, the auxiliary heater activation time for additional heating has been reduced by 21 % compared to SCS with non-modified thermal storage tank. This is due to more stable thermal insulation/retention which would reduce energy consumption and will increase the lifetime of the SCS.

The specific Economical audit software tool is used to run simulations to determine total energy consumption and CO_2 emissions over the service life of the system. The main phases of the simulation tool include material and manufacturing process, as well as transportation and end-of-life potential. The cost of capital of the system can be categorized among the individual components, with collectors and the chiller which accounts for most of the system cost (30–40 %). Next most expensive part is the cooling tower, then the control costs, and finally the thermal storage unit (about 5 %). The low cost of thermal storage provides the potential to enhance total system performance at a very little additional capital cost.

4. Conclusions

Research investigates the efficiency of the developed latent energy storage for solar cooling system to increase COP of such systems. The main indicators, including environmental impact and economic calculations, were identified. The economic impact of modified thermal storage on solar cooling performance depends on many factors, including the electricity charges used in traditional compressor-based cooling systems. The possibility of using PCM as a storage instead of water also depends on the system properties such as operating temperature set points. This study presents an analytical methodology that allows the selection of the optimal size of thermal storage as well as to quantify the benefits of this thermal storage in terms of additional solar fraction. This can be used to maximize the added economic value of the storage for different

Parameters/Configuration	Tube	Tube with circular fins
Cumulative energy charged [kJ]	9555.0	10501
Cumulative energy lost [kJ]	552.3	589.3
Effective energy charge [kJ]	8665	9935
Cumulative energy discharge [kJ]	4966	7591.1
Storage efficiency (%)	62.2	75.2

Table 2. Energy charged and discharged and storage efficiency.

solar cooling systems.

It has been found that PCM can reduce the demand for an auxiliary heat source during peak loads and low radiation periods.

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