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Experimental and numerical studies of PCM-based storage for solar thermal energy storage applications

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In the world, buildings are responsible for 40% of the world's total annual energy consumption, which is responsible for one-third of greenhouse gas emissions worldwide. The significance of this energy is used for lighting, heating, cooling and air-conditioning purposes. Raising concern about the environmental impact of greenhouse produced by conventional power plants caused renewed interest in environmentally friendly technologies, including heating and cooling systems for buildings. This work was conducted to investigate and explore the possibilities of solar energy storage using phase change materials (PCM) and using that energy to heat water for daily applications. By carrying out charging of the latent heat storage (LHS) based on PCM which is paraffin wax in the current study, its energy storage capacity was calculated and compared with the storage tank without PCM but filled with water only - sensible heat storage (SHS). As a result, LHS was able store 40% more thermal energy compared to SHS. Moreover, charging process of the LHS was numerically investigated to visualize the thermal field in the PCM based storage. The results show that the numerical results agree with the experimental results which indicated the correctness of the mathematical model and simulation results.
Key words: Phase change material storage, latent heat storage, thermal energy storage.

Фазасы өзгеретін материал негізінде күн жылу энергиясын сақтауды эксперименттік және сандық зерттеу

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Қазіргі таңда, ғимараттар, бүкіл әлемдегі жылу энергиясының 40% тұтынуына жауапты, және бұл энергия тұтыну әлемдегі жалпы парниктік газдардың атмосфераға бөлінуінің үштен бір бөлігіне жауапты болып табылады. Осы энергияның көп бөлігі жарықтандыру, жылыту, салқындату және ауа кондиционерлері үшін пайдаланылады. Дәстүрлі жылу станцияларының қоршаған ортаға әсеріне байланысты, қазіргі таңда экологиялық таза жылу энергия көздерін пайдалануға қызығушылық туғызды. Бұл жұмыс күн энергиясын фазасы өзгеретін материял арқылы сақтау, оны күнделікті су жылыту үшін пайдалана отырып, күн энергиясының сақтау мүмкіндіктерін зерттеу және зерделеу үшін жүргізілді. Негізінде фазасы өзгеретін материал жатқан, бұл жағдайда парафин, латентті жылу сақтағышты зарядтау барысында, оның жылу сыйымдылығы анықталды және фазасы өзгеретін материалсыз жылу сақтағышпен, тек сумен сақтағанда, салыстырулар жүргізілді. Нәтижесінде, латенттік жылу сақтағыш фазасы өзгеретін материалсыз жылу сақтағышқа қарағанда 40% -ға артық жылуды сақтады. Сонымен қатар, негізінде фазасы өзгеретін материал жатқан латенттік жылу сақтағыштың жылу өрісінің өзгерісі сандық түрде зерттелген. Нәтижесінде, сандық әдіспен алынған нәтижелер эксперименталды түрде алынған нәтижелерімен келісетінін байқадық және бұл математикалық моделдің және моделдеу нәтижелерінің дұрыстығын көрсететті.
Түйін сөздер: латенттік жылу сақтағыш, жылуды сақтау, фазасы өзгеретін материалда жулыды сақтау.

Экспериментальные и численные исследования хранения тепла на основе МФП для солнечной тепловой энергии

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На данный момент здания ответственны за 40% от общего годового потребления энергии в мире, которая отвечает за одну треть выбросов парниковых газов по всему миру. Значительная часть этой энергии используется для освещения, отопления, охлаждения и кондиционирования воздуха. Повышение обеспокоенности по поводу воздействия на окружающую среду парниковых газов, производимых обычными тепловыми станциями, вызвали новый интерес к экологически чистым технологиям, в том числе систем отопления и охлаждения для зданий. Эта работа была проведена с целью исследования и изучения возможностей хранения солнечной энергии с использованием материалов фазового перехода (МФП), используя эту энергию для нагрева воды ежедневного применения. Путем проведения зарядки латентного теплового аккумулятора (ЛТА) на основе МФП, который в данном исследовании является парафином, чья энергоемкость была рассчитана и проведены сравнения с теплоаккумулятором без МФП, заполненный только водой, - физическим хранением тепла (ФХТ). По результатам экспериментального исследования, ЛТА на основе МФП смог сохранить на 40% больше тепловой энергии по сравнению с ФХТ. Кроме того, процесс зарядки ЛТА на основе МФП был численно исследован для визуализации теплового поля в аккумуляторе. Результаты показывают, что численные результаты согласуются с экспериментальными результатами, которые показывают правильность математической модели и результатов моделирования.
Ключевые слова: латентный теплоаккумулятор, хранение тепла, хранение тепла в фазовом изменений материала.

1 Introduction

In recent years, due to problems in the rapid depletion of traditional energy sources and the growing demand for energy, the implementation of proper storage of thermal energy is one of the most important questions in energy conversion systems. Latent heat storage (LHS) in phase change materials (PCM) has been adopted as one of the most effective methods of using solar energy and the recovery of industrial waste heat, look (Belen, 2003: 251–283). The main advantage of these systems appears to be the ability to store large amounts of energy in a relatively small volume at a constant temperature transition. Thus, many authors have reported the results of studies on the thermal storage during melting and solidification process in the energy storage systems, look (Agyenimet, 2010: 615–628).

Changing phase solid-liquid by melting and solidification can store a large amount of heat or cold. Melting characterized by a small change in volume, generally less than 10%. If the container can fit the material while it is in a liquid state, the pressure does not change significantly and therefore, melting and solidification of the material flowing to storage at constant temperature, look (FQ, 2002: 1273). Upon melting, while heat is transferred to the storage material, the material still retains its melting temperature at a constant temperature, also called phase transition temperature, look (Mehling, 2008: 179). Once phase transition is complete, a further heat transfer again leads to sensible heat accumulation. The heat supplied during melting is called latent heat, or latent heat storage process, look (Fan, 2010:24–46).

Storage of heat energy plays an important role both in heating and cooling applications, such as residential or commercial buildings, and also in industrial processes. Some of the technical solutions based on phase change materials can help to preserve and improve energy efficiency when used in the correct temperature levels at which the PCM changes its phase. Thus, only a few degrees difference in temperature, a large amount of energy can be saved. PCM based LHS can find its application in the elimination of energy storage problems in various fields, where they can function as a heat battery, look (Vakilaltojjar, 2001:249–263). PCM can afford to keep the temperature stable in the storage due to their high energy storage density. PCM can help to maintain the level of tank water temperature to a certain point. Successful use of LHS is not only a question of storing energy density, but also, the question of correct charge and discharge of energy accumulated at a rate suitable for the desired application, look (Mohammed, 2004:1597–1615).

Publications are available in the literature, which deals with an experimental study of the thermal characteristics of PCM storage with different storage configurations. Suitable PCM is also expected to increase the storage capacity. In this context, paraffin wax appeared as interesting topic among researchers for its attractive properties such as good heat storage density, melt or solid state compatibility with little or no significant super-cooling effects, non-reactivity with the most common chemical reagents and low cost, look (Bathelt, 1979:453–458), (Rieger, 1982:137–147), (Rabienataj, 2013: 155–163) and (Donald, 2013:393–403).

The co-author, Prof. A. Georgiev and his team from the Technical University of Sofia, Plovdiv Branch, designed and developed latent heat storage, look (Popov, 2013:1–6). Aim of the current study is concentrated on experimental and numerical analysis of LHS charging process, heat transfer and fluid flow processes in LHS and its performance compared to the same size sensible heat storage (SHS). Such study is very important in understanding of advantages and disadvantages of the design features of the latent heat storage and its efficiency in terms of charging and PCM properties.

2 Literature review

2.1 Modeling of phase change process

The change in the phase of the material from the liquid state to the solid state can be described as the time evolution of the liquid/solid boundary through the volume studied. Therefore, determining the location of this interface at a specific time is the goal of phase transition problems. This position directly depends on the rate at which heat is absorbed by the material, hence, on the thermal properties of the material. However, these properties (thermal conductivity, specific heat, density, etc.) often change significantly between liquid and solid states. Thus, phase change modeling involves knowing the position in time and space of the liquid/solid interface so that the relevant properties can be applied on both sides. The complexity of the phase change problem is caused by the fact that this interface position is both a solution to the problem and the required input; Such types of problems are called moving boundary value problems and were studied as early as 1831 by Clapeyron and Lamy when studying the formation of the earth's crust. However, the work on ice formation in 1889 by Joseph Stefan really represented a common class for these problems, known further as Stefan's problems.

2.2 Modeling PCM encapsulated in rectangular capsules

The phase change material, enclosed in flat rectangular containers, was modeled by various researchers using air as the coolant. Dolado et al. (2006) developed various numerical models simulating the behavior of flat plate PCM capsules subject to airflow, each of which takes into account various modeling assumptions. Two models are based on difference differences and only conductivity inside PCM is taken into account, without regard for any effect that natural convection can have, while PCM is in the liquid phase. One model considered a one-dimensional conductivity in the PCM in a direction perpendicular to the HTF, while the other considered conductivity in the PCM both in parallel and in the normal HTF flow. Comparison of numerical results with previous experimental data Belain Zalba (2002) confirmed that a one-dimensional model can reproduce experimental data with the required accuracy. Consequently, the simulation of conductivity inside the PCM in the direction of the HTF flow did not lead to a significant increase in the accuracy of the numerical results.

2.3 Experimental data on phase change material thermal storage tanks

Moreno et al. (2014) experimentally tested the use of a horizontal clamp to store PCM data to change the daily load for cooling a small space. The PCM tank was connected to a water-to-water heat pump and a ventilation unit connected to the canopy building, which was used to represent the internal space, the temperature of which should be maintained. The productivity of a horizontal water storage tank with identical dimensions was compared with the characteristics of a tank packed in PCM capsules that are commercially available, rectangular in shape and made of high-density polyethylene.

Such detailed experimental tests exist for other PCM capsule geometries, such as plastic bags (Saied Mohammad Vakilaltojjar, 2000, Zukowski, 2007), plastic vertical plates (Lazaro, Dolado, Marnn and Zalba, 2009; B. Zalba, Marin, Cabeza and Mehling , 2004), as well as spherical capsules (J. Wei, Kawaguchi, Hirano and Takeuchi, 2005), as well as spherical capsules (Bedecarrats, Castaing-Lasvignottes, Strub and Dumas, 2009; IW Eames and Adref, 2002; Nallusamy, Sampath and Velraj, 2007). However, a careful analysis of the behavior of commercially available PCMs studied in this project has not been found in the literature.

3 Materials and methods

3.1 Characterization of PCM

As in any other application, the selection of the PCM to be used is a crucial point. The temperature of water to be stored as domestic hot-water is about $60°C$; therefore, the melting temperature of the PCM should be around $60°C$. In the market, different PCMs with this melting temperature can be found. Three paraffins were studied (E53, ECP, E45) in laboratory of Birmingham Centre for Energy Storage (UK) using Differential Scanning Calorimetry and density meter to evaluate their heat capacities, thermal conductivity and density changes for temperature range of $25°C$ up to $90°C$. Finally, E53 with a melting temperature of $59°C$ was chosen for the experimental and numerical studies of latent heat storage presented in this paper. As illustrated in the Figure 1, it can be noticed that E53 has two phase transition regions: solid-solid phase transition in the temperature range of $35 - 50°C$ and solid-liquid phase change around $55 - 65°C$ temperature range. Furthermore, the density of the E53 is higher in the solid state (around 0.87 mg/m^3) and lower in the liquid state (approximately 0.78 mg/m^3).

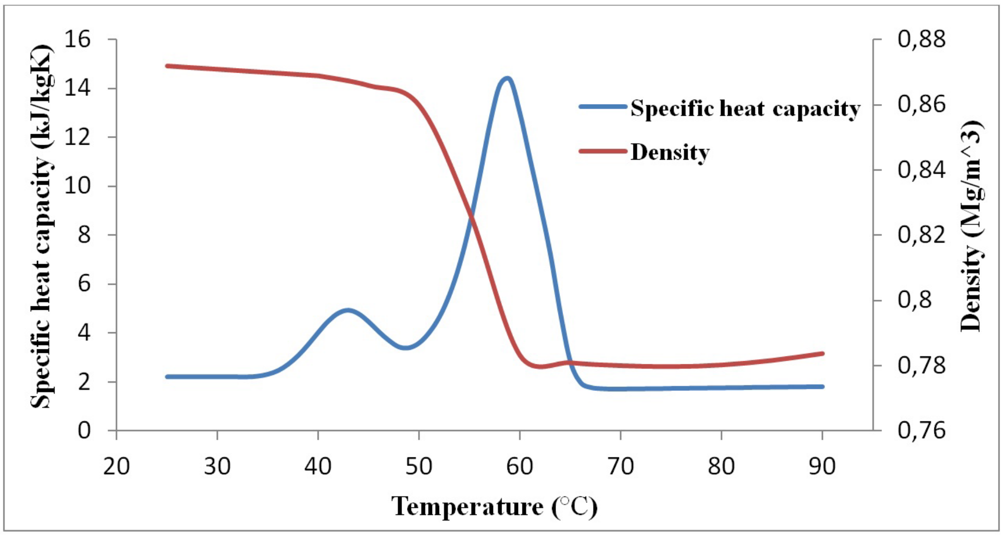

Figure 1 – Thermal properties of paraffin E53

3.2 Methodology of tests

Figure 2 shows the latent heat storage tank equipped with 39 PCM containers filled with paraffin E53, and figure 3 illustrates the schematic diagram of the experimental setup for the experimental studies. The PCM-based tank is heated up using an electrical heater attached to the base. The power input to the electrical heater is controlled by an AC power variable transformer connected to the 230V AC. The voltage across the heater and the current through the heater are measured to determine the power input to the heater. PCM-based tank with container is insulated on all sides to minimize heat loss.

Detailed illustration of the latent heat storage and its design features are shown in Figure 4. PCM containers have rectangular cross section with dimensions 950 x 80 x 50 mm, look (Stoyanova, 2013:28–31). They are placed into the vertical cylinder tank (storage) with 1 m height and 0.3 m radius. The tank and containers are made of stainless steel grade AISI 304L. Number of PCM containers are 39 and they are located coaxially in the storage. There are two concentric circles: external circle contains 26 containers and the inner circle has 13 containers. All the containers are fixed with brackets to the lower and upper parts of the storage tank in order to make them stable during charging and discharging regimes. There are three inlet pipes in the bottom side of the storage where the heat carrier fluid flows into the storage. In the upper part of the storage other three pipes are connected to the storage to discharge the heat carrier fluid from the storage.

Temperature is measured at the inlet, at outlet and inside the container. These temperature sensors and flow meter are connected to a data acquisition system for continuous monitoring and recording of the data.

Two types of experiments were conducted. The first is about the constant voltage charging of LHS filled with PCM paraffin E53. In the second experiment, LHS was filled with water as a heat storage medium. The second experiment was carried out in order to evaluate and compare the effectiveness of LHS (filled with paraffin E53) and water only (without paraffin).

Figure 2 – Latent heat storage which contains 39 PCM containers filled with E53

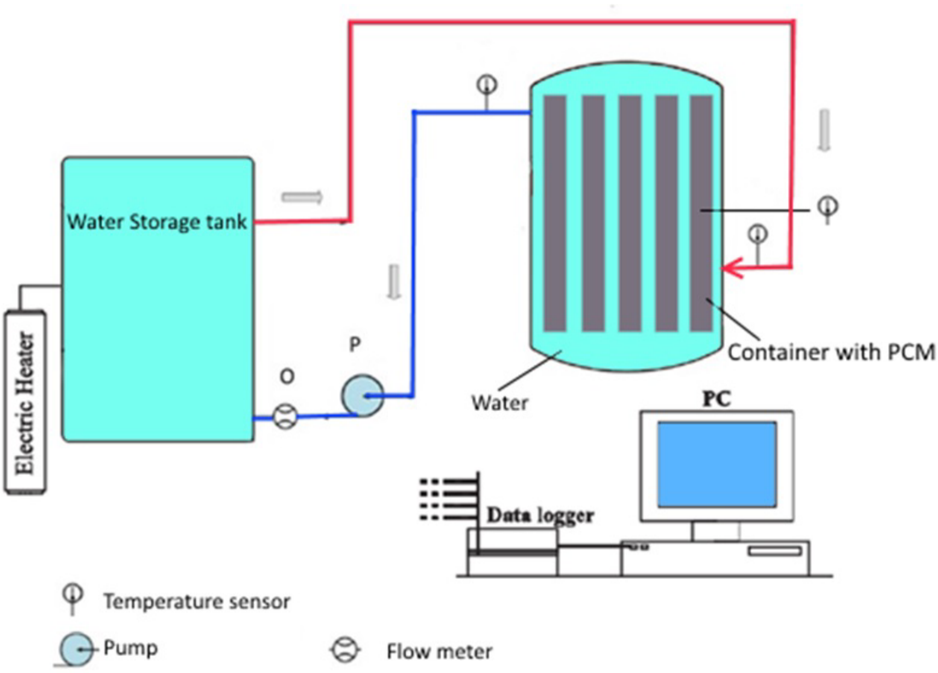

Figure 3 – Experimental setup

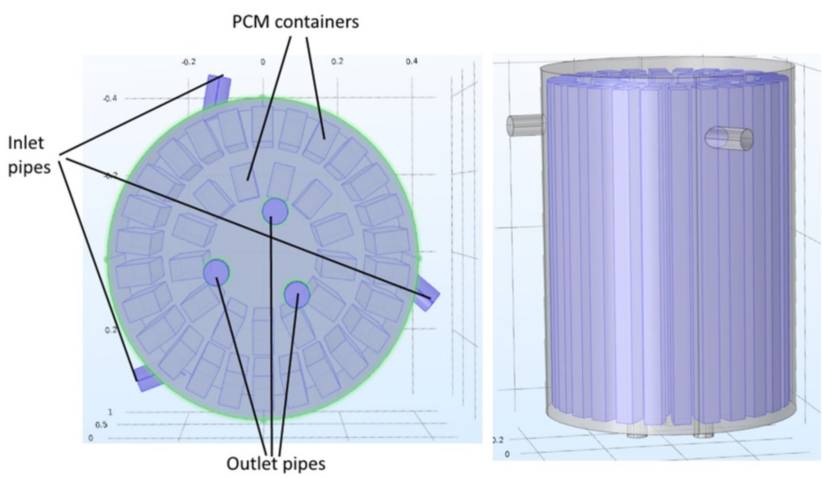

Figure 4 – Design features of the latent heat storage

3.3 Equations

Simulation is conducted in three dimensional space in a time dependent manner by means of finite element method based on Comsol multiphysics. The geometry used to perform the simulation of charging and discharging of LHS is presented in figure 4. The containers which enclose PCM (e.g. paraffins) are thermally insulated at the top and bottom. Moreover, it is assumed that the volume of the PCM does not change during phase transition. Such assumption, allows introducing simpler mathematical models, although, according to the experimental investigations, paraffins change their volume during melting or solidification.

Moreover, to avoid intensive numerical calculations, the containers are considered as highly conductive layers.

In order to simulate the dynamic behaviour of the heat carrier fluid flowing inside the LHS, the continuity and Navier-Stokes equations must be solved simultaneously. Continuity equation takes the form, look (Chung, 2002:1007):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) \tag{1}$$

where ρ - density, kg/m^3 and u - velocity, m/s. The Navier-Stokes equation which accounts for the conservation of the momentum is given by:

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u = -\frac{1}{\rho}\nabla p + \nu \nabla^2 u + F \tag{2}$$

where p - pressure in the fluid, Pa, ν - kinematic viscosity, m^2/s. Heat transfer from the water to the wall of the PCM containers takes place in the form of convection. Therefore, complete energy equation has to be solved by using the velocity field obtained from the solutions of Eqns. (1) and (2). Thus, the energy equation describing the heat transfer process is given by:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \cdot \nabla T = \nabla \cdot (k \nabla T)$$

c_p - specific heat capacity, J/kgK, k - thermal conductivity of the material, W/mK, T - temperature of the heat carrier fluid, K.

The energy equation for the phase change material including latent heat transfer during phase change is:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \cdot \nabla T = \nabla \cdot (k \nabla T) \tag{3}$$

$$k = \theta_1 k_{phase_1} + \theta_2 k_{phase_2} \tag{4}$$

$$c_p = \theta_1 c_{p_{phase_1}} + \theta_2 c_{p_{phase_2}} + L\frac{d\alpha}{dT} \tag{5}$$

$$\rho = \frac{\theta_1 c_{p_{phase_1}} \rho_{phase1} + \theta_2 c_{p_{phase_2}} \rho_{phase2}}{\theta_1 c_{p_{phase_1}} + \theta_2 c_{p_{phase_2}}} \tag{6}$$

where $\theta_1 = 1 - \alpha$ and $\theta_2 = \alpha$ corresponds to phase 1 and phase 2 respectively. Moreover, L is the latent heat fusion of phase change and α is the liquid volume fraction in the phase change material and it is a function of temperature:

$$\begin{aligned} &\alpha = 0 \qquad T < T_{solid} \\ &\alpha = \frac{T - T_{solid}}{T_{liquid} - T_{solid}} \qquad T_{solid} \le T \le T_{liquid} \\ &\alpha = 1 \qquad T < T_{liquid} \end{aligned} \tag{7}$$

In the stream of PCM containers buoyancy melted part of the PCM due to the temperature difference was not considered in the model, but only conduction heat transfer occurs in both melted and the solid part of PCM. Thus, the difference between melting and solid phases is based on its thermal conductivity coefficients k, specific heat capacities c_p and densities ρ. Moreover equations (4) - (7) do not consider the effects of hypothermia modeling processes during phase changes. And, other properties of phase change materials are paraffin for simulation purposes were taken from experimental results (Hamid, 2009:247–254).

3.4 Initial and boundary conditions

or liquid flow, the boundary conditions (BC) on solid surfaces such as the inner wall of the vessel and on the surface of containers are considered PCM without slipping BC. Furthermore, it is assumed that the storage tank has been completely isolated, which is defined by the formula look (Chung, 2002:1007):

$$-n \cdot (-k\nabla T) = 0 \tag{8}$$

where n - normal vector to the heat transferring surface. Therefore, heat transfer occurs only by means of inlet and outlet pipes. The containers are considered as highly conductive layers, where heat exchange takes place between heat carrier fluid and phase change material which can be described as:

$$-n \cdot (-k\nabla T) = d_S(Q_S - \rho_S c_{pS}\frac{\partial T}{\partial t}) - \nabla_t \cdot (-d_S K_S \nabla_t T) \tag{9}$$

where d_S - layer thickness which is taken as 0.01m in our case, Q_S - layer internal heat source and it is zero in our modeling, J, ρ_S - layer density, kg/m^3, c_{pS} - layer specific heat capacity, J/kgK, k - layer thermal conductivity, W/mK - they are taken from material properties and it was mentioned above that the PCM containers are made from stainless steel.

Temperatures of the PCM and working fluid filling the storage tank, inlet velocities and inlet temperature we take from the experimental data.

Outlet BCs for the velocity was set up in terms of the pressure with suppress backflow which adjusts the outlet pressure in order to prevent fluid from entering the domain through the boundary. And, temperature BC is Neumann type:

$$-n \cdot (-k\nabla T) = 0 \tag{10}$$

4 Results and discussion

Figure 5 illustrates the cumulative heat stored in SHS and LHS system for a constant HTF flow rate. This clearly shows that the thermal energy stored in the LHS systems far exceeds SHS preservation system of the same size and volume of the storage tank. Thus, LHS system can provide substantial reduction in the volume for storing the same stored heat, compared with SHS systems. From figure 6, we can see that the SHS system of charges to a maximum temperature of $70°C$ for 40 minutes before the LHS system. The average time in the SHS charging systems are faster than the LHS of the system for 30-60 minutes, depending on the flow rate. Charging time will be accredited to the lack of phase change materials in SHS

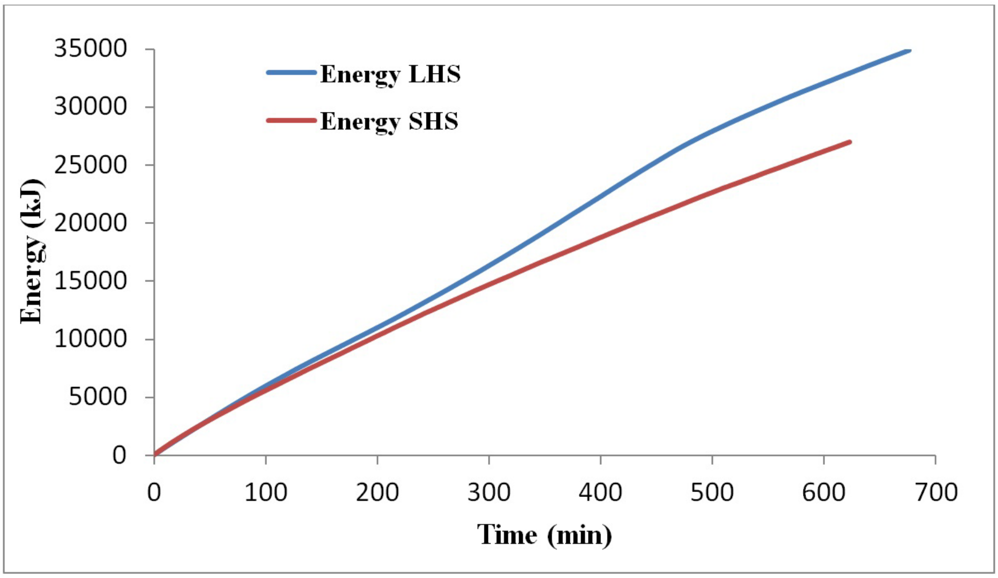

Figure 5 – Comparison of Cumulative energies in LHS and SHS systems

systems. On the other hand, the heat transfer between the HTF and PCM latent heat in the system reduces the temperature gradient and increases the HTF charging time.

The effectiveness of the heat exchanger ε is defined by equation (12) below (Incropera, 2007:675–707) and is presented in figure 7 for the solidification process.

$$\varepsilon = \frac{T_{in} - T_{out}}{T_{in} - T_{HE}} \tag{11}$$

where T_{in} - inlet temperature, T_{out} - outlet temperature, T_{HE} - temperature in heat exchanger.

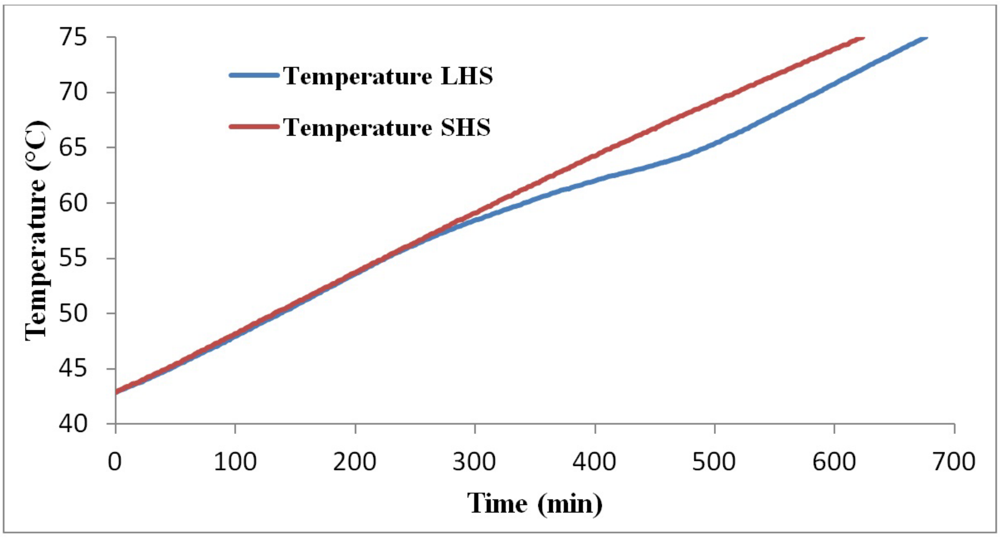

Figure 6 – Temperature histories of HTF during SHS and LHS charging process

Figure 7 shows a comparison of the effectiveness of the system of systems SHS and LHS. It is seen from the figure that the effectiveness of SHS system varies for different periods of time,

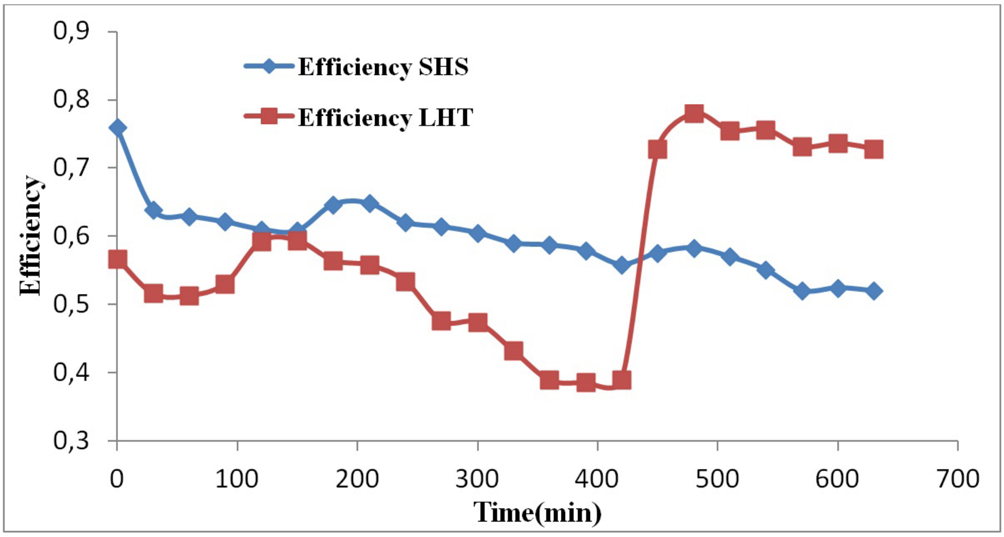

Figure 7 – Effectiveness of heat exchanger system during charging of LHS and SHS

whereas the efficiency of the system is constant LHS phase transformation temperatures, and it also shows a higher efficiency. Thus, LHS system is more efficient.

As seen in figure 7 that the efficiency is high at the beginning and at the end of the solidification process, while it is smaller therebetween. This behavior corresponds to the high efficiency of heat transfer of the physical PCM and lower efficiency in the melting process, which may occur due to the slow rate of absorption of latent heat by melting.

Figure 8 shows an example of the computed temperature profile at a point in the PCM domain, which was computed numerically and measured experimentally. It can be seen that the temperature profile of the paraffin E53 during charging process is divided into 3 regions which represent the solid, phase change zone and liquid phase. The temperature rise in solid phase region and liquid phase region was due to the sensible heat added (Figure 8b). Temperature between $53°C$ to $59°C$ was the phase change region where the melting of PCM started at $53°C$ and completed at $59°C$. The temperature gradient of this region was smaller due to the large amount of energy, in the form of latent heat of fusion, was needed to melt the PCM (Figure 9).

The temperature evolution at middle positions in PCM container and the temperature evolution on outlet of PCM during charging are shown in figure 8. The continuous lines represent the numerical results, while the circles represent the experimental results. By comparing numerical and experimental curves for the charge case, it is apparent that the results are very similar. Moreover, it appears that the experimental and numerical curves are similar, which indicates that the phenomena are numerically well represented.

Figure 10 shows streamlines of velocity and temperature distribution on the PCM containers. The PCM containers which are in the inner circle charged first in a short time and outer circle containers were charged after that. It can be concluded that outer circle PCM containers are very close to the storage tank walls, therefore, those areas does not allow fluid flow and heat transfer processes to be intensive. As the result of the numerical simulation, thermal field in the LHS was visualized in detail and based on it one can analyze the phase change zones in the storage. Moreover, by means of the numerical studies the deficiencies or

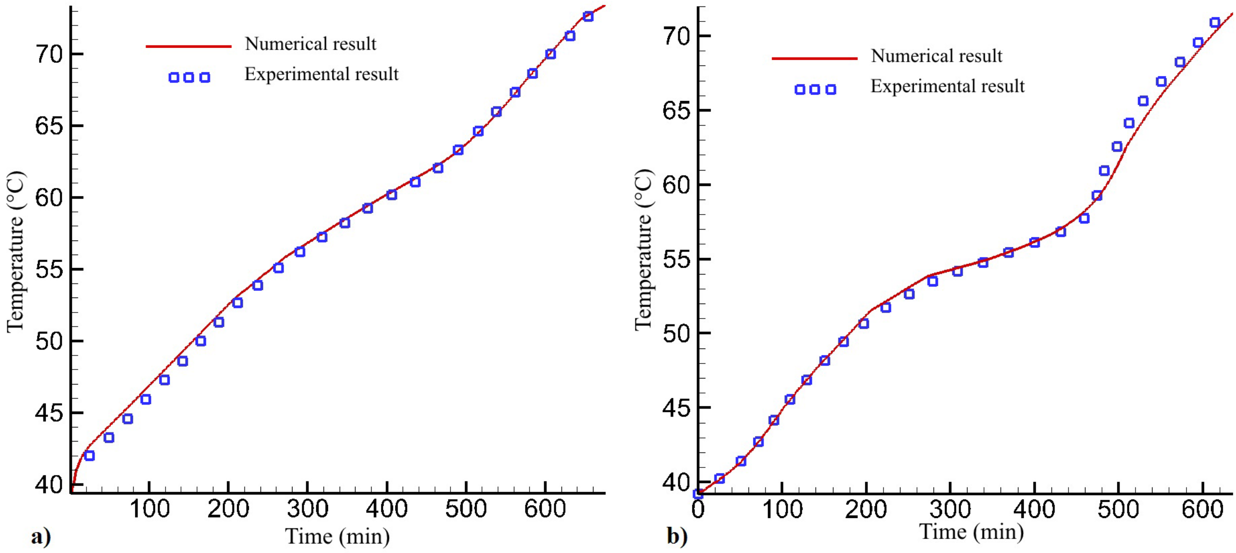

Figure 8 – Comparison of the experimental and numerical results for charging LHT with PCM. Oulet temperature (a) and temperature at middle position in PCM container (b)

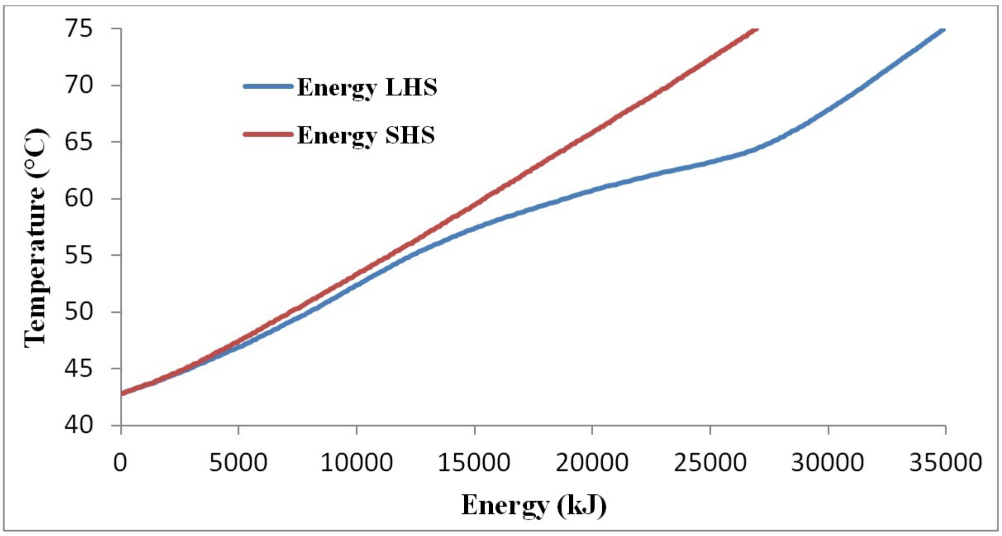

Figure 9 – Temperature histories of HTF during SHS and LHS charging process

drawbacks of the storage design can be studied which is usually impossible in experimental studies.

5 Conclusion

The aim of the investigation was to find out how effectively LHS based on paraffin, E53, could store the thermal energy compared to the similar-sized storage tank without PCM (e.g. SHS). Moreover, the charging mode of the LHS was numerically studied with the purpose of evaluating the thermal field in the tank. Such evaluation allows to visualize the thermal field

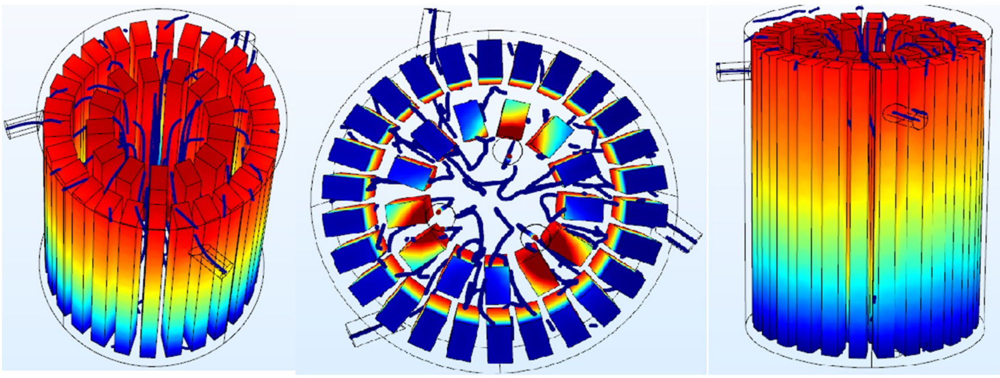

Figure 10 – Streamlines of velocity and temperature distribution on the PCM containers

in the PCM containers as well as the storage tank, including the flow field of the heat transfer fluid and understand the charging processes in detail. Thus, according to the results, as the charging takes place from 25°C up to 75°C at constant heat rate, the LHS could store 40% more energy compared to SHS. It should be noted that the LHS and SHS are the same storage tanks: (i) in case of LHS, the total volume of the storage was $0.3m^3$ of which $0.15m^3$ was filled with PCM and (ii) in case of SHS, the containers were removed and the tank was filled with water as the sensible storage material. In a word, when approximately the half of the storage rank filled with PCM, 40% more thermal energy could be stored in the tank. Although, the charging time took 53min more time compared to SHS, which is not a problem since duration of solar radiation takes more than 3-4 hours daily. Furthermore, the charging of LHS was numerically studied and development of the thermal field in the storage was simulated. The results of the numerical studies were compared with the experimental ones, thus, correctness of the numerical approach was verified. It was visualized that the phase change processes occur in the inner circle PCM containers since the inlet pipes were located in the centre part of the storage tank bottom. To melt the PCM in the outer circle containers took some time because the flow of heat transfer fluid was intensive in the central part of the storage but not on the areas of the side walls. Thus, the modeling assisted in understanding the phase transition zones in the storage, and fluid flow processes and showed the detailed thermal performance of the PCM filled storage. In the future, authors are planning to study the energy performance and efficiency of the LHS integrated with solar collectors which will give more realistic understanding of the charging processes. Moreover, the LHS will be integrated to the consumer side (e.g. hot water application systems), thus, allowing to evaluate the storage performance in case of thermal energy discharge from the storage.

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