Experimental Achievement and Improvement of Latent Heat Energy Storage Unit

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ABSTRACT

Thermal energy storage systems by latent heat, in which phase change materials are used, are the subject of many scientific works. These systems are designed to guarantee the energy saving through promising technology. The present work concerns the experimental study of thermal performances of a latent heat thermal storage device made in our laboratory (ETAP). The PCM (paraffin) is stored in the vertical finned U-shaped tubes of the exchanger. The air is used as the heat transfer fluid. The storage unit use several identical heat exchangers filled with paraffin. The study examines the complete cycle with the two processes of charging (melting) and discharging (solidification) to analyse the effect of the numbers of exchangers on the thermal performance of the thermal storage. The obtained results showes that the storage unit with three exchangers stores 73 and 32% more thermal energy than a storage unit with one and two exchangers. At the end of the discharging duration, the first exchanger releases its total heat in Conf. 1, 2 and 3 respectively, after 126, 149 and 160 min.

Nomenclature

Symbols :

ΔT temperature difference, °C
T_{in} inlet air temperature, K
T_{out} outlet air temperature, K
$\dot{m}_{HTF}$ air flow, $kg.s^{-1}$
$C_{p_{HTF}}$ air heat capacity, $J{\cdot}kg^{-1}{\cdot}K^{-1}$
T time, min
N number of exchangers
Q_{st}, Q_{re} thermal energy stored, recorvered, kJ

Indices / Exponents :

in inlet
HTF heat transfer fluid
Conf 1 with 1 exchanger
Conf 2 with 2 exchangers
Conf 3 with 3 exchangers
LHTES latent Heat Thermal Energy Storage

I. Introduction

Over the past few decades, energy has become a vital resource for development. Its consumption has become very important, which puts our planet in lasting and dangerous problems following the depletion of fossil fuel resources, as well as the increase of the greenhouse gases [1,2] due to global warming. So how can we reconcile development needs and environmental constraints with the energy that is at the heart of this dilemma? One of the solutions to guarantee and restore part of the energy is the storage of thermal energy.

The energy storage system is an eminent chain which makes it possible to have recourse to renewable sources of energy whose capital interest is to consent to the outcome of a reliable energy, see the improvement of energy efficiency. The storage and transport of thermal energy by "solid-liquid" phase change is one of its storage methods and fits perfectly into a policy of controlling energy demand. A disruption in energy supply can seriously disrupt the economy of a country and endanger vital functions: industry, transport, defence, health system, etc. It is therefore essential to have sufficient stocks to cope with a disruption in supply flows. In general, the term storing energy consists in storing it during a period when it is abundant or less expensive to use it during a period during which it is rare or more expensive.

Abhat [3] proposed in 1983 a review in which are presented the essential points for the choice of PCM and a storage system of thermal energy by latent heat. This review is comforted 20 years later by M. Farid and al [4]. F. L. Tan et al. [5] have shown the role of buoyancy in the management of water resources by the melting of paraffins. They filled a spherical glass capsule with a PCM and placed 11 K-type thermocouples inside along the axis of symmetry. The solid is sub-cooled to 1 °C and the temperature of the surface of the sphere is maintained at 40 °C. The authors showed at the beginning that the heat transfer is dominated by conduction, because the shape of the PCM remains spherical. After 40 minutes, convection will gain momentum because the ovoid shape of the solid phase shows the presence of movement of the liquid phase from the bottom to the top of the sphere. Along the same lines, A.F. Regin et al. [6] analyzed the behavior of melting PCM (paraffin) inside cylindrical capsules, placed horizontally in a domestic hot water storage tank exposed to a solar field. A visualization system placed at the end of the capsules made it possible to see the evolution of the melting front without disturbing the exchange. At first, they noticed a concentric fusion around the capsule, then the fusion of the upper zones, while the lower part remained almost solid until the end of the test. Y. Varol et al [7] experimentally determined the performance of a solar collector using sodium carbonates decahydrate ($Na_2CO_310H_2O$) as PCM. The melting temperature is 33 °C. The latter was placed at the bottom of the collector and added a special oil to speed up the heat transfer. The experimental study took place in March. The experimental results were compared with those of a conventional system without PCM. They have shown that the solar collector with PCM ($Na_2CO_310H_2O$) is more efficient than a conventional collector (without PCM) because of the large storage of energy during the day. M. Ahmad et al [8] simulated numerically with TRNSYS 15 then, validated by an experimental study, the thermal behavior of a cell with walls associating PCM and VIP by comparing it to a cell without PCM. The authors have shown that using PCM in the wall of the building makes it possible to increase the thermal inertia while keeping thin wall thicknesses (25 mm). As well as the coupling with a super-insulator (VIP) makes it possible to further increase this inertia during the destocking. They observed that the temperature of the cell with PCM approached 23 °C while the outside temperature was close to 12 °C. Micro-encapsulation consists in trapping PCM in capsules of small sizes, in different forms (spheres, rollers, or small longitudinal cylinders, etc.). The latter have the advantage of considerably increasing the exchange area. T. Kousksо et al [9] presented a solar system using PCM consisting of a solar collector heating the air associated with a cylindrical tank and containing spherical capsules filled with PCM. The numerical model shows that the thermal efficiency of the system can be considerably improved for a certain melting temperature range of the PCM and can also reduce the irreversibility inside the system while using a multiple PCM. Zukowski [10] proposes an exchanger-storage with horizontal plates composed of polyethylene bags filled with RT56 paraffin used to heat the air. The exchanger-stocker consists of 3 plates. The paraffin melting temperature is 50 °C, its total mass of PCM is 1.92 kg and occupies 76% of the surface of the plates. Cycle times are short due to the very high air flow compared to the mass of PCM. The improvement of heat transfers is carried out by the addition of fins which serve to increase the exchange surface. A. F. Regin et al [11] analyzed the behavior of a thermal energy storage system by latent heat of the Garni bed, composed of spherical capsules, filled with paraffin wax (PCM) and then coupled with a solar heating system. The study deals with the thermal effects at the inlet of the hot fluid transferred to the PCM, the mass flow, the range of temperatures at phase change and the thermal performance of the capsules of the different radius studied. The authors conclude that the time for complete solidification is too long compared to the melting time. Similarly, the charge and discharge rates for capsules with a smaller radius are significantly higher than those with a larger radius. Oudrane et al [12], studied the thermal comfort in new habitable architectures for a dry climate in the region of Adrar in Algeria, the results of numerical investigation of different variables such as: internal temperature, external temperature and the density of the solar flux, we show ourselves such an approach which allows improving the thermal comfort in this architecture. H. S. Fath 1991 [13] examined the performance of a horizontal shell heat exchanger in which the PCM has the size of the shell and the heat transfer fluid circulates inside the tube. The melting point of PCM is around 50 °C. An analytical model

based on the quasi-stationary approximation is developed to predict the performance of the system. The author reports that the increase in mass flow, the initial temperature of the fluid and the length of the exchanger increase the heat transfer and the accumulated energy absorbed by the PCM. Thus, a single exchanger is thermally more efficient than two parallel heat exchangers. To better understand the impact of the longitudinal fins, H. Shokouhmand et al. [14] studied a modeling of the melting of a paraffin with a melting temperature varying between 46 ÷ 48 °C in a horizontal exchanger with two and four longitudinal aluminum fins. These performances are compared with a smooth exchanger. They found that natural convection greatly influences the exchange during horizontal fusion as it allowed the upper half of the heat exchanger to melt first. The fins have greatly improved the melting performance since, at the same time; the proportion of liquid is even greater than there are fins in the exchanger. According to the authors, the proportion of liquid is multiplied on average by 2 with two longitudinal fins and by 2.9 with four longitudinal fins. De Jong and Hoogendoorn [15] have shown the importance of the surface of the fins in the thermal performance of the system. For this, they used two walls in their studies. The first study is done with a thin metal wall; the bottom and the top were well insulated. The paraffin was cooled for 80 min. In the second case, the cooling is done by a fin wall; the paraffin is cooled after 40 minutes. In parallel, the study by Caron-Soupart et al [16] highlights the interest of fins in increasing the heat transfer surface. The fins tested are of axial shape in steel and radial in copper. The whole is compared with a reference case without fin. The annular space between the exchanger and the casing is filled with paraffin. Experimental results show that the fins in the PCM could greatly improve the heat transfer in the thermal storage unit.
In the present work, the authors study experimentally the performance of a novel LHTES unit using a finned U-tubes exchanger filled with paraffin. In order to increase the energy stored by the LHTES unit, it is necessary to increase the number of the exchangers used. This study proposes to analyze experimentally the effect of coupling several exchangers on the energy stored.

II. Experimental Procedure

In previous works [17], we made an experimental thermal storage device in our laboratory (ETAP), in which several effects are studied: effect of the power at the inlet and effect of the air flow considered to be HTF. Figure 1 represents the experimental bench of the air thermal storage device on which we carried out our experiments. The ambient air (HTF) is forced into the inlet by a variable fan and then it is heated directly by resistors. The hot air passes through an isolated channel (18 cm in diameter and 1.20 m in length) and arrives in an enclosure (43 x 38 x 36 cm) where the exchangers filled with solid paraffin are placed. These recover heat from the air and transmit it to the paraffin which changes state and becomes liquid. The less hot air is discharged through the outlet channel. The discharging phase is carried out by the direct circulation of ambient air through the hot exchangers by liquid paraffin which transfers its heat to the air and which leaves hotter. The paraffin changes state and becomes solid.

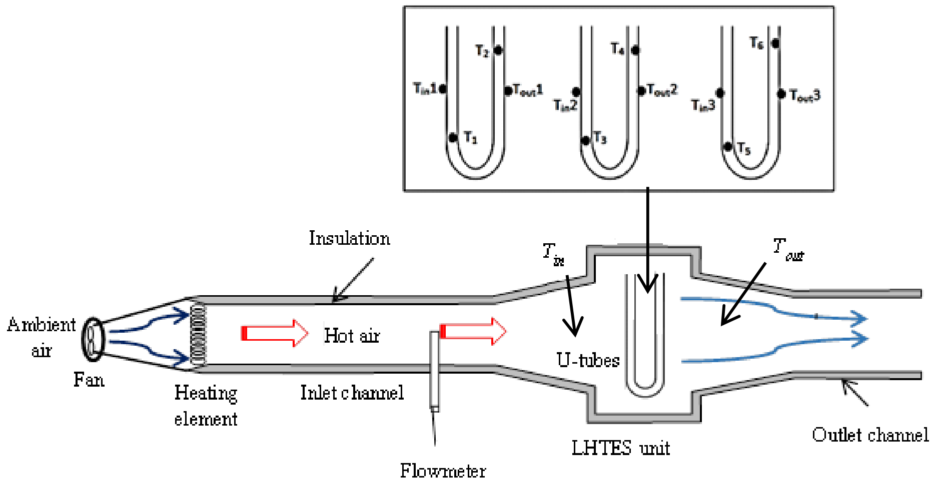

Figure 1. Schematic diagram of experimental setup and arrangements of exchangers

Table 1. Thermal physical properties of material used

Denomination	Solid density 25°C (kg/m³)	Liquid density 80°C (kg/m³)	Melting enthalpy kJ/kg	Heat conductivity W/m.K	Specific heat capacity kJ/kg.K	Melting point °C
$C_{24}H_{50}$ Tetracosane	912	769	162.42	0,2	2	49÷54

The temperatures recording are carried out by a data logger (LabView). The data are generated and saved by a developed program in an Excel file. Two thermal sensors (type K) are placed inside each exchanger at depths of 12 and 18 cm in the paraffin. As well as two other sensors are connected to the outside to measure the temperature of the air entering and leaving the exchanger (Figure 1).

First, a fan speed is set to deliver an axial air speed of 0.43 m/s (air flow rate of 0.846 kg/min). The speed is controlled by a hot wire anemometer. Thereafter, the maximum thermal power is then fixed at 25 W. Then storage is started while at the same time activating the temperature recorder. The air begins to heat up and crosses the insulated channel, then crosses the fins and the tubes of the exchangers thus promoting the fusion of the PCM inside. This is called the storage process, which ends when the melting temperatures and steady state are reached. At this time, the heating resistors are stopped and only cold (ambient) air pass with the same flow rate through the same channel in order to discharge all the heat stored subsequently in the exchangers. This is the discharging process.

III. Results

III.1. Storage tank with a single exchanger (Config. 1)

Figure 2 represents the temporal evolution of the paraffin temperatures according to the positions depth of 12 and 18 cm. We can see that the temperatures T_1 and T_2 are almost identical. In fact, the fins placed in the exchangers help to homogenize the temperature in the PCM. On the other hand, the position of the exchanger 1 that is placed at the entrance of the channel promotes a rapid heating and cooling of the exchanger. A melting and solidification process are enough rapid. At 6 min, the paraffin is still in the solid state and the heat is stored by sensible heat (conduction) from 19.5 °C to 48 °C. At this time, we are assist the start of the melting of the paraffin which lasts 10 min, the storage is carried out by latent heat and the temperature pass from 48 °C to 54 °C. Afterwards, the paraffin becomes completely liquid and the storage is carried out by sensible heat (convection + conduction).

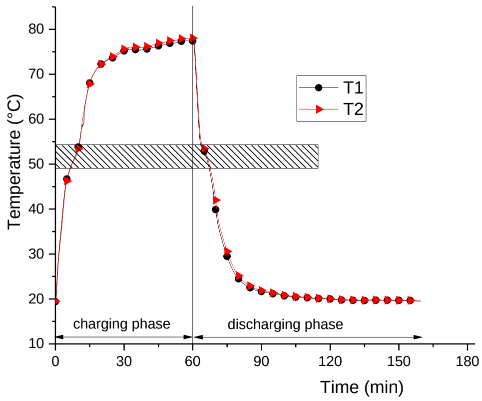

Figure 2. Behavior of paraffin through 1 exchanger

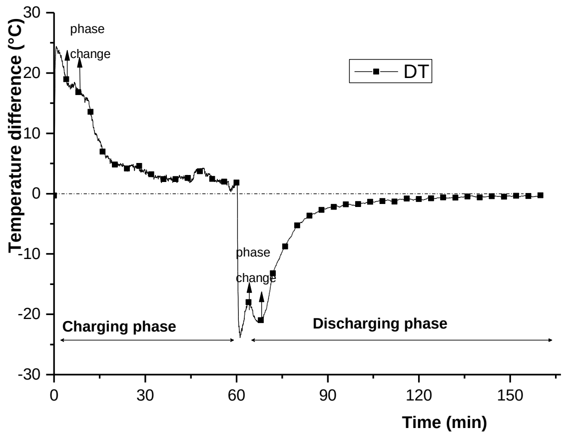

Figure 3. Temporal evolution of the air temperature

difference for a single exchanger

During the storage phase, the air temperature difference ($\Delta T = T_{in}$ - T_{out}) increases rapidly and reaches a maximum of 24 °C at 46 s (Figure 3). Then, it begins to decrease gradually to reach 17 °C after 6 min (start of paraffin melting) with a speed of 0.000332 °C/min. During the phase change, there is a change in the profile of the temperature difference which decreases less rapidly to 15.89 °C with a speed of 0.00014 °C/min (57.8%). From this instant, the temperature difference drops rapidly to reach at 33 min, 2.5 °C and 0.92 °C at the end of storage (1h).

During the discharging process (Figure 2), the paraffin begins to solidify, reaching 54 °C after 64 min (discharging by sensible heat). The start of phase change which marks recovery of the stored latent heat lasts up to 68 min. From this moment, the paraffin becomes solid and the discharging is ensured by sensible heat (conduction) until the end (2h37min) around 19 °C.

During the discharging phase (Figure 3), the oulet air temperature becomes higher than that at the inlet and the temperature difference becomes negative (recovery of the stored heat). The discharging by sensible heat reaches a peak of 24 °C at 61 min and decreases to 19 °C at 64 min (start of solidification). At this instant, an increase in the temperature difference is observed due to the recovery of the latent heat to reach 21 °C after 68 min (end of solidification). Afterwards, the temperature difference decreases again and reaches a minimum of 0.3 °C at the end.

III.2. Storage unit with two exchangers (Config. 2)

Figure 4 shows the temporal evolution of the paraffin temperature of the storage tank with 2 exchangers (Conf. 2) spaced 2 cm apart. Like a Config. 1, the temperatures T_1 and T_2 are almost identical. However, the gap exiting between T_3 and T_4 is due to the position of the exchanger 2 which is placed behind the exchanger 1. The melting and solidification process become slower and the phase change interval is more visible.

During the thermal storage phase, the fusion starts first in exchanger 1 after 6 min and ends at 10min40s. Then it starts in exchanger 2 at 14min4 s and ends after 24min36s. Exchanger 2 registers a delay of 7min54s and 13min56s respectively at the beginning and at the end of the fusion. Exchanger 1 and exchanger 2 reach their thermal equilibrium after 34min32s and 55min46s to reach 81 and 78 °C, respectively.

We remark that the melting in exchanger 1 is more homogeneous compared to exchanger 2. Indeed, the fusion of point T_3 is faster than that of point T_4. This phenomenon is explained by the fact that exchanger 1 is exposed directly to the flow of hot air, and it heats up faster than exchanger 2.

During storage, the temperature of exchanger 1 is higher than that of the second. Indeed, the amount of heat stored in exchanger 1 is greater than that of the second since it is upstream and closer to the heat source. To be able to compare the thermal behavior with the (Config. 1), the storage time is fixed at 1 h.

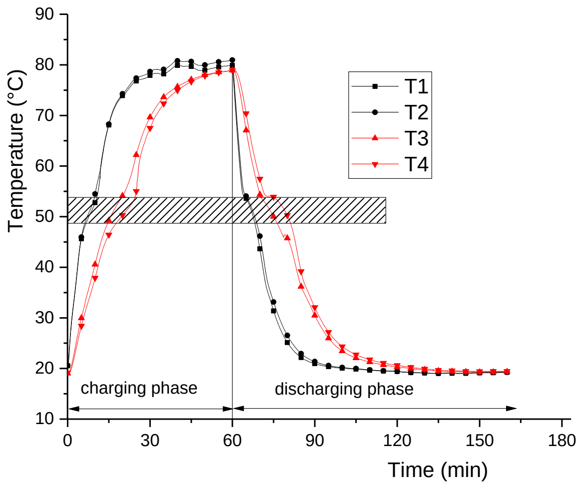

Figure 4. Behavior of paraffin through 2 exchangers

During the discharging phase, solidification starts in exchanger 1 after 65min50s and ends at 69min58s. Exchanger 2 registers a delay of 4min20s and 11min42s at the beginning and at the end of solidification. Exchanger 1 provides all its heat (out of service) after 1h58min66s, while exchanger 2 registers a delay of 24min06s. Therefore, exchanger 1 cools (more homogeneously) faster than the second since it is exposed to the cold incoming air flow.

III.3. Storage unit with three exchangers (Config. 3)

Figure 5 shows the temporal evolution of the temperature of the paraffin of the storage tank provided with 3 exchangers spaced 2 cm apart. The results show that the exchanger 1 starts its fusion at 5 min and ends around 8 min. The exchanger 2 and the exchanger 3 register respectively a delay of 10 min and 15 min from the start of the fusion and 12 min and 20 min from the end of the fusion relative to the exchanger 1. At the end of the storage, the exchanger 1, 2 and 3 reach respectively the maximum temperatures of 81, 78 and 74 °C. More the exchanger moves away from the inlet, the lower its temperature, causing the stored heat to decrease.

During the discharging process, the solidification starts at instants 67, 75 and 84 min and ends at 68 min, 82 min and 87 min respectively for exchangers 1, 2 and 3. The exchanger 2 and 3 record a respective average delay of 11 and 18 min relative to the exchanger 1. The exchangers 1, 2 and 3 each release their total heat after 126 min, 149 min and 160 min.

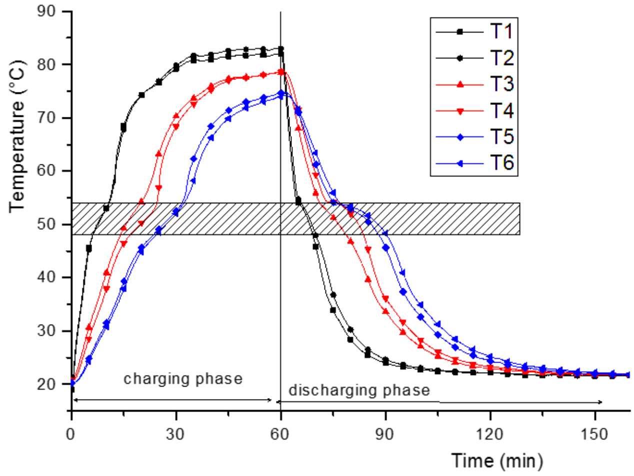

Figure 5. Behavior of paraffin through the 3 exchangers

III.4. Effect of the number of exchangers on the energy exchanged

Figure 6 represents the behavior of the time evolution of the temperatures of the paraffin only of the exchanger 1 in Conf. 1, 2 and 3. The thermal behavior of exchanger 1 in Conf. 1 and 2 is identical until the start of fusion in exchanger 2 of the Conf. 2 which is around 24 min. We note the same previous phenomenon, that is to say the thermal behavior of the exchanger 1 in Conf 2 and 3 is identical until the start of the fusion of the exchanger 3 in Conf 3 which is around 29 min. More the number of exchangers is increased, more the speed of the air flow decreases, due to friction causing the temperature of the exchanger 1 to increase, which reaches 78, 80 and 83 °C respectively in the Conf 1, 2 and 3. At the end, exchanger.1 releases its total heat in Conf. 1, 2 and 3 respectively, after 126 min, 149 min and 160 min.

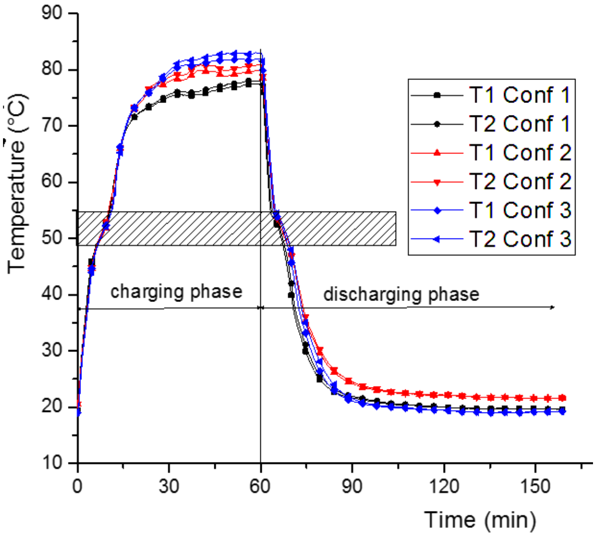

Figure 6. Comparison of the time evolution of PCM temperature of exchanger 1 in Conf. 1, 2 and 3.

Figure 7 represents the thermal energy (stored $Q_{st}(N,t)$ and (recovered $Q_{re}(N, t)$) as a function of the number of exchangers and the time during the operation of the storage device, correlated by the following 2 equations:

$$Q_{st}\left(N,t\right)=\left(296-653N\right)\exp\left(-\frac{t}{501+497N}\right)+611N-257 \tag{1}$$

$$Q_{re}\left(N,t\right)=\left(20000-3150N\right)\exp\left(-\frac{t}{600+325N}\right)+80N-60 \tag{2}$$

N: number of exchangers
T: time

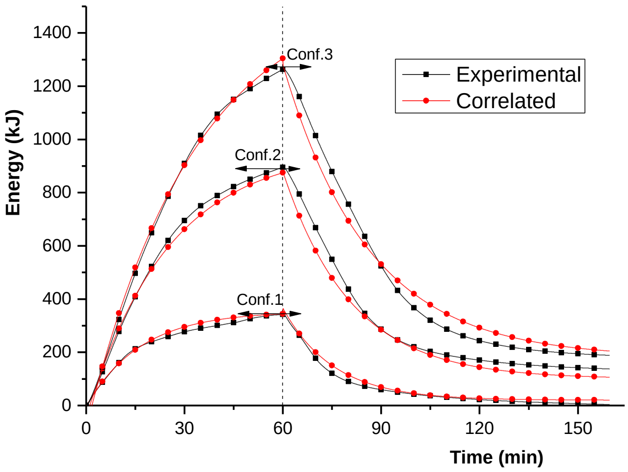

Figure 7. Analytical and experimental comparison of the evolution of energy.

During the storage phase, the quantity of stored energy increases exponentially and reaches (after 1h) the maximum values of 342, 896 and 1263 kJ for Conf. 1, 2 and 3. During the discharging, the energy released decreases exponentially and reached at the end 3, 137 and 188 kJ for the three configurations. Thus, increasing the number of exchangers improves and increases the amount of heat stored. A storage unit with three exchangers stores 73 and 32% more thermal energy than a storage unit with one and two exchangers. Thus, increasing the number of exchangers contributes to increasing both the exchange surface and the quantity of paraffin used for the latent heat storage.

IV. Conclusion

The objective of the study is to improve the storage/discharging of a latent heat energy store. The improvement was based on the increase in the number of exchangers as well as the space used between the exchangers. The temperature measurements are carried out using temperature sensors immersed inside the heat exchangers filled with paraffin wax (Tetracosane). Temporal changes in temperature in 12 different points are acquired using an acquisition chain. The study made the following conclusions:

1. The first exchanger at the inlet of the storage unit is exposed directly to the flow of hot (or cold) air and heats (or cools) faster than the other exchangers. Thus, the further the exchanger is from the inlet, the more the maximum temperature reached by the exchangers' decreases resulting in the reduction of its stored heat.
2. The increase in the number of exchangers leads to an increase in the amount of heat stored, an improvement in its thermal efficiency and an extension of the operating time of the storage device. A stocker with three exchangers saved 73 and 32% more thermal energy than a storage unit with one and two exchangers.
3. During the discharging process, the second and third exchangers register a solidification delay of (11 and 18 min) compared to the first one. The latter totally releases its stored heat 23 and 34 min before the second and third exchangers.
4. The increase in the number of exchangers causes the reduction in the air flow speed due to friction, thus causing the temperature of the first exchanger to increase, of the air temperature difference and the thermal efficiency of the store.

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