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Conference paper

Experimental and CFD Analysis of a Solar Air Heater Integrated with Ribs Filled with PCM Materials: Drying applications

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ABSTRACT

The major challenge of renewable energies, including solar, is their intermittent nature. Therefore, the issue of energy storage becomes crucial to meet demand when the main source is not available. In this context, this article aims to improve the thermal performance of a solar air collector by integrating a latent heat storage system. Both numerical and experimental procedures were achieved, allowing the characterization of the conventional solar air heater's operation and highlighting its efficiency dependence on solar radiation. A 2D transient numerical analysis using an enthalpy-based phase change model, based on the finite volume method (ANSYS Fluent), was conducted to compare two collectors: the first without storage and the second with PCM storage. Experimental data on solar radiation and ambient temperature were introduced as time-varying boundary conditions to account for the intermittency of real weather conditions. The results highlighted the charging and discharging phases of the storage system. It was observed that the use of phase change materials (PCM) improves the solar collector's performance during the afternoon (when solar radiation intensity decreases) by improving its efficiency and extending its operating period for drying purposes.

1. INTRODUCTION

In the current context of growing concern for the environment, transitioning to more sustainable energy sources has become a global priority, and the use of renewable energy plays a crucial role in this shift. Among these energy sources, solar energy stands out due to its inexhaustible potential and limited

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environmental impact. Solar air heaters offer a promising solution to harness this abundant energy source by converting solar radiation into thermal energy to heat air, which can be used for urban heating or other applications.

One of the most well-known applications of solar air heaters is the solar dryer, which is a device used to dry various products (fruits, vegetables, herbs, fish, etc.) using solar energy. It works by capturing the sun's heat and using that heat to evaporate moisture from the products. This allows for longer preservation, as drying reduces the water content, which slows down degradation by microorganisms. There are different types of solar dryers, but the most common include:

- Natural convection dryers: warm air rises naturally and circulates around the products to be dried.
- Forced convection dryers: a fan is used to force the circulation of warm air.

In a research article published by Boulemtafes-Boukadoum et al. (2008), the researchers conducted a thermal and energy analysis of drying mint using solar energy. The experiment was carried out using a solar air collector operating in natural convection, and they measured various thermal parameters such as temperatures, humidity, airflow rate, and solar irradiance. The researchers calculated the efficiency and performance of the solar collector throughout the day.

Fig 1. Natural convection solar dryer at CDER (Boulemtafes-Boukadoum et al., 2008)

However, a major challenge of renewable energies, including solar energy, is their intermittent nature. The issue of energy storage thus becomes crucial to meet demand when the primary source is not available. In this context, optimizing the performance of solar air collectors and integrating thermal storage systems become important areas of research (Boukadoum et al., 2023).

One of the promising storage technologies in solar collectors is thermal storage by latent heat, which is a process where energy is stored in the form of latent heat in materials known as phase change materials (PCMs). The material changes its physical state (solid/liquid) or (liquid/gas) so that it can store more energy (Figure 2).

The uniqueness of this thermal storage method is its ability to store a large amount of energy in small volumes due to the high latent heat value of the materials used. Another advantage of this type of storage, compared to other thermal storage methods, which requires a significant increase in the storage medium's temperature, is that latent heat storage can continue to store energy even within a small temperature range. This is possible because the phase transition occurs at a nearly constant temperature, and the amount of energy stored explicitly depends on the mass of the material and the value of its latent heat, as described by the equation:

$$Q = m.L \tag{1}$$

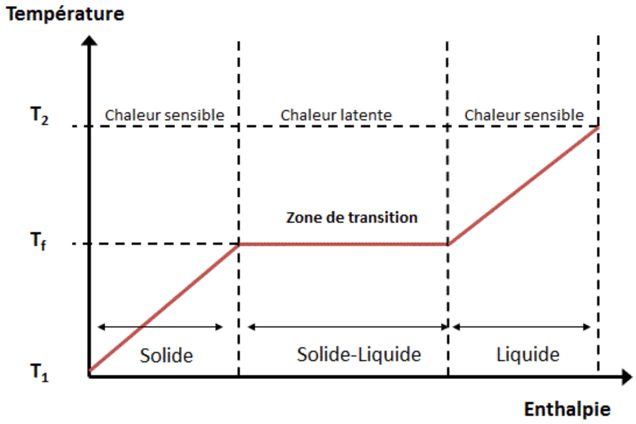

Fig 2. Sensible and Latent Heat [3]

The efficiency of latent heat storage relies on the choice of storage material. To this end, researchers conduct experiments to determine whether certain materials can be used as phase change materials (PCMs) for latent heat storage. For example, in the study by Aadmi et al. (2013), the researchers conducted an experiment to create a database on the thermal parameters of a PCM dedicated to thermal storage in buildings. The authors recreated the phenomenon of thermal energy storage and release in a composite loaded with RT27 paraffin balls immersed in epoxy. Samples were prepared, and a Differential Scanning Calorimetry (DSC) experimental study was conducted to measure various thermal parameters (latent heat of fusion, melting temperature, etc.) to characterize this PCM. The study was followed by a numerical study conducted using the finite element method (COMSOL Multiphysics) to validate the mathematical model. The numerical results were validated against the experimental results obtained and other reference results available in the literature.

An example of the application of phase change materials (PCMs) in solar collectors can be observed in the work of Parsa et al. (2023), where the researchers studied the impact of integrating latent heat thermal storage on the performance of a solar collector. First, the researchers designed a solar air collector equipped with parallelepiped structures filled with PCMs. A heater was installed on the absorber to produce a thermal flow similar to solar radiation. For the numerical procedure, 25 configurations of solar collectors were created, with different shapes of PCMs arranged and placed differently in each configuration to determine the optimal configuration. Several results were obtained regarding the temperatures and efficiencies of each configuration for different Reynolds numbers. The researchers found that the optimal configuration was Case 0, where the collector was equipped with small parallelepiped-shaped obstacles parallel to the flow.

A similar research study on solar air collectors was conducted by Tuncer et al. (2023). In this study, three prototypes of solar air collectors were designed: a simple collector, an "upward" collector equipped with cylindrical cans filled with PCMs installed parallel to the airflow, and another double-pass collector with PCM cans installed in both parts of the circulation. The numerical study focused on these three collectors, similar to those tested experimentally, to compare the numerical results with the experimental results. To simulate the flow conditions, a radiative model was chosen, replicating solar radiation at the same location as the experimental part (Burdur, Turkey). The results obtained showed the distribution of temperatures and thermal flows in the collectors, as well as an improvement in efficiency by integrating the PCMs. The researchers found that the optimal efficiency was achieved with the "upward" collector equipped with PCM cans.

Similar to the solar air collector, the same system was designed for a solar water collector. In an article by Abdalaali et al. (2022), the researchers improved the performance of a solar water collector by integrating a latent heat storage system. The authors conducted an experimental procedure where they connected a flat solar collector to a storage tank charged with cylindrical and spherical capsules filled with PCMs. These materials change their phase during charging to store more energy and return to their initial phase during discharging, thus creating a latent heat storage system. The numerical analysis was performed using the finite volume method (Ansys Fluent) based on the enthalpy method. The simulation was carried out with the experimental conditions to validate the experimental results. The researchers also studied the effect of varying the mass of the PCM on the performance of the collector and the amount of energy stored.

Among the applications of PCMs, thermal storage in buildings is noteworthy. This is achieved by integrating PCM boards into the walls or injecting microcapsules into concrete to maintain a comfortable thermal temperature inside the building. A study was conducted by Guichard (2016) to demonstrate the effectiveness of PCMs in reducing energy consumption. In his thesis, the author discussed types of thermal storage and performed a mathematical study on latent heat storage while highlighting the importance of integrating PCMs into buildings. Addressing the phenomenon of phase change, the author provided analytical models of phase change (the Stefan problem) and their solutions under various boundary conditions, subsequently using the enthalpy method. He carried out a numerical study using the finite difference method (CODYRUN/ISOLAB/MATLAB), including the modelling of radiative, convective, and conductive heat transfer between the PCM and the heat transfer fluid in the numerical code. To validate the previous results and calculate the effectiveness of PCM installation in buildings, the author conducted an experimental study in a chamber equipped with a roof and a PCM storage system underneath, measuring the temperature inside the chamber over a day, thereby demonstrating the thermal impact of the PCM on energy efficiency.

Additionally, in the thesis of Ferfera (2020), the author studied thermal storage methods and the importance of PCMs in latent heat storage, citing the advantages and disadvantages of using PCMs for thermal storage, as well as their types and applications. He also introduced solutions to one of the disadvantages of PCMs, which is their low thermal conductivity. One solution is the injection of a metallic foam. The author modelled the energy and flow in a porous medium (metallic foam and PCM). An experimental study was conducted to characterize the effect of the metallic foam on five different PCMs. He then introduced the governing mathematical equations, followed by a numerical study using the finite element method (COMSOL Multiphysics) with a VER and CUR approach. In the end, he analysed the numerical and experimental results, demonstrating the effect of the metallic foam on conductivity and thermal storage.

Among the methods to ensure thermal storage in internal spaces and the integration of PCMs in windows, the article by Kułakowski et al. (2023) proposes a solution for thermal insulation in non-residential buildings. This involves integrating PCMs into windows with an air gap between the two panes. This issue consists of achieving thermal insulation while simultaneously ensuring optical access. To this end, the author provided a less costly mathematical model that optimizes the number of iterations and used the finite difference method (COMSOL) for numerical simulation. The experimental part was conducted in a chamber with a single window insulated with PCM to validate the numerical calculations, thus demonstrating the effectiveness of the PCM in optimizing energy consumption for internal heating.

Heat exchangers are urban heating devices that operate by passing a heat transfer fluid through finned tubes. These tubes release heat from the heat transfer fluid to the environment through convection, consequently heating the building. Heating is the most energy-intensive domestic application. To save energy, thermal storage techniques have been developed and integrated into heat exchangers, including the use of phase change materials (PCMs) for latent heat thermal storage.

Another study was conducted by Zhang et al. (2024), where the researchers examined latent heat thermal storage by integrating PCMs (MPC A27) into urban heating systems, highlighting its impact on energy savings and temperature stability. A numerical study based on the finite volume method (SolidWorks/ANSYS Fluent) was performed to gain insights into the storage and release processes within the heat exchanger (Figure 2). Subsequently, a prototype of a finned-tube heat exchanger with PCMs was developed and installed in the ventilation duct of a chamber. The experimental study involved measuring the thermal flow and comparing it with the numerical results. The authors calculated the thermal efficiency and energy consumption, demonstrating the impact of installing a PCM on the performance of a heat exchanger and its energy efficiency.

In the research article by Zhang & Zhu (2024), the researchers examined the importance of latent heat thermal storage and its applications in various fields, particularly in energy storage in heat exchangers. They proposed a more effective and optimal storage method, which involves cascading two different PCMs in the annular space between the hot and cold heat transfer fluids in the heat exchanger. The researchers then mathematically modelled the problem by introducing the governing equations for the PCM, the wall, and the heat transfer fluid. The mathematical resolution was performed using the finite volume method (ANSYS Fluent), comparing the performance of three models: without storage, with simple storage, and with cascading storage.

Based on this bibliographic survey, we aim to investigate the effect of the integration of PCM storage material in a solar air collector used for drying purposes. Both numerical and experimental studies were achieved to highlight the improvement of thermal performance of the solar collector and the extension of its operation period when sunlight decreases.

2. STUDY OF THE SOLAR AIR HEATER WITHOUT HEAT STORAGE

The experimental part of our project aims to measure characteristic parameters (solar radiation, temperature, heat transfer fluid flow rate, etc.) in order to study the operation of a conventional solar air collector and analyse its thermal performance. The collected data will be used for the numerical simulation of a solar air collector equipped with a latent heat thermal storage system, in order to approximate the actual functioning of the solar air collector. The experimental study was conducted at the Centre for the Development of Renewable Energies, where the CDER provided us with the experimental test bench as well as the necessary instruments and devices to successfully carry out the experimental part of this project.

2.1 Experimental study

The experimental study was conducted at the CDER site in Bouzareah (36°48' N, 3°02' E, 300 m) from March to May 2024.

- Solar air heater: The main element of this experiment, which operates using forced convection. It is connected to a duct equipped with an air extractor to ensure air circulation within the collector. The solar collector has a rectangular structure with dimensions of ($L \times W \times h = 2$ m $\times$ 1 m $\times$ 0.075 m).

- The Pyranometer: It is a device for measuring radiative flux.
- Thermocouples Type K: we used them to measure the local temperature at different locations within the solar air heater.
- The Data Acquisition Station.
- Cup Anemometer.

2.2 Results

After several days of testing, we retrieved the file from the data acquisition station and analyzed the results. We then sorted the data and selected the 24-hour measurements for the numerical study, from 10/05/2024 at 00:04 to 11/05/2024 at 00:04:

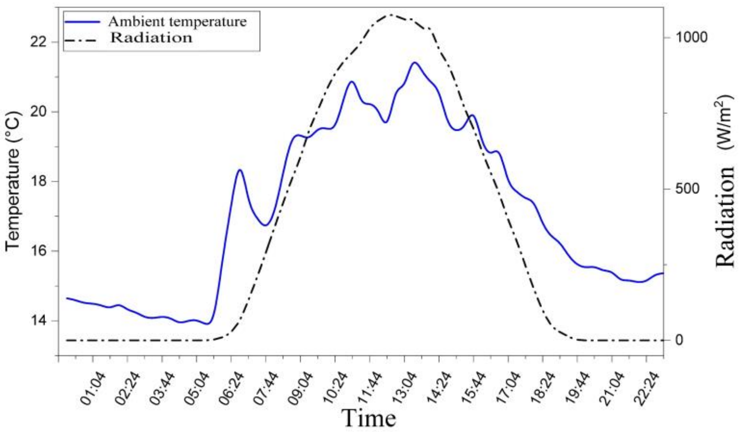

Fig 3. Curves of Ambient Temperature and Solar Radiation Measured on 10/05/2024

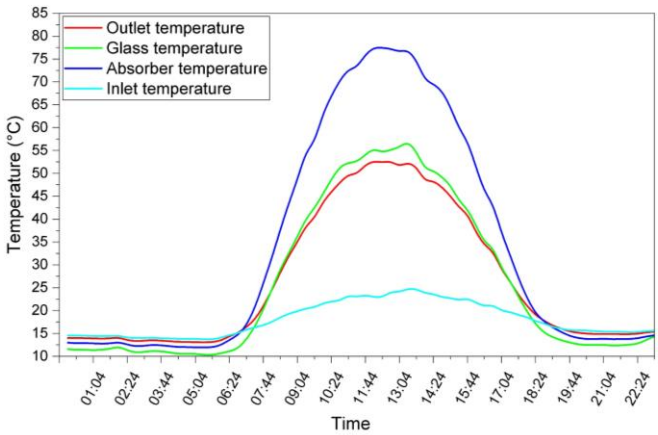

Fig 4. Curves of Measured Temperatures for an Inlet Air Speed of V = 1.2 m/s on 10/05/2024

The thermal efficiency of the solar air heater is calculated by dividing the useful heat obtained by the thermal flux received by the collector, as shown in the equation:

$$\eta = \frac{\dot{Q}_u}{A.GI} = \frac{\dot{m}c_p(T_s - T_e)}{A.GI} \quad (2)$$

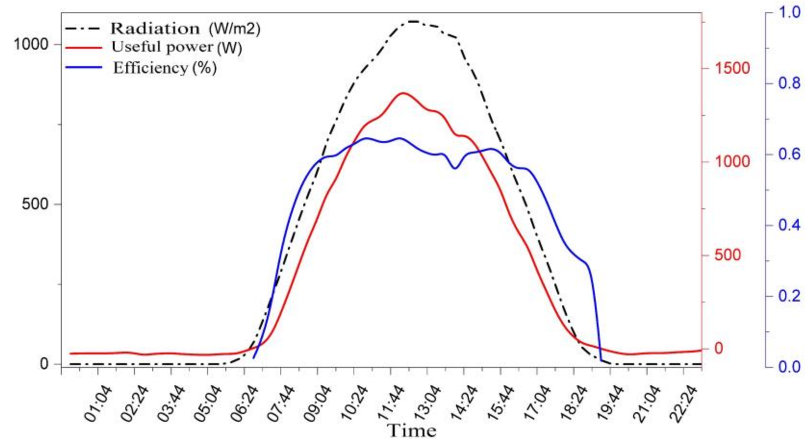

Fig 5. The variation of radiation, the useful power produced by the collector, and the efficiency of the collector for an air velocity of V = 1.2 m/s on the day of 10/05/2024

Figure 3 shows the daily evolution of the global inclined solar radiation received by the collector, as well as the ambient temperature for the day of 10/05/2024. The solar radiation curve has a bell shape, indicating a sunny day with only slight cloud cover. It is observed that the radiation intensity is zero during the night and gradually increases, reaching a maximum value of approximately 1100 W/m² around noon. Afterward, it starts to decrease until it reaches zero after sunset. The ambient temperature fluctuates between 14°C and 21°C throughout the day.

Figure 4 illustrates the variation in temperature at various positions of the collector over time, which is a variation similar to the evolution of the solar radiation received by the collector.

In Figure 5, we have plotted the daily evolution of the useful power and the instantaneous efficiency of the solar collector. From the graph, it can be observed that the useful power and efficiency increase throughout the day in accordance with the solar radiation curve, and then decrease as night approaches.

However, this is only observed during the day (when the sun is present). As soon as the sun disappears, the air temperature at the outlet drops. This poses a problem for solar applications such as drying, where it is not possible to operate the system continuously.

2.3 Numerical study

We performed a 2D numerical simulation of a solar air heater without storage using ANSYS FLUENT. The objective was to replicate the functioning of the solar collector and analyse the transfer phenomena occurring within it. To achieve this, we numerically modelled an upward solar air heater similar to the one used in the experiments (see Figure 8). We then imposed variable boundary conditions based on time and experimentally measured conditions to closely match the actual operation of the experimental collector, where we obtained the results depicted in Figure 6.

From the graph (Figure 6), we can notice a similarity between the numerical results and the experimental data, thus proving the validity of the numerical model. A discrepancy of 5 °C is observed around noon, which can be attributed to several reasons, including: The difference in the type of solar collector used (downward for the experimental and upward for the numerical), the presence of the greenhouse effect in the collector, which was not accounted for in the numerical calculation due to the complexity of the radiative model, making the simulation heavier and also in the numerical calculation, we assumed an external air speed of 2 m/s throughout the day, which leads to significant convective thermal losses at the glazing, which is probably not the case in the experimental setup where the wind speed is variable.

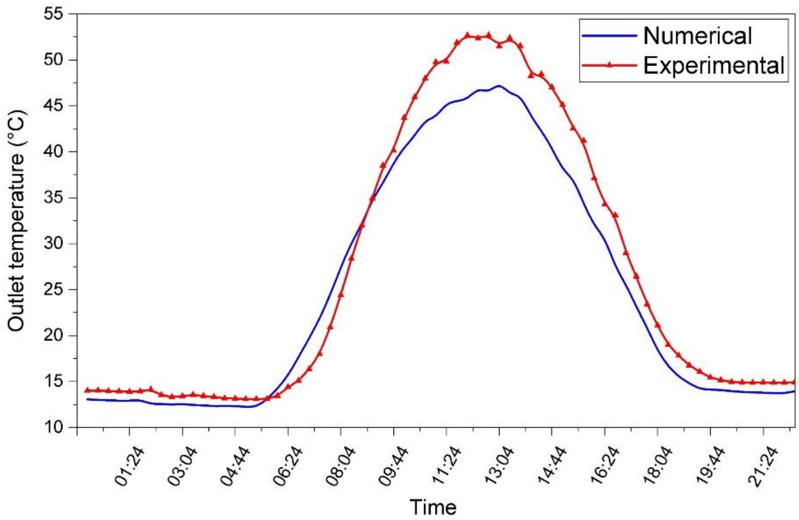

Fig 6. Comparison between the experimentally measured outlet temperature and the outlet temperature of the numerical model for a velocity of V=1.2m/s

3. STUDY OF THE SOLAR AIR HEATER WITH HEAT STORAGE

To study the effect of thermal energy storage through latent heat on the thermal performance of the solar collector, a numerical analysis was conducted on an air solar collector with two different geometric structures:

- A conventional air solar collector (without storage).
- A solar collector with latent heat storage.

The distinction between these two structures lies in the presence or absence of square-section conduits containing the phase change material (PCM) on the absorber, which are dedicated to thermal energy storage through latent heat.

The numerical simulation will be carried out with real operating conditions (experimental data on solar radiation and ambient temperature) to closely approximate the actual operating conditions of an air solar collector.

3.1 Study Geometry

Using the ANSYS Workbench environment, we developed the geometry of an air solar collector. This is an upward-type solar collector with dimensions L×W×h (2×1×0.075 m), which are the actual dimensions of the experimental solar collector, as shown in Figure 7. The absorber is equipped with square-section transverse conduits containing a phase change material (PCM) across the entire width of the collector. Considering that the width W of the collector is significantly greater than its height h (i.e.,W≫h), we opted for a 2D simulation. This approach is sufficient to describe the flow and heat transfer within the collector without complicating the calculations with a 3D analysis (see Figure 8).

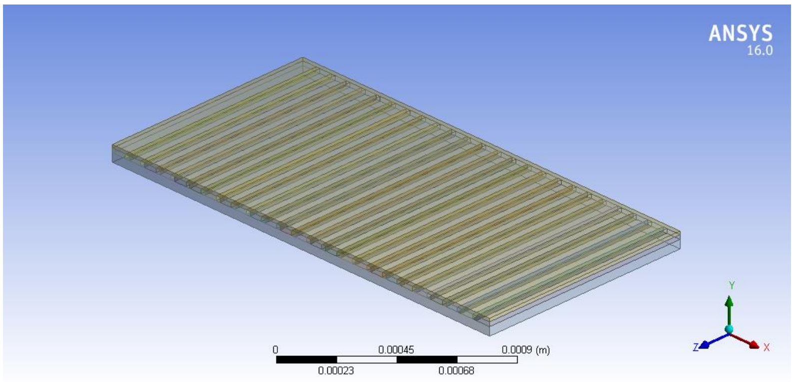

Fig 7. 3D Numerical Structure of a Solar Air Heater with Storage

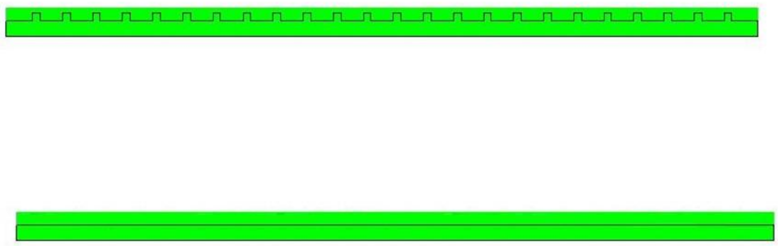

Fig 8. 2D Geometric Structures of the Two Solar Air Heaters Without and With Storage

For the numerical simulation, we used the following thermo-physical properties of the solar air heater components (Table 1):

Table 1. The thermophysical properties of the components of the solar collector

Component	Insulation	Glass	Metal	PCM(RT58)*	Air
Density (kg/m^3)	30	2550	8825	840	1.225
Specific Heat (J/kg.K)	1600	778	389	2100	1006.43
Thermal Conductivity (W/m.K)	0.029	0.779	44	0.2	0.0242
Viscosity (kg/m.s)	-	-	-	0.0269	$1.789.10^{-5}$
Latent Heat of Fusion (J/kg)	-	-	-	180000	-
Solidus Temperature (K)	-	-	-	321	-
Liquidus Temperature (K)	-	-	-	335	-

*Buonomo et al. (2017)

3.2 Mathematical Equations and Assumptions

To mathematically model the physical phenomena in a solar air heater with latent heat storage, it is necessary to make simplifying assumptions to solve the systems of equations. The assumptions are as follows:

Air is considered an incompressible and Newtonian fluid, the solid and liquid phases of the PCM are considered homogeneous and isotropic, the thermophysical properties of the solid and liquid are assumed to be constant and finally the volume changes due to the phase change are negligible.

To model the phase change in the PCM, it is necessary to have an overview of the existing mathematical models that characterize the phase change phenomenon in general, we used the program ANSYS Fluent that itself adapts the enthalpy approach (Swaminathan & Voller, 1992) to model the phase change in a medium:

$$\rho\left(\frac{\partial H}{\partial t}+\vec{V}.\vec{\nabla}H\right)=\vec{\nabla}.(\bar{\lambda}.\vec{\nabla}T) \quad (3)$$

$$H=c_pT+f_lL_f$$

with

$$f_l=\begin{cases}0 & T>T_l\\ \dfrac{T-T_s}{T_l-T_s} & T_l<T<T_s\\ 1 & T>T_s\end{cases}$$

With: $\bar{\lambda}=f_s\lambda_s+f_l\lambda_l$

Following the review of the various existing models, we chose the enthalpy method, as it is the only one available in the CFD code ANSYS Fluent. Thus, using the classical equations of mass, momentum, and energy balances, we write the governing equations for a 2D, transient flow with phase change:

$$\vec{\nabla}.\vec{V}=0 \quad (4)$$

$$\frac{\partial\rho\vec{V}}{\partial t}+\vec{\nabla}.\left(\rho\vec{V}\vec{V}\right)=-\vec{\nabla}P+\mu\vec{\nabla}^2\vec{V}+\rho\vec{g}\beta(T-T_0)+\vec{S} \quad (5)$$

$$\frac{\partial\rho H}{\partial t}+\vec{V}.\vec{\nabla}(\rho H)=\vec{\nabla}.\left(\lambda\vec{\nabla}T\right) \quad (6)$$

S is the source term of momentum related to the porosity of the mushy region (solid/liquid mixture zone) (Raj et al., 2020):

$$\vec{S}=\frac{\left(1-{f_l}^2\right)}{\left({f_l}^3+\varepsilon\right)}A_{mush}(\vec{V}-\vec{V_p})$$

A_{mush} : Constant of the mushy region
ε : A predefined constant to avoid division by zero
$\vec{V_p}$: pull velocity is the velocity at which the fluid is drawn from the porous medium

3.3 Numerical resolution

For the numerical resolution, we used the ANSYS Fluent software, a CFD code that employs the finite volume method to solve the governing equations. We selected the 2D Pressure-based solver for an unsteady regime, the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm for velocity-pressure coupling, the STANDARD model for pressure calculation, and the Second Order Upwind scheme for discretizing the equations (continuity, momentum, energy, turbulent kinetic energy, and specific dissipation rate). For temporal resolution, we opted for the First Order Implicit scheme. Default relaxation factors were maintained for solution control, and the convergence criterion was set to 10^{-6} for all residuals (continuity, x-velocity, y-velocity, energy, k, and ω). In order to determine the influence of buoyancy on the system and identify the predominant type of convection, we calculated the Richardson number ($Ri = Gr^*/Re^2$) for each airflow velocity. When natural convection is dominant, the Boussinesq model is activated for the density calculation. For turbulence modelling, we calculated the Reynolds number for each airflow velocity to verify the turbulent regime, and we selected the k- ω SST model.

3.4 Boundary conditions and mesh generation

Using the measurements obtained during the experimentation, we imposed the following unsteady boundary conditions:

- The air temperature at the inlet was set as the daily ambient temperature recorded at the Bouzareah site.
- The thermal flux values on the absorber and the walls of the square MCPs represented the solar irradiation received and transmitted by the glazing (experimental data recorded at the Bouzareah site) throughout the day.
- For the glazing, we chose the mixed option for radiative and convective heat exchange.
- For the lateral and bottom walls of the insulation, we imposed an adiabatic condition.

For the numerical simulation of the solar collector, we created a quadratic mesh of the geometric structure, tightened exponentially toward the squares of the phase change material (PCM) and the absorber to ensure the accuracy of the results and avoid any loss of information due to sudden variations in velocity and temperature in that region. To achieve an optimal mesh, which means obtaining good precision in the results while maintaining a reasonable computation time, we created several meshes with different cell sizes to compare the results of each mesh and select the most suitable one (Table 2).

Table 2. Results of the mesh test

Grid	T_s	y^+	Number of nodes	Percentage deviation
mesh 1	div	7.1	35502	-
mesh 2	div	3.885	74920	-
mesh 3	306.42	2.021	142679	-
mesh 4	306.48	1.91	154815	0.02
mesh 5	306.77	1.47	287720	0.09
mesh 6	306.75	1.1	469455	0.01
mesh 7	306.81	0.92	630549	0.02

According to the results obtained and with reference to the three parameters (number of nodes, y^+, and the percentage deviation from the previous mesh), we find that mesh 7 is the optimal mesh for the next numerical simulations.

3.5 Validation Case

To verify the accuracy and validate the numerical model used in our project, we reproduced the work of Muhammad et al. (2015). In this study, the researchers numerically studied the phase change in a cylinder filled with PCM (N-eicosane), comparing their numerical results with the experimental results of Jones et al. (2006), where the researchers constructed a cylinder prototype with an acrylic base and top, and polycarbonate side walls. The cylinder was immersed in a water bath maintained at 70°C, establishing a Dirichlet boundary condition on the side wall, while the base was kept at 32°C and the top was insulated.

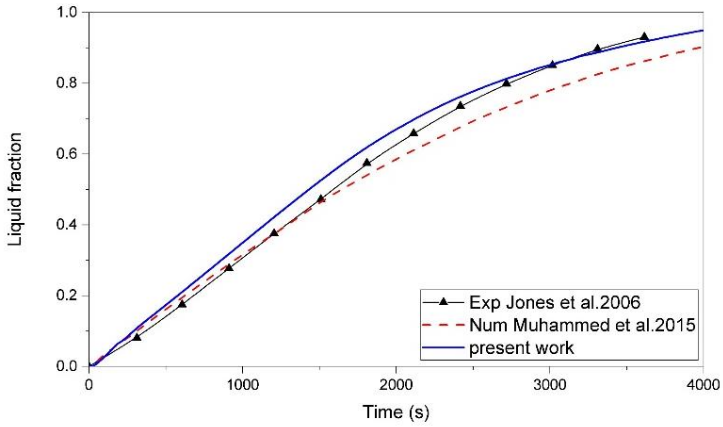

Fig 9. Comparison between the liquid fraction recorded experimentally by Jones et al., the numerical work of Muhammad et al. (2015), and the present work

By observing the curve of the liquid fraction results in the cylinder (Figure 9), comparing the experimental results of Jones et al. with the numerical results of Muhammad et al. and our own numerical results, we note that the relative error remains within an acceptable range. It is even notable that our results are closer to the experimental data compared to those of Muhammad et al. (2015), which validates our numerical model.

3.6 Results and discussions

In the following section, we will analyse the effect of introducing MCP squares on the flow dynamics and heat transfer within the solar collector.

When comparing the temperature contours throughout the day in the smooth collector with those in the collector containing the MCP squares (Figure 10), we note:

- On one hand, the thermal inertia provided by the integration of phase change materials: the decrease in temperature is less rapid compared to the smooth solar collector, thanks to the latent heat storage achieved by the MCP squares.
- On the other hand, the enhancement of thermal transfer from the absorber to the air: there is improved heat release from the absorber due to the recirculation zones caused by the MCP squares.
- Furthermore, during the discharge phase (complete solidification of the MCP and decrease in solar radiation), it is observed that the air temperature remains higher for the collector with storage, demonstrating the effectiveness of latent heat storage.

Figure 11 illustrates the daily evolution of the liquid fraction in the PCM. In the morning, as solar radiation increases, the PCM starts to melt, marking the start of the charging phase where heat absorption leads to energy storage as latent heat. By midday, when radiation peaks, melting is at its maximum. As radiation decreases in the afternoon, the PCM releases the stored energy, solidifying during the discharging phase.

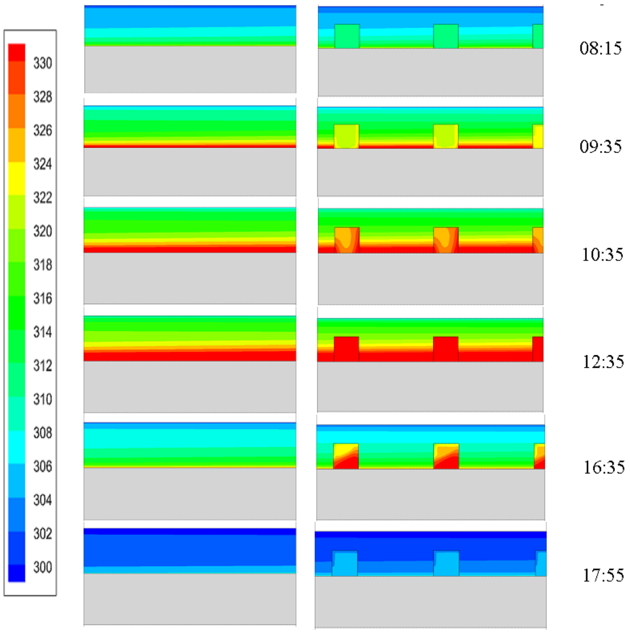

Fig 10. The temperature contours in the solar collector with and without thermal storage throughout a day

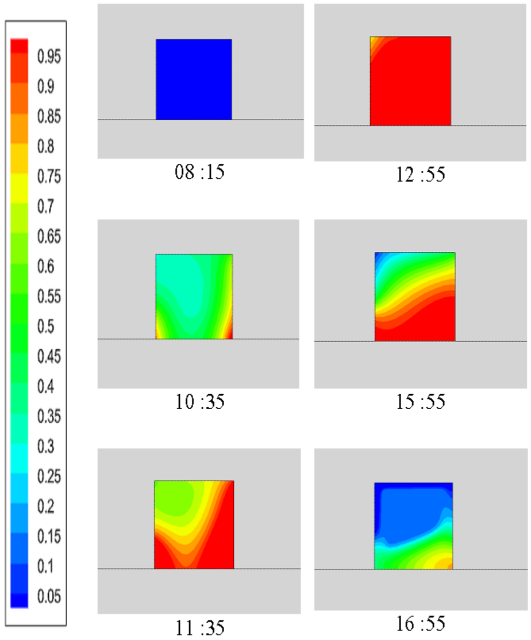

Fig 11. The liquid fraction contours in the PCM squares throughout a day in solar collector

During the numerical simulation of the two solar collector models—smooth and with MCP squares—we recorded the temperature variations throughout the day at several positions: the absorber, mid-height of the air flow zone, and the outlet.

During the numerical simulation of the two solar collector models—smooth and with MCP squares—we recorded the temperature variations throughout the day at several positions: the absorber, mid-height of the air flow zone, and the outlet. The absorber temperature curve (Figure 12) shows a 19 °C difference between the collectors, as the MCP squares absorb part of the heat flux, lowering the absorber's temperature while enhancing heat transfer to the air. Figure 13 displays the air temperature curve at mid-height, indicating that the collector with storage maintains a higher temperature, with a difference peaking at 8 °C during solar radiation and stabilizing at 2 °C during discharge. For the outlet temperature (Figure 14), both curves align in the morning. However, in the evening, the storage collector's temperature decreases more slowly, indicating the MCP squares are releasing stored energy, dampening the temperature drop. The temperature gain of 5°C persists even after the discharging phase ends.

The thermal performance of the air solar collector is assessed by calculating its useful power, thermal efficiency, and outlet temperature. To highlight the benefits of integrating a thermal storage system, we conducted a numerical study on two types of air solar collectors: one without storage and one with it. This study is based on experimental results from a 24-hour period, from May 10, 2024, at 00:04 to May 11, 2024, at 00:04. The useful power curve shown in Figure 15 reveals a significant difference of 18% between the two collectors, indicating that integrating thermal storage through latent heat increases the available useful power.

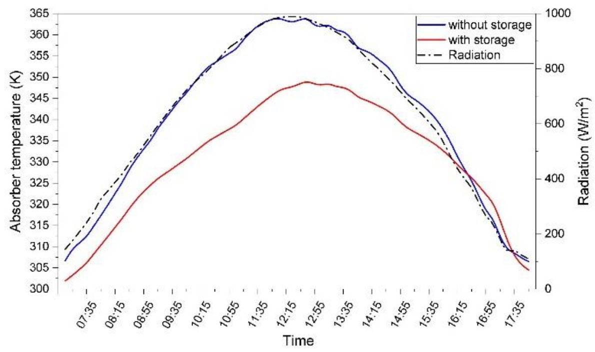

Fig 12. Absorber temperature for the two solar collectors, with and without storage, at a flow rate of V=1.5 m/s

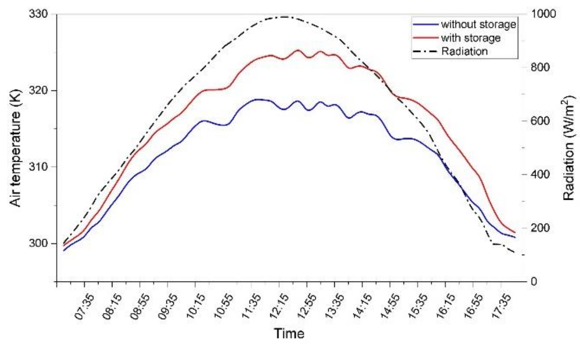

Fig 13. Air temperature inside the two solar collectors, with and without storage, at a flow rate of V=1.5 m/s

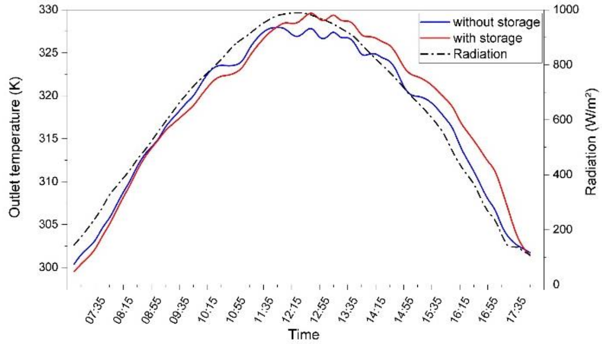

Fig 14. Outlet temperature for the two solar collectors, with and without storage, at a flow rate of $V = 1.5\, m/s$

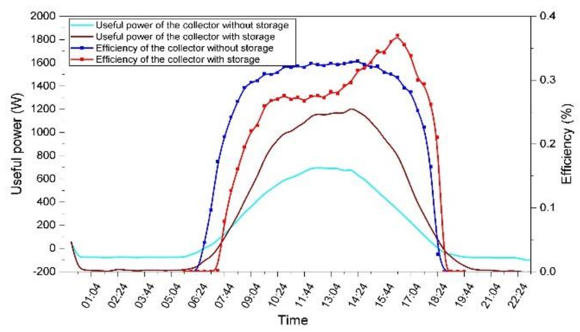

Fig 15. Comparison of useful power and efficiency between the two collectors, with and without storage, at V = 1.2 m/s over 24 hours

4. CONCLUSION

In this project, we studied and analysed the operation of a solar air heater (for drying purposes) integrated with phase change materials (PCMs), aiming to improve its efficiency and extend its operating period by for energy storage and usage in the absence of sunlight. The first part of the work was conducted experimentally on a conventional solar air heater to characterize its performance, thermal efficiency, and heat production. The second part focused on numerical analysis using the finite volume method (ANSYS Fluent) to compare two collectors: one without storage and the other with storage. We summarized the main results obtained:

- The analysis highlighted the charging and discharging phases of the storage system through the evolution of key parameters of the solar air heater, such as air outlet temperature, thermal efficiency, and useful power.
- Comparing the results of collectors with and without latent heat storage, we found that using phase change materials (PCMs) improves the solar collector's performance and extends its operating period.
- The PCM squares enhance thermal transfer within the solar collector due to the recirculation zones they create.

This work paves the way for further research on the geometry of the PCM container and the exploration of new phase change materials with better characteristics for thermal storage.

NOMENCLATURE

Symbols		**Dimensionless Numbers**	
Q	Heat	Ri	Richardson number
m	Mass	Gr^*	Grashof number
L	Latent heat	Re	Reynolds number
$\dot{Q}_u$	Useful power		
A	Illuminated surface	**Abbreviations**	
GI	Global incident radiation on the collector	PCM	Phase changing materials
$\dot{m}$	Airflow rate	DSC	Differential Scanning Calorimetry
c_p	Specific heat		
T_s	Outlet temperature	**Greek Letters**	
T_e	Inlet temperature	η	Efficiency
H	Enthalpy	ρ	Density
$\vec{V}$	Velocity vector	λ	Thermal conductivity
f_l	Liquid fraction	μ	Dynamic viscosity
P	Pressure	β	Thermal expansion
$\vec{g}$	gravity vector		
$\vec{S}$	Source term		
y^+	Length ratio		

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