Experimental Study of Energy Storage and Recovery with Fluid Change: Application in a Cylindrical Enclosure Filled with a Porous Terracotta Medium at Thiki in the Thiès Region

by Jana Publication & Research

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Abstract :

This study presents an experimental investigation into energy storage and recovery through fluid exchange, applied to a cylindrical enclosure filled with a porous medium composed of terracotta balls from Thiki, located in the Thiès region. The goal of this research is to contribute to improving energy efficiency, a critical factor in reducing greenhouse gas emissions in the industrial sector.

The objective of the study is to achieve optimal energy efficiency by testing the device with clay balls exhibiting a porosity of 0.57. A 180-ohm thermal resistor, providing a maximum power of 60 watts, serves as the energy source. To gather thermal data, ten thermocouples were positioned at various locations within the enclosure and linked to an Agilent data acquisition system.

The findings of this experiment demonstrate a significant thermal storage capacity in the porous medium created by the Thiki terracotta. We examined the temperature evolution, as well as the changes in energy and power over time, underscoring the potential of this material for thermal energy storage applications.

Nomenclatures

Cp heat capacity [J/K·kg]

D diameter of the tank [m]

d diameter of the billes

E energy [J]

g gravity [m/s2]

H height of the tank [m]

T températures [K]

P puissance [watt]

Greek symbols

Δt difference de temperature [K]

ε porosity

INTRODUCTION

Natural convection has long piqued the interest of researchers, both from a theoretical and practical standpoint, due to its numerous industrial applications. This phenomenon, which has been studied for more than a century, garnered considerable attention after its discovery through Bénard's experiments and Rayleigh's theoretical analysis in the early 20th century. To address the rising energy demands, developing nations must innovate in their energy supply strategies. In this regard, environmental and social considerations are now just as significant as economic factors when evaluating projects. Numerous energy conservation and efficiency initiatives have been launched in recent years, highlighting the increasing focus on diversifying energy sources.

To meet this escalating energy demand, governments have traditionally relied on fossil fuels and electricity. However, a recent shift has seen the integration of environmental and social goals with economic ones when assessing large-scale projects. The challenge lies in promoting sustainable energy development, prompting governments to invest in energy demand reduction initiatives and energy efficiency projects.

Our literature review reveals extensive research conducted globally in this field. For instance, B. Dhifaoui et al. [1] investigated thermal energy storage in a vertical channel filled with glass beads, heated by a constant flow over a wall, to optimize sensible heat storage. Due to its high thermal inertia, this system enables the slow release of heat. Nasrallah et al. [2] examined heat transfer via transient free convection in a vertical cylinder filled with grains, heated by a constant flow, using temperature models to simulate thermal evolution and pressure. Faye et al. [3] conducted experimental studies on energy storage in a cylindrical enclosure containing a porous medium, demonstrating the potential of Thiki clay as a high-capacity material for energy storage.

Moreover, Combarnous and Bories [4] utilized the transfer coefficient to model thermoconvective movements in a porous medium under steady-state conditions, with results affirming the impact of the thermal properties of the phases within the medium, as also confirmed by Bejan and Khair [5] and Ameziani et al. [6]. These studies underline the considerable potential of porous media for energy storage. However, the materials commonly used to form these media are often metallic [9], prompting us to explore more accessible and cost-effective alternatives, such as locally available materials.

For example, Prasanth et al. [11] enhanced the thermal conductivity of phase change materials (PCMs) for solar heat storage using metallic foams, with results indicating increased thermal efficiency and improved heat extraction, particularly for aluminum foam.

In light of this, our study focuses on exploring the potential of Thiki clay for energy storage and recovery through fluid charge in a cylindrical enclosure filled with a porous medium subjected to varying heat flows. In this work, we evaluate the energy storage capacity of this system, made up of cylinders filled with terracotta balls of different diameters and porosities. We modeled the energy storage by predicting the temperature profiles (thermal stratification in the cylinder during charging and discharging phases), determining the amount of energy stored and released, and calculating the thermal power generated by the Thiki clay.

I - Experimental Setup

The experimental setup was designed to observe heat transfer within a porous medium. The system's geometry was kept simple and tailored to accommodate bidirectional heat transfer.

I-1. Measurement Instrumentation

The primary measurement apparatus consists of a thermally insulated cylindrical casing, measuring 528 mm in height and 102 mm in internal diameter. This cylinder is designed to hold the porous medium and water, and was used to conduct two types of experiments in this study.

Composition of the Porous Medium

During testing, the tube was filled with water and a porous medium composed of solid particles with diameters ranging from 12.5 mm to 16 mm and a porosity of 0.57 (refer to Photo A). The cylindrical casing is encased in glass wool insulation at its vertical end (Photo B) and sealed with another steel cylinder. The entire assembly is maintained in a vertical position on a support.

Heating Element

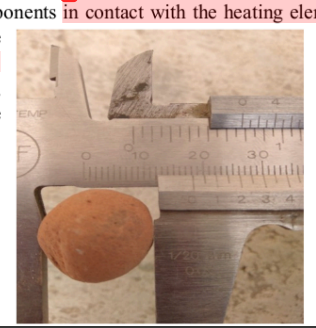
A thermal resistor with an approximate resistance of 180 ohms (Photo C) is attached beneath the base of the cylinder, delivering a maximum power output of 60 watts. The resistor terminals are connected to a stabilized power supply, which is adjustable in both current and voltage, enabling precise control of the power.

Temperature Measurement

A stainless steel sheathed thermocouple is affixed to the electrical coil support to monitor temperature via a thermal regulator. Glass wool is placed inside the support block to reduce heat dissipation in directions other than the axis of the tube.

Insulation and Thermal Contact

The copper surfaces of the components in contact with the heating element are also insulated with glass wool to enhance thermal insulation and ensure efficient thermal contact. The porous medium is thus contained within the tube, optimizing heat transfer conditions for accurate experimental results.



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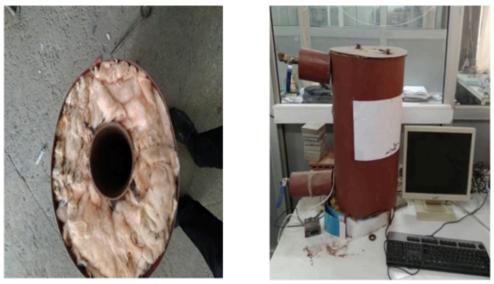

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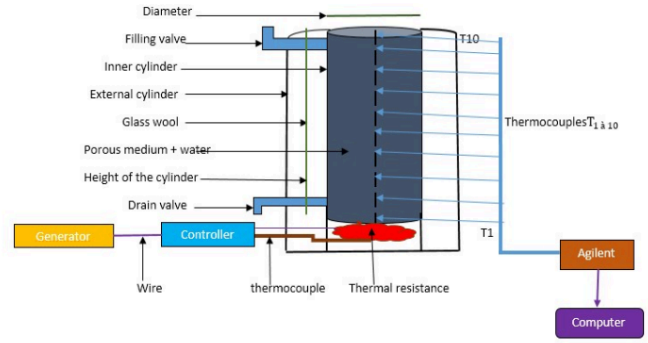

Fig1 : Description du dispositif expérimentale

I-2. Thermal Data Acquisition and Measurement Methods

Thermocouples are strategically positioned at regular intervals (approximately 52 mm) along the tube to monitor temperature fluctuations. Each thermocouple is inserted into a small metallic casing affixed to the upper wall of the enclosure. Once accurately aligned along the vertical axis of the tube, the thermocouples are soldered at the tube junctions to ensure an airtight seal with the surrounding environment. The thermocouples employed are of type K, with a diameter of 0.25 mm.

All the thermocouples within the tube are connected to distinct channels, numbered from 1 to 10, on an Agilent data acquisition system. This system reads and logs temperature data at various tube levels, offering precise and continuous tracking of thermal fluctuations.

II -1 Description of the Experimental Procedure

The experimental setup, shown in the figure, includes a generator that maintains a constant current and voltage. A temperature controller is linked to the generator to stabilize the temperature at the heating resistor. This resistor is positioned beneath the base of the tube. The tube is filled with a porous material, composed of ceramic spheres with diameters ranging from 12.5 mm to 16 mm, along with the fluid (water). Inside the tube, thermocouples are placed to measure thermal fluctuations, and the entire assembly is sealed with a steel cover.

The porous material consists of a loose arrangement of ceramic beads, for which we calculated an overall porosity (ε) of 0.57 by measuring the total mass and volume of the stack. To ensure the porous material is saturated with water, we carefully imbibe it until all the pores are completely filled. Once the initial vacuum is achieved (absence of air), saturation is reached by simple soaking, eliminating any risk of trapped air.

During the tests, the saturated porous material remains in continuous contact with a water reservoir at a constant level to maintain the upper surface of the medium at saturation. Before each test, we consistently verify that the medium is fully saturated to ensure optimal conditions.

II-2 Thermal Test of the Porous Medium

The porous material was previously saturated as thoroughly as possible with distilled water. We assume that the temperature T0 inside the tube is approximately room temperature. In the presented test, this temperature is T0 = 27°C. The top of the tube is thermally insulated (adiabatic). The power dissipated in the thermal resistor (R = 180 ohms) is sufficiently low to prevent boiling, with a power setting around 0.8 watts. Once the porous material is saturated with water, the test involves imposing a constant temperature T1 using a thermal resistor controlled by a regulator positioned beneath the tube. This temperature must be high enough to induce convection within the material. Additionally, the upper end of the porous medium is kept thermally insulated (adiabatic). The porous medium is allowed to stabilize at steady-state conditions, after which the fluid is replaced to observe the discharge of the porous medium over time.

II-3 Steady-state test results

In this experimental phase, we obtained the first results. Figure 7 shows the variation in temperature as a function of tube height for a porosity of ε = 0.57.

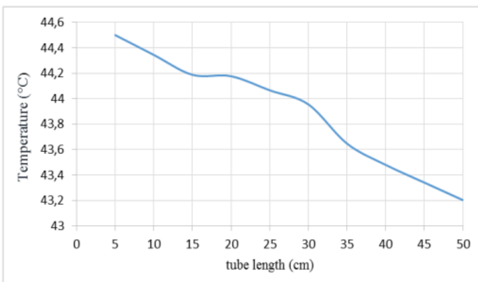

Figure 1: variation in temperature as a function of length

III. Results and Discussion

During the experiment, we recorded the temperatures captured by the thermocouples at approximately 1-minute intervals. These readings, obtained from different locations, were used to plot the temperature profiles presented in Figures 2 and 3 below.

- Temperature

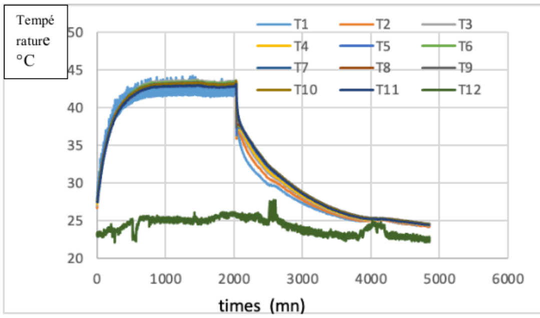

Figure 2: Temperature variation as a function of time

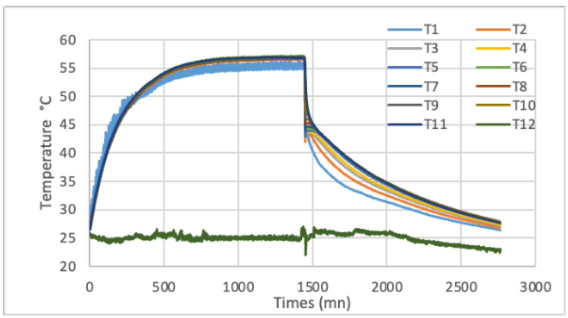

Figure 3 : Temperature variation as a function of time

The variation of temperature along the centerline of the system over time is shown in Figures 2 and 3 for a porosity of $\varepsilon = 0.57$. A uniform and gradual rise in temperature is observed along the tube.

After the fluid is replaced, a temperature peak emerges, followed by a decline until a minimum temperature is reached. This behavior is explained by the upward motion of the heated particles inside the tube: these particles ascend until they reach a buoyancy limit, then descend. The hottest particles, being less dense, tend to rise, while the cooler ones sink to the bottom, creating a continuous convective flow. This process results in a nearly uniform temperature distribution within the tube. The increasing portion of the curve indicates that heat is being supplied to the system.

This temperature rise corresponds to the absorption of thermal energy, causing heat to accumulate within the system. Conversely, the declining phase of the curve represents a reduction in thermal energy, suggesting a cooling process where the system releases heat into the surroundings.

The slopes of the various segments of the curves (Figures 2 and 3) provide insight into the rate at which heat is either absorbed or released. A steep slope during the rising phase indicates rapid heat absorption (as seen in Figure 3), while a gentler slope indicates slower absorption (Figure 2). In the cooling phase, a steeper slope suggests quicker heat loss, as in Figure 2 compared to Figure 3, likely due to a greater temperature difference between the system and its environment.

- **Stored energy**

The duration required to accumulate energy depends on the initial conditions. The energy stored at any given moment in the material comprising the porous bed can be determined using the following equation:

$$E = m_t\, c\, \Delta T \qquad (1)$$

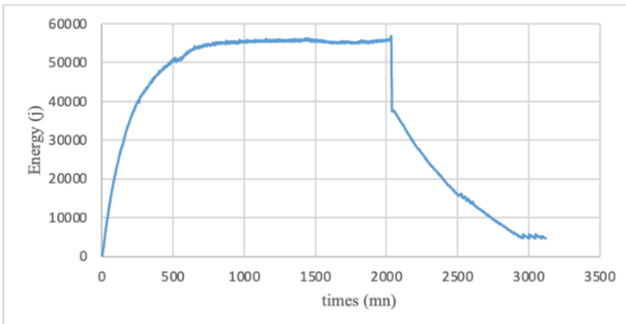

Figure 4: Energy variation as a function of time

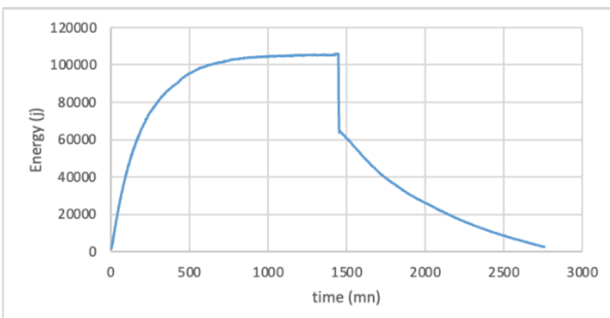

Figure 5: Energy variation as a function of time

hese graphs illustrate the variation in thermal energy (in joules) over time (in minutes).

Initial Phase (0 to ~500 minutes) for both Figures 4 and 5: Energy increases rapidly, suggesting that thermal energy is being accumulated or generated at a high rate. This phase likely represents a heating process, where an energy source works to elevate the system's thermal energy.
Stabilization Phase (~500 to ~1500 minutes) for Figure 5 and (~500 to ~2000 minutes) for figure 4 : Energy levels stabilize around a maximum value (approximately 60,000 J for Figure 4 and 100,000 J for Figure 5). This indicates that the input of energy and its losses are balanced, resulting in a steady state. This could suggest a constant temperature phase, where the system maintains a consistent level of thermal energy.
Decay Phase (from ~2000 minutes) for Figure 4 and (from ~1500 minutes) for Figure 5:
The energy level drops sharply and then gradually decreases over time. This is likely a cooling or energy dissipation phase, during which the energy source is removed or reduced, causing thermal energy to dissipate gradually.
This curve likely corresponds to a heating and cooling cycle. Initially, the energy source supplies heat, increasing the system's thermal energy up to a peak. Once the source is turned off, the system cools by releasing energy to the surroundings, potentially through conduction or convection.
Application context: This type of curve is commonly observed in thermal systems with heating and cooling cycles, such as heat exchangers or other thermal management devices.

- **Power**

La puissance thermique est donne par la relation suivante

$$P = \frac{E}{\Delta t} \quad (2)$$

Figures 7 and 8 show the variation in power as a function of time.

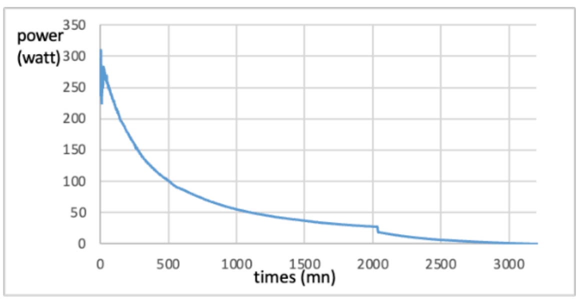

Figure 7: Variation in power as a function of times

At the beginning of Figure 7, the power is high, close to 300 W, then decreases rapidly.

There are fluctuations at the very beginning, which may be due to initial variations or adjustments to the system at start-up. Then there is a rapid decrease followed by a gradual decline.

After the initial fluctuations, the power decreases rapidly over a relatively short period, indicating high heat dissipation at the beginning.

The curve then gradually flattens out, indicating that heat dissipation slows down over time.

After 2000 minutes, the curve is almost horizontal and close to zero. The remaining thermal power is low and continues to decrease very slowly.

This indicates that the system is approaching thermal equilibrium with its environment, with very little heat to dissipate.

This curve is typical of cooling or heat dissipation from a cooling object or system.

The initial rapid decrease in thermal power could be due to a large temperature difference between the solid and its surroundings, resulting in more rapid heat loss.

The exponential decrease in heat output indicates a thermal dissipation process where heat loss depends on the temperature difference between the solid and its surroundings.

Towards the end, the thermal power approaches zero, suggesting that the system is in thermal equilibrium with its environment and that there is no heat left to dissipate.

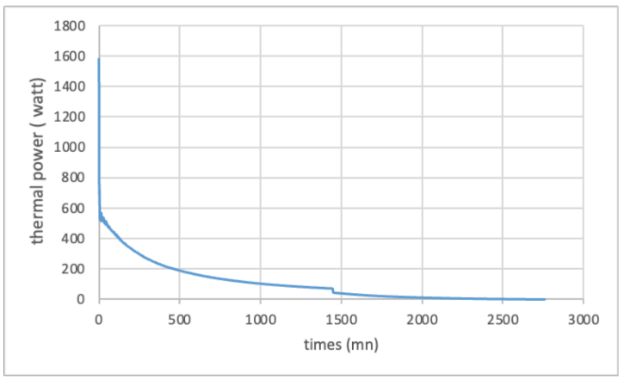

Figure 8: Variation in thermal power as a function of time

This figure shows thermal power (in watts) as a function of time (in minutes). It has a typical exponential decay form, which means that the thermal power decreases rapidly at the beginning and then slows down gradually over time.

The thermal power starts at a high value (around 1600 W) and drops rapidly in the first few minutes. This could be related to a system that rapidly loses initial thermal energy, such as a hot material that is cooling down.

After the first few moments, the curve gradually flattens out, indicating a slower decrease in thermal power. This could correspond to the moment when the system's temperature begins to stabilise or approach that of its environment.

From around 1500 minutes onwards, the curve is close to zero, suggesting that the residual thermal power is very low. The system is probably close to its state of thermal equilibrium, where there is almost no heat left to dissipate.

This curve could represent the heat loss of an isolated object or system that cools down until it reaches thermal equilibrium with its surroundings.

Conclusion

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