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Research Article

EXPERIMENTAL STUDY OF ENERGY STORAGE IN A CYLINDRICAL ENCLOSURE CONTAINNING A POROUS MEDIUM MADE OF THIKI TERRACOTTA THE THIES AREA

***Souleye Faye, Sidy Mactar Sokhna, Sory Diarra, Ousmane Sow, Vincent Sambou and Youssouf Mandiang**

Laboratories, Water, Energy, Environmental, and Industrial Process, Polytechnic School of Dakar, Dakar, Senegal

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Abstract

This work is dedicated to the experimental study of energy storage in a cylindrical container containing a porous medium made of Thiki terracotta in the Thiès region of Senegal. The purpose of this study is to obtain efficient performance by testing the device using different diameters of terracotta beads, resulting in porosity values of 0.55 and 0.57. The energy source consists of a thermal resistance of 180 ohms, generating a maximum power of 60 Watts. To properly conduct the experiment, we conducted thermal data measurements using 10 thermocouples connected inside the device and to the Agilent data acquisition center. The results of this experimentation shed light on the high thermal storage capacity of the porous medium formed by Thiki terracotta. Therefore, we analyzed the evolution of temperature as a function of time and the porosity of the medium. In addition to studying the thermal properties of Thiki terracotta, this research could have broader implications for the field of energy storage. The use of porous materials for energy storage has the potential to be more cost-effective and environmentally friendly compared to traditional energy storage methods, such as batteries. Additionally, the use of different bead diameters to vary porosity levels could lead to the development of more efficient and customizable energy storage devices. Overall, this study demonstrates the potential of Thiki terracotta as a high-capacity and cost-effective material for energy storage, and highlights the importance of experimental research in developing innovative solutions for energy storage and sustainability.

Keywords: Porous, Thiki, Energy, Storage, Terracotta.

INTRODUCTION

Natural convection has always attracted the interest of numerous scientists, both theoretically and practically, with an infinity of industrial applications. Research in this field has been conducted for a little over a century. A considerable number of works have been undertaken following the discovery of the phenomenon by Bernard's experiments and Rayleigh's theoretical analysis in the early twentieth century. In order to meet their ever-increasing energy needs, underdeveloped countries must innovate in terms of energy supply. Projects are facing a new context where environmental and social objectives are as significant as economic objectives in project evaluation. In this context, many energies efficiency and conservation programs have emerged in recent years, and there is a growing interest in energy diversification. We observe that to meet this growing energy demand, governments have until now favored the exploitation of fossil and electric energies. However, the recent trend to consider environmental and social objectives on an equal footing with economic objectives in the evaluation of major projects, as well as the challenge of ensuring energy development compatible with certain concepts such as sustainable development, are leading governments to invest in demand reduction programs and to participate in the development of energy optimization-oriented projects. According to our research, we have found that many works oriented in this direction have been carried out around the world. Thus, we can mention the work of: (Shafabakhsh *et al.,* 2019) investigated the influence of heterogeneity on free convection flow and solute transport in porous media. Their findings indicated that in fractured media, instability sets in at a lower critical Rayleigh number, suggesting that fracture networks contribute to destabilization (Haddad *et al.,* 2014). Explored the impact of permeability variation on heat flow and transfer, focusing on mixed convection vortex instability and the initiation of convection in vertically stratified porous materials. Through an auxiliary integral equation, it was demonstrated that subcritical instabilities are absent and the global stability condition can be obtained in closed form (Hassanien *et al.,* 2004). Examined both linear and nonlinear convective instability in a saturated porous medium, considering a non-zero inertia term and permeability variation in the vertical direction (Roblee *et al.,* 1958). studied the effect of variable permeability on vortex instability in horizontal natural convection through a porous medium adjacent to a horizontal surface. Their findings suggested that variable permeability enhances heat transfer rate and disrupts the flow. (Benenati *et al.,* 1962) conducted numerical simulations of natural convection within a square cavity containing a sinusoidal cylinder of varying amplitudes. Their results highlighted the potential to alter the heat transfer coefficient by adjusting the amplitude or angle, thereby influencing temperature and fluid dynamics significantly. (Schwartz *et al.,* 1953) and (Chandrasekhara *et al.,* 1984) demonstrated that porosity near a solid wall is not uniform but varies, leading to permeability fluctuations. Such heterogeneity in permeability distribution can also be observed in man-made porous materials like granulates in chemical engineering processes and fibrous materials in insulation applications. (Chaudhary *et al.,* 2003) presented experimental data revealing regions of high porosity extending two or three particle diameters from the flat wall container. Their results indicated that unless the D/d ratio exceeds 30, significant velocity variation occurs across the packed bed. Focused on "Experimental study of the dynamic behavior of a porous medium submitted to a wall heat flux in view of thermal energy storage by sensible heat". In fact, we have observed

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Corresponding Author:** ***Souleye Faye,
Laboratories, Water, Energy, Environmental, and Industrial Process, Polytechnic School of Dakar, Dakar, Senegal

that much research has been conducted on energy production and storage, especially in a container equipped with porous media. (Dhifaoui *et al.,* 2007) The broad potential for using porous media for energy storage, widely used in the literature (Ben Nasrallah *et al.,* 1997; Bejan *et al.,* 1985; Fard, 2010; Ameziani *et al.,* 2007; Edhari *et al.,* 2017; Edhari,2017; Kimura *et al.,* 1992; Javed *et al.,* 2016; Prasanth *et al.,* 2020; Benmansour ,2007; Mohammed Bechiri et Kacem Mansouri, 2013; B. Pekmen Geridonmez et Hakan F. Oztop 2019 ; and Young 1986), has aroused our curiosity about the use of local materials that could serve to create the porous medium. The materials used to constitute porous media being mostly metallic [15]**,** we have thus found an alternative to these materials by using a locally accessible, less expensive material. It is in this perspective that the present study focuses on the potential use of "Thiki" terracotta for energy storage in a cylinder by natural convection subjected to different imposed heat flux conditions. Thus, in this study, we investigated the energy storage capacity of our device consisting of a cylinder filled with fired clay beads, and the study was carried out with different bead diameters, conferring different porosities. We thus solved the problem of energy storage in a porous medium, which boils down to predicting the temperature fields, i.e., the temperature stratification in the cylinder (charge and discharge), then we determined the amount of energy stored, which finally allowed us to determine the energy efficiency produced by the "Thiki" terracotta. Cylinder filled with fired clay balls, and the study was carried out with different diameters of balls, giving different porosities. We thus solved the problem of energy storage in a porous medium, which boils down to predicting the temperature fields, i.e. the stratification of the temperature in the cylinder (charge and discharge) as a function of the porosity, and then we determined the amount of energy stored, which finally enabled us to determine the energy efficiency produced by "Thiki" terracotta.

Experimental apparatus

The experimental setup was designed to observe heat transfer in a porous medium. During the design of the setup, we aimed to create a simple geometry that would facilitate bidirectional heat transfer. This approach was motivated by the need to investigate the behavior of a porous medium under different heat flux conditions. To achieve this, we designed a device that would enable us to study the thermal behavior of a cylinder filled with clay beads of different sizes, allowing for the creation of different porosities. As a result, several studies have focused on the production and storage of energy in porous media, especially in industrial applications. In this context, the potential use of locally-sourced materials for creating porous media has been explored, with the aim of reducing costs and promoting sustainability. By using a porous medium, we aim to predict the temperature distribution within the cylinder during charging and discharging, which will help us determine the amount of energy stored and the energy efficiency of the "Thiki" terracotta. Overall, our experimental design was intended to provide insights into the behavior of a porous medium under different heat transfer conditions, with the ultimate goal of promoting the use of sustainable materials in energy storage applications.

The Measurement Tools

First and foremost, it is made up of a thermally insulated cylindrical envelope, 528 mm in height and 102 mm in inner diameter, which is intended to contain the porous medium and water. Two types of tests were used in this study. First, the tube used in the tests is filled with water and the porous medium. The porous medium consists of solids with a diameter d1 ranging from 12.5 mm to 16 mm and a porosity of 0.57 (Photo A). Next, the diameter of the beads is changed by adding water and the porous medium (solid) again. The diameter d2 of the beads is between 16 mm and 20 mm, with a porosity of 0.55 for the porous medium (Photo B). This envelope is surrounded at its vertical end by an insulator (glass wool) (Photo C) and then closed with another steel cylinder. The entire apparatus is held vertically on a support. A heating element, specifically a thermal resistance (Photo D) of approximately 180 ohms, is attached below the base of the cylinder fig.1 and 2. The terminals of the heating element are connected to a stabilized power supply, adjustable in both current and voltage, providing a maximum power of 60 watts. The end of a stainless-steel insulated thermocouple is brazed to the support of the electric coil to monitor the temperature with a thermal regulator. The inside of the support block is filled with glass wool to limit thermal dissipation in directions other than that of the tube. The surfaces of the various copper parts in contact with the heating element are covered with glass wool to improve thermal contact. The porous medium under study is confined inside the tube, within the tube.

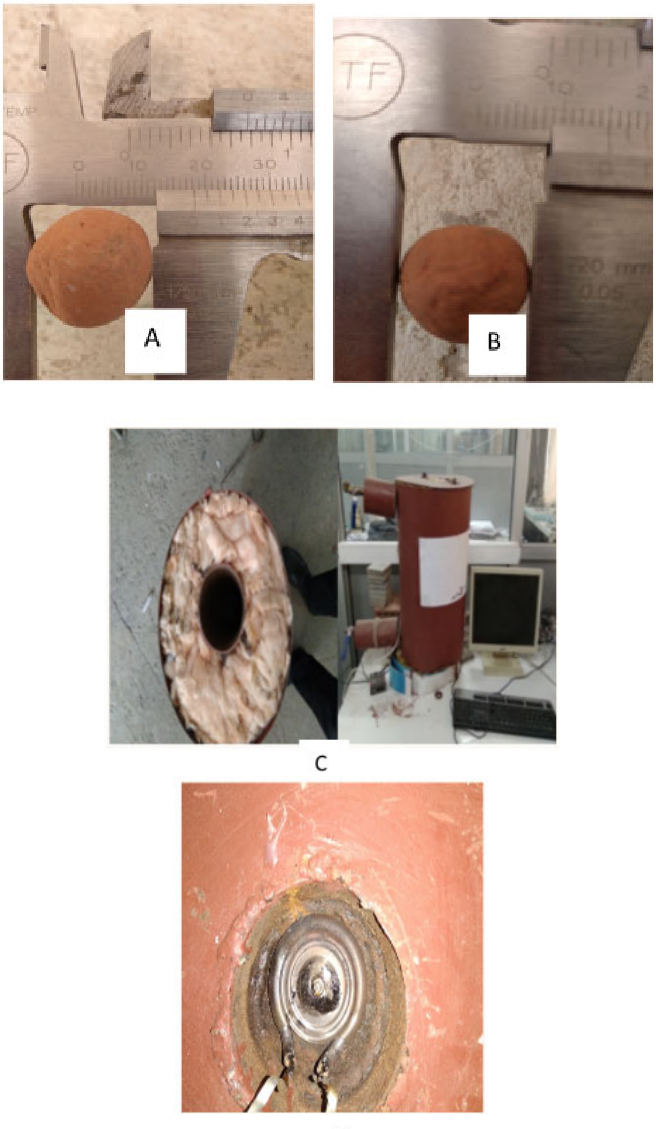

Figure 1. System components illustrated in pictures (A, B, C, D)

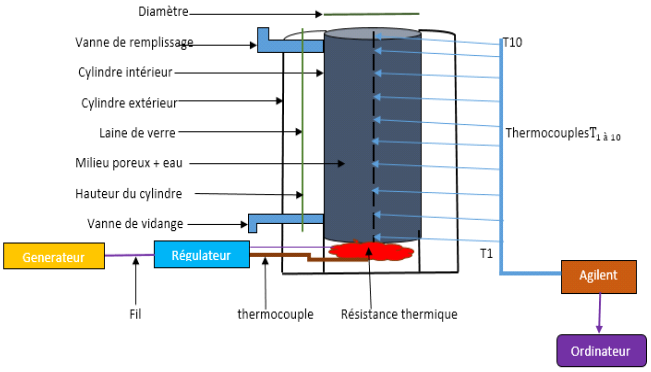

Figure 2. Description of the experimental device

Techniques for measuring and acquiring thermal data

At regular intervals (about 52 mm) along the tube, passages for thermocouples are installed. These passages consist of small metal tubes inserted into the upper wall of the cylinder. Once positioned along the vertical axis of the tube, the thermocouples are brazed at the passage height within the tubes to ensure a perfect seal with the surrounding medium. Type K thermocouples with a diameter of 0.25 mm are used for the measurements. All thermocouples placed within the tube are connected to different numbered channels (1 to 10) and are mounted within a device called the Agilent. This device is used to measure the temperature of the tube at different levels. The thermocouples allow for precise temperature measurements at various points along the tube, providing valuable data for the study.

Description of test procedure

The device shown in the figure consists of a generator that maintains a constant current and voltage. A thermal regulator is connected to the generator to maintain the temperature at the level of the heating resistance. The thermal resistance is fixed below the base of the tube which is filled with the porous medium (solid) and the fluid (water). Thermocouples are placed inside the tube, and the whole system is closed with a steel cover. The porous medium used is a "bulk" stack of ceramic balls with diameters ranging between 12.5 mm < d_1 < 16 mm or 20 mm < d_2 < 25 mm (Photo. 6). We determined the overall porosity of the medium by first measuring the mass and total volume of the stack. This overall porosity is equal to the value of ε:

ε = 0.57 for 12.5 mm < d_1 < 16 mm.
ε = 0.55 for 20 mm < d_2 < 25 mm.

The porous tube needs to be saturated with water for imbibition to occur. Once the primary vacuum is reached (absence of water), saturation can be achieved by simple imbibition since air trapping phenomena disappear. The saturated porous medium remains in permanent contact with a constant level water reservoir to ensure the maintenance of the upper surface saturation. Before each test, we verify the saturation of the medium. The thermocouples are arranged at regular intervals (approximately 52 mm) along the tube. They are made up of small metal tubes inserted into the upper wall. After positioning their end on the vertical axis of the tube, the thermocouples are brazed at the passage height in the tubes to ensure perfect sealing with the ambient medium. The thermocouples used are of type K and have a diameter of 0.25 mm. All the thermocouples placed in the tube are connected to different channels numbered from 1 to 10, and everything is mounted in a device called Agilent. This device is used to read the temperature of the tube at different levels.

Thermal test of the Porous Medium

The porous medium was previously saturated with distilled water as best as possible. We assume that the temperature T_0 inside the tube is close to ambient temperature. In the test we present, this temperature is T_0 = 27 °C. The upper face of the tube is adiabatic. The power dissipated in the thermal resistance R = 180 ohms is low enough to avoid boiling phenomena. We chose a power of around 0.8 Watt. Once the porous medium is saturated with water, the test consists of imposing a constant temperature T_1 = 65 °C through a thermal resistance supplied by a regulator on the lower face of the tube. The value must be high enough to allow convection to appear in the medium. Moreover, the upper end of the porous medium is kept adiabatic. This surface remains saturated with liquid thanks to the constant level device.

Steady-state test results

In the experiment we were able to show the first results. Figure 3 shows the variation in temperature as a function of tube height for ε = 0.55. In this figure, we can see that the temperature varies according to the height of the tube due to the permanent regime.

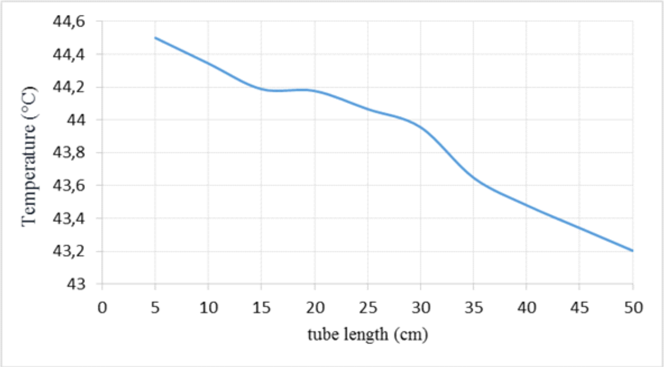

Figure 3. Variation of temperature with length

NUMERICAL STUDY

From the point of view of solving the equations governing flows, fluid mechanics has for a long time been confined to models using simplified formulations, in particular those of boundary layer flows. This approach is still important in certain fields, but it does not provide an accurate description of heat transfer, especially in enclosures. Since the introduction of computers and the development of numerical analysis methods, the models processed have become increasingly close to reality. The numerical approach allows, on the one hand, total control of fluid properties, flow parameters and boundary conditions and, on the other hand, perfect and infinite reproducibility of simulations. Various methods for solving the Navier-Stock, heat and matter equations exist and are used with varying degrees of success. However, of all those likely to be used to solve the equations, the method chosen must have good characteristics and, among other things, a turnaround time on the computer that is as reasonable as possible in relation to the calculations.

CFD Modelling of Water Heat Transfer in a Porous Tube

A computational fluid dynamics CFD tool was used to study the convective heat transfer of water in a porous tube. The effects of some important parameters such as pressure, inlet temperature, heat flux and wall porosity on the temperature distribution and local heat transfer coefficients were studied numerically by (Ahmed J. Al Edhari **,** 2017 et Ioan Sarbu and Calin Sebarchievici,2018).

We were unable to determine the equations of continuity, motion and heat.

- Equation of continuity:

$$\varepsilon \frac{\partial \rho_f}{\partial t} + \vec{\nabla}(\rho_f \vec{v}) = 0 \tag{1}$$

- Equation of motion:

$$\rho_f \left[\frac{1}{\varepsilon}\frac{\partial v}{\partial t} + \frac{1}{\varepsilon} \vec{\nabla}\left(\frac{1}{\varepsilon}\vec{v}\vec{v}\right)\right] = -\frac{1}{\varepsilon}\vec{\nabla}(\varepsilon P) + \frac{\mu}{\rho_f}\frac{1}{\varepsilon}\nabla^2\vec{v} - \frac{\mu}{k}\vec{v}$$

$$-\frac{C_f \rho_f}{k^{1/2}} \mid \vec{v}|\vec{v} + \rho_f \vec{g} \tag{2}$$

- Equation heat:

$$(\rho Cp)_m \frac{\partial T}{\partial t} + (\rho Cp)_f \, v\vec{\nabla}T = \vec{\nabla}(\lambda_m \vec{\nabla}T) \tag{3}$$

In this article, CFD simulations were carried out with the large balls in steady state. Considering the same boundary conditions as the experimental ones (Joshua Mctigue, 2018). The method of resolution considered is to draw the diagram above in Ansys Fluent with design modeler. The geometry used is meshed using the tetrahedral method and the number of elements obtained is equal to 12,645,000. Next, we take the standard viscosity model k-. The SIMPLER method is chosen, coupling velocity and pressure with second order **(**Rodriguez I. *et al.,* 2002**)**. The energy and continuity equations are subject to non-linear boundary and partial conditions. After the simulation, the temperature of the medium was plotted as a function of the length of the tube in steady state Figure 4 and 5. We can see the same variation in temperature with the experiment.

Comparison of numerical and experimental results

To find the regression line R^2, plot the numerical steady-state temperature results against the experimental results for equals 0.55 figure 6. These value of R^2 found, we can say that the results are consistent by (Zachár al., 2003)**.**

RESULTS AND DISCUSSION

During the test, we record the temperatures measured by the thermocouples with an acquisition period of about 1 minute. These measurements were taken at different points, resulting in temperature curves represented in the figures 7 and 8 below.

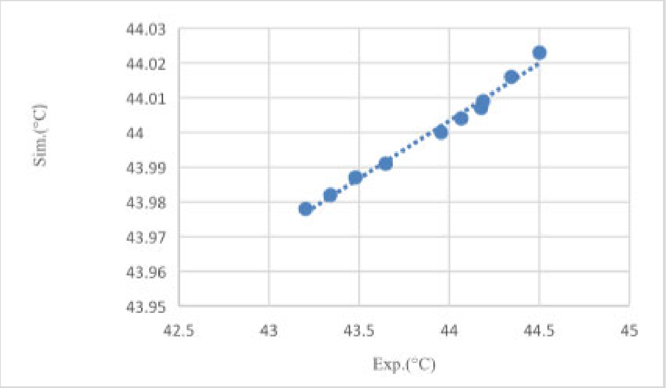

Figure 6. Representation of the regressive right

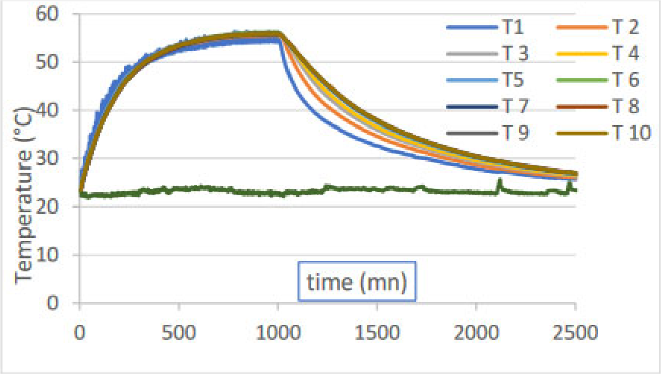

Figure 7. Evolution of the temperature as a function of time for a porosity ε = 0.55

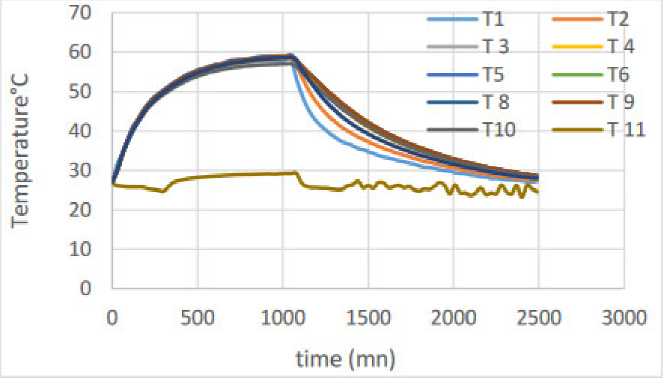

Figure 8. Evolution of the temperature as a function of time for a porosity = 0.57

The evolution of the temperature in the system along the median line as a function of time is shown in Figures 7 and 8 with the porosity = 0.55 and = 0.57. It can be seen that the temperature increases steadily and progressively along the length of the tube before decreasing unsteadily until it reaches the ambient temperature of 27 °C for both porosities. This is due to an upward movement of the hot particles inside the tube until they reach the buoyancy threshold and sink back down into the tube. The hottest particles have a low density, so they tend to rise, and those that are less hot tend towards the bottom of the cylinder, creating this continuous rotational movement. As a result, the temperature inside the tube is almost uniform. In the charge, the constant temperature is due to the turbulent regime. We also note that the decrease in temperature is observed more quickly for = 0.55 where discharge begins just after 1000 min. In contrast, for = 0.57 this decrease is observed around 1100 min due to the importance of porosity which favours particle movement.

The absence of stratification is more visible in figure 8 with a porosity = 0.57 than in figure 7 with = 0.55 because the movement of these particles is faster when the porosity increases. We have deduced that the temperature stored in Figure 8 is higher than that in Figure 7 at t = 1000 min. We can see that the temperature gradually decreases, and the temperature stratification is visible from the middle to the bottom of the tube (no insulation at the bottom of the tube) (Janne Dragsted, 2017; Dehghan, 2011; Qiong Li *et al.,* 2011 and Rodriguez I *et al.,* 2002)**.** Destocking is very slow in Figure 7 compared with Figure 8 because the hot molecules tend to sink, so the smaller the porosity, the slower the destocking. This results in a slower removal time compared with storage. As far as energy is concerned, storage time decreases as porosity increases, thanks to the high storage capacity of the beads.

The energy stored at each instant in the materials making up the bed can be obtained by the following relationship :

$$E\,(J) = m_t\,Cp\,T \tag{4}$$

Figure 9 and 10 shows the evolution of the energy stored in the bed as a function of time, which follows the same trend whatever the configuration used.

The temperature difference increases as a function of time, so the energy also increases. In both of the above cases, the stored energy increases with time to reach a maximum value for each configuration, a value that remains constant even though heating continues. By comparison, we have deduced that the stored energy increases with the porosity of the medium. This phenomenon can be explained by the fact that the particles are more mobile and reach the upper wall of the device more quickly as the porosity increases by (Ismail *et al.,* 1997)**.** This result has important implications for the design and optimization of thermal energy storage systems, as it suggests that increasing the porosity of the medium can lead to a higher energy storage capacity by (Bouhal *et al.,* 2017, Ching-Yang Cheng, 2010, Rashidi *et al.,* 2018). Additionally, the constant stored energy despite continuous heating suggests that the system reaches a steady-state, which is a critical consideration for the long-term performance and stability of energy storage systems.

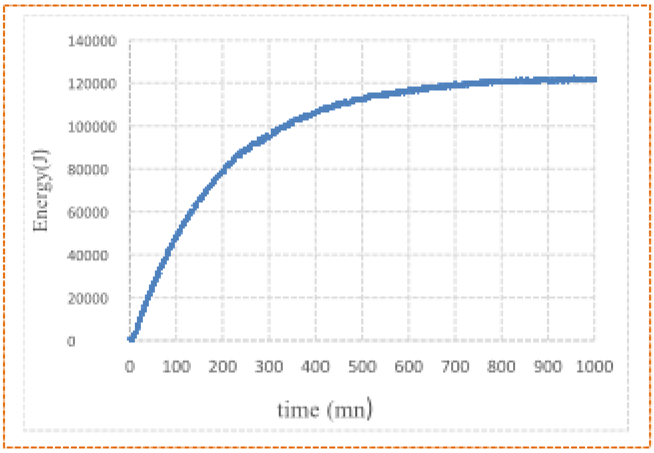

Figure 9. Variation of energy as a function of time for a porosity = 0.55

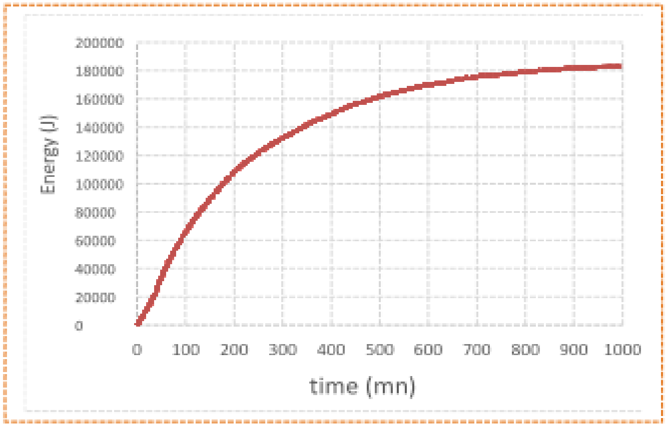

Figure 10. Variation of energy as a function of time for a porosity = 0.57

SYSTEME EFFICIENCY

The efficiency of the porous system can be determined by the following correlation given by (Zachár *et al.,* 2003 and Advaith *et al.,* 2020)

$$E_{ff} = \frac{T_m - T_0}{T_1 - T_0} \tag{5}$$

The calculated steady state efficiency is 47 $_0/^0$ for = 0.57 and 41 $_0/^0$ for = 0.55. Porosity has a significant effect on heat transfer. Increasing porosity increases heat exchange between particles.

Conclusion

In this work, we developed an experimental model to predict the temperature distribution of the water and the material, as well as the amount of energy stored during the process of storing and recovering thermal energy in a fixed bed composed of ceramic balls. The results showed that the use of the "Thiki" soil leads to a stable temperature stratification and a very satisfactory energy gain. We also concluded that the temperature and energy stored increased with the porosity of the medium, indicating the high energy storage capacity of "Thiki" clay. We have also shown that the porous medium is very efficient at storing energy. In the future, we plan to couple the experimental model to a numerical model and apply the study to a multi-layer, multi-section bed. This will enable us to gain a better understanding of the heat transfer mechanisms and optimise the design of thermal energy storage systems using 'Thiki' clay.

Nomenclatures

C_P : heat capacity [J/Kkg]
D : diameter of the tank [m]
d : diameter of the balls [m]
E : energy [J]
E_{eff} : efficacité
g : gravity [m/s2]
H : height of the tank [m]
K : permeability [m^2]
T : temperature [K]
t : time [s]
V : [m/s]

Greek symbols

T : difference in temperature [K]
: density [kg/m^3]
: porosity
: dynamic viscosity [kg/ms]

Indice

m : porous medium

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