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A New Criterion for Quantitative Comparison of Heat Retention Capacities of Different Materials

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Abstract

This paper introduced the concept of relative fractional area (FA) for comparison of materials for thermal retentivity. This concept was used as a criterion in selecting the best heat retention materials among sand, gravel, salt, red clay, kaolin and bentonite. The fractional areas for the materials were computed from experimental data obtained under similar conditions. Kaolin and red clay with the highest FA of 0.2039 and 0.1999, respectively were found to be the best heat retention materials, while sand with the least FA of 0.1862 had relatively poor thermal retention. The paper also showed how FA aligned in a similar trend as to the specific heat capacities of the materials.

Keywords: *Heat retention, Fractional area criterion for thermal retentivity, Thermal energy storage*

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1. Introduction

The global energy related challenges seek a robust, reliable and sustainable energy mix solution. Emerging technologies have focused on renewable energy sources, however, most of these sources are transient (Socaciu, 2012). Therefore, there is a need for energy storage systems that would level up demands at all time. Thermal Energy Storage (TES) are systems that accumulate thermal energy in a medium to be used at a later time. The storage medium stores the thermal energy by heating or cooling and likewise releases the energy for heating or cooling applications and power generation (Sarbu and Sebarchievici, 2018). TES has attracted growing interest in thermal applications such as hot water, space heating, cooling, and air-conditioning (Dincer and Rosen, 2011; Jaisankar et al., 2011). Currently, thermal energy storage systems use three main principles: sensible heat, latent heat and thermochemical storage systems. In a sensible heat storage system, the thermal storage material is heated to a high temperature and the heat absorbed is released when needed by the cooling process without a change of phase. The reverse thermal route also holds, (that is, when a cold thermal storage material is used to reduce the temperature of a system). The latent heat storage system makes use of phase-change materials (PCMs) driven by the high latent heat of phase change during melting of a solid to a liquid., while thermochemical energy storage systems use chemical potentials of high energy chemical reaction to store energy and the stored energy as heat when required (Jurigova and Chmurny, 2016). The thermal energy storage systems are rapidly evolving route for storing the transient renewable energy for steady energy utilization. However, latent heat storage system is relatively expensive, required for high energy density utilization and suitable for a constant temperature energy conversion technologies (Alva et al., 2017).

The selection of suitable thermal storage materials and storage systems for particular application depends chiefly on: costs implication, material availability, storage time, thermal stability, environmental impact, supply and utilization temperature requirements, storage capacity, heat losses and available space (Abedin and Rosen, 2011). Sensible heat storage systems are the most commonly used storage systems and the choice of the thermal storage material/medium is critical in the overall performance of the system (Jurigova and Chmurny, 2016). Primarily, a good thermal storage material should be able to retain absorbed heat to some reasonable extent.

Some studies have compared heat retention capacities of materials based on time it takes the materials to dissipate pre-absorbed heat, while some findings have based it on other qualities/properties such as the specific heat capacities (Socaciu, 2012; Akhmetov et al., 2016; Alabi et al., 2017). It becomes difficult to use the later if working with material(s) of unknown specific heat capacities or the property under consideration. However, materials with high specific heat capacities absorb comparatively more heat than those with lower specific heat capacities (Incropera and Dewit, 2002). Socaciu (2012) also agrees that desirable sensible heat storage requires the thermal storage material with high specific heat capacity. Alabi et al. (2017) had compared the heat retention capacities of fresh water and different sugar solutions. The research based the criterion for the best heat retention solution (concentration) on the time it would take the solution to either freeze or boil. Aleksandrova et al. (2023) highlighted among others enthalpy melting value ΔH_L, hypothermia value and melting point T_L for consideration when selecting phase-change materials for thermal energy storage systems. Using these criteria, magnesium sulphate heptahydrate was selected in the midst of nine other materials as the best suitable phase-change thermal storage material for application in pottery house construction. Akhmetov et al. (2016) had compared thermal storage systems based on the storage volume for $1m^3$ of water equivalent. That is, the volume of the heat storage material that could store equal amount of thermal energy as does one cubic meter of water.

The current work is aimed at introducing another criterion for quantitatively comparing the heat retention capacities of different materials using the area under the curve of temperature-time plot produced by the materials.

2. Materials and methods

2.1 Material selection

In the study, various materials were selected for comparison based on their potential for heat retention. The materials included metals, ceramics, polymers, and composite materials. To evaluate their heat retention capacities, a controlled experimental setup was designed. Each material was subjected to a standardized heat source for a specific duration, and the temperature change was measured over time. The experiments were repeated thrice to ensure accuracy and reliability of the results. The materials whose relative heat retention capacities were being investigated were red clay, salt (Sodium Chloride), gravel, kaolin, bentonite and sand. These materials were all locally sourced in Port Harcourt, Nigeria. Also, advanced analytical tools and statistical methods were employed to analyse the data and draw meaningful conclusions. The combination of careful material selection, precise experimentation, and rigorous data analysis allowed for a comprehensive and objective comparison of the heat retention capacities among the different materials.

2.2 Experimental procedure

100g of sand sample was heated in a crucible placed on an electric hotplate until its temperature was raised to 270ºC. The temperature attained was measured and recorded. Immediately the heating was stopped, the sample was removed from the hotplate, transferred into an iron container and then allowed to cool naturally by the ambient air. The changes in temperature were monitored with the aid of Infrared Thermometer for every 1 minute up to 90 minutes and the results were tabulated. The above procedure was repeated thrice for samples of gravel, salt, clay, kaolin and bentonite. The images on the first and second quadrant of Fig. 1 show temperature reading of sample with infrared thermometer and the heating of clay sample on a hotplate respectively; while the images on third and fourth quadrant show the gravel and kaolin samples respectively.

Fig. 1: Experimental set-up with thermal materials

2.3 Criteria for heat retention

In an ideal isolated system, the temperature of a thermal storage material is expected to be constant. That is, the storage material is able to perfectly retain the heat that was pre-absorbed and the temperature-time curve would be a horizontal line parallel to the x-axis as shown in Fig. 2. However, in a real system, the temperature of the storage material drops with time as shown by the curve in Fig. 2. The area under this curve is the orange shaded part; while the area under the perfect curve includes the blue shaded area together with the orange shaded part.

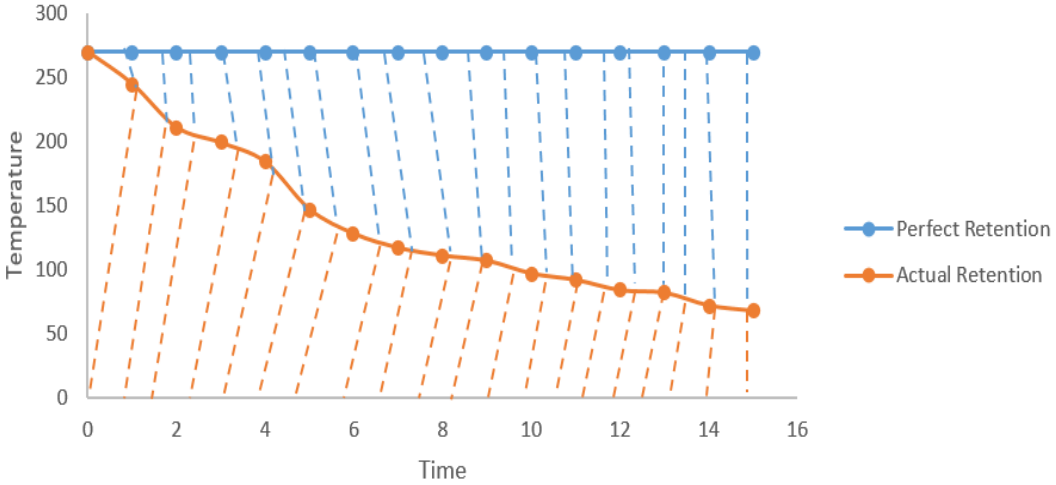

Fig. 2: Theoretical temperature-time curve for a storage material

The area under the temperature-time curve should be proportional to heat retained by the material. This is called Fractional Area (FA) in this work. FA is defined as:

$$FA = \frac{Actual\ Area}{Ideal\ Area} = \frac{Area\ shaded\ with\ orange}{Area\ shaded\ with\ (blue{+}orange)} \quad (1)$$

FA represents the material's relative thermal retention capacity. The area under the curves were calculated by numerically integrating the temperature-time experimental data using Simpson's 1/3 rule implemented with Microsoft.

3. Results and discussion

3.1 Probit analysis for toxicity testing

The temperature variation with time for the six storage materials (sand, gravel, clay, salt, kaolin and bentonite) are shown in Fig. 3. As can be seen in the figure, the temperature drop was faster at the beginning and later became steady as time progresses but slower at the later time. The Fourier conduction heat transfer equation and the convection heat transfer equation imply that the heat transfer is proportional to the temperature difference. That is, the higher the temperature deference the higher the amount of the heat that would be transferred (if other parameters are kept constant). Conversely, the lower the temperature difference the smaller the amount of heat that would be transferred. That explains why the heat transfer rate was high at the beginning when the temperature difference of each material to its surrounding was high. But at the later stage when the temperature of the materials was low, the heat transfer rate was low.

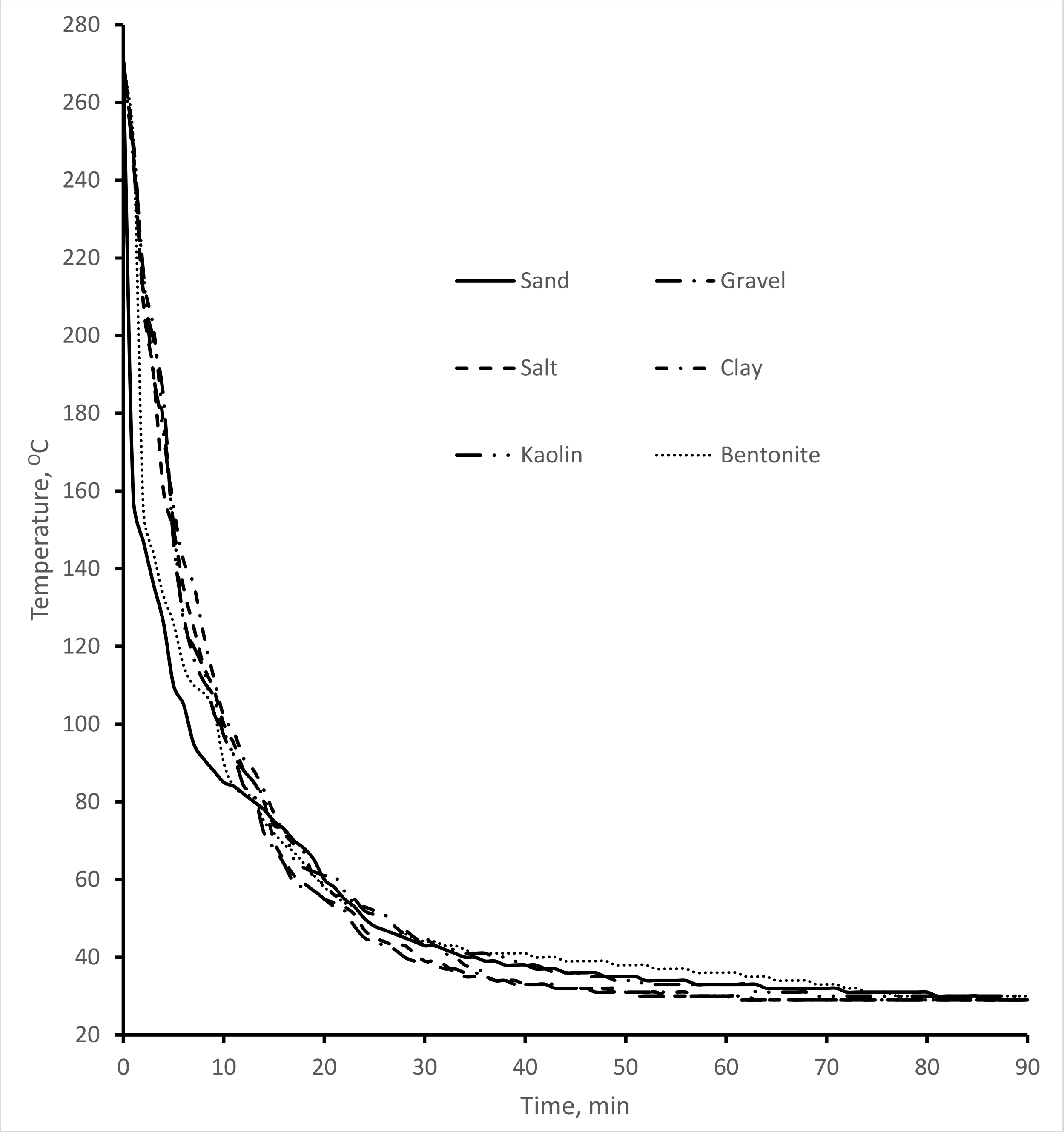

Fig. 3: Experimental temperature variation with time for 6 different heat storage materials

The rate at which the materials dissipate heat differs. This difference could be explained by the difference in the specific heat capacities of the materials. Among the materials under test, bentonite has the highest heat capacity (1.15 J/g.K) and followed by kaolin (0.945 J/g.K). Higher specific heat capacity of a material implies that higher amount of heat is required to raise the temperature of a unit mass of that material by 1 degree. And to that same extent, equal amount of heat must be dissipated to reduce the temperature of that same material by 1 degree. That is, the higher the specific heat capacity, the more tendency of the material to retain heat. The calculated FA values using the experimental values shown in Figure 3 are tabulated in Table 1. Kaolin and red clay have the highest FA values. This corresponds to their higher specific heat capacities except for bentonite. Gravel and sand have the least FA values, which also corresponds to their low specific heat capacities.

Table 1: Fractional area of the materials under 90 minutes

Materials	Actual Area (ºC.min)	Ideal Area (ºC.min)	Fractional Area (FA)	Specific Heat Capacity (J/g.K)
Kaolin	4918.33	24120.0	0.2039	0.945
Clay	4876.33	24390.0	0.1999	0.94
Bentonite	4801.33	24390.0	0.1969	1.15
Salt	4687.33	24300.0	0.1929	0.86
Gravel	4643.00	24210.0	0.1918	0.84
Sand	4491.00	24120.0	0.1862	0.8

The bentonite used for this experiment has very fine particles (70μm) and some of them escaped as dust when the material was being heated to 270ºC. This phenomenon may have caused variation in mass and hence variation in the amount of heat it could retain. In spite of this challenges, bentonite still ranked high in FA above salt, gravel and sand. Consequently, the plot of FA versus specific heat capacity for the remaining five materials are shown in Fig. 4. Fig. 4 confirms the linear relationship between FA and specific heat capacity for the 5 materials and can be represented by the equation:

$$FA = 0.1079C_p + 0.1003 \tag{2}$$

with $R^2 = 0.9643$ where R^2 is the coefficient of regression and C_p is the Specific Heat Capacity, (J/g.K)

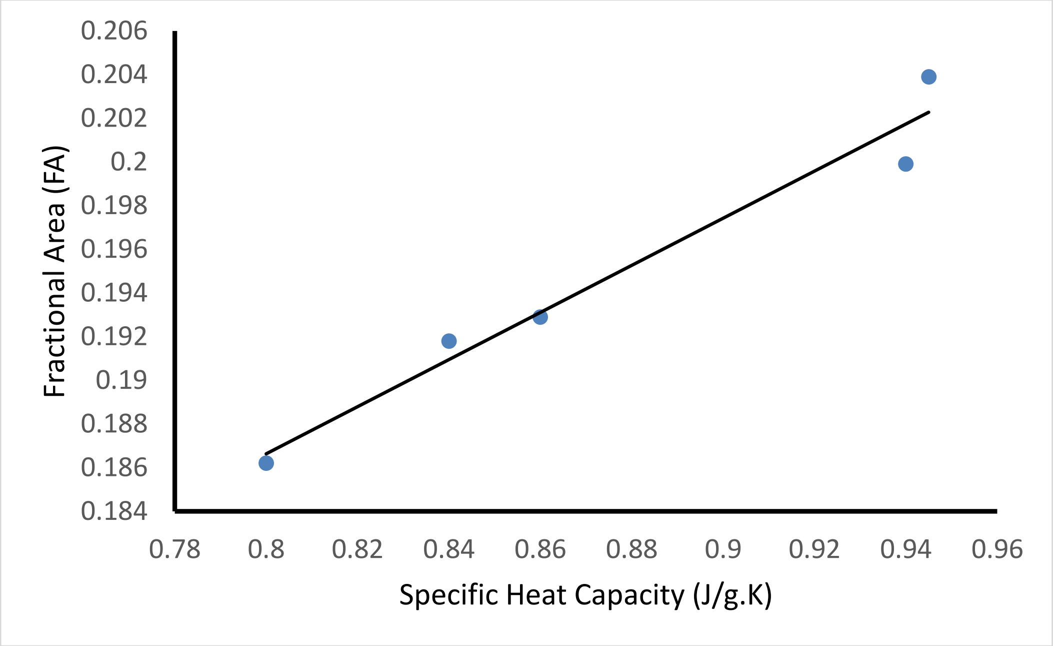

Fig. 4: Linear relationship between FA and specific heat capacity

4. Conclusion

A linear relationship exists between fractional area and heat capacity of material. The larger the fractional area, the higher the heat retention capacity of the material. Kaolin and red clay with the highest FA of 0.2039 and 0.1999, respectively were found to be the best heat retention materials, while sand with the least FA of 0.1862 had relatively poor thermal retention. The results obtained showed that fractional area method developed in this work is a valuable approach for comparing the heat retention capacities of different materials and identifying those with superior thermal properties. This information can be crucial for various applications, such as building materials, insulation, and energy-efficient systems, thereby contributing to the advancement of sustainable and energy-saving practices.

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References

Abedin, A.H. and Rosen M.A. (2011) A Critical Review of Thermochemical Energy Storage Systems. The Open Renewable Energy Journal, 4: 42-46.

Akhmetov, B., Georgiev, A.G., Kaltayev, A., Dzhomartov, A.A., Popov, R. and Ungatarova, M.S. (2016) Thermal energy storage systems – review. Bulgarian Chemical Communications 48(E), 31–40.

Alabi, A.A., Ogungbe, A.S., Adewale, A.O., Makinde, V. and Agbabiaka, J.T. (2017) Comparison of Heat Absorption and Retention Capacity in Fresh Water and Sugar Water Solutions. Ilorin Journal of Science 4(1): 182–193.

Aleksandrova, O., Zhmykhova, T., Värnik, R. and Viira, A.H. (2023) The One-Way Analysis of Variance of Heat-Storage Materials Used in Building of Poultry Houses. Processes 11: 104.

Alva, G., Liu, L., Huang, X. and G., F. (2017) Thermal energy storage materials and systems for solar energy applications. Renewable and Sustainable Energy Reviews 68: 693-706.

Dincer, I. and Rosen, M.A. (2011) Thermal Energy Storage Systems and Applications, Second Edition. John Wiley & Sons. 107-108. 978-0-470-74706-3.

Incropera, F.P. and Dewit, D.P. (2002) Fundamentals of heat and mass transfer. 5th ed. John Wiley and Sons.

Jaisankar, S., Ananth, J., Thulasi, S., Jayasuthakar, S.T. and Sheeba, K.N. (2011) A comprehensive review on solar water heaters. Renewable and Sustainable Energy Reviews 15(6): 3045-3050.

Jurigova, M. and Chmurny, I. (2016) Systems of Sensible Thermal Energy Storage. Applied Mechanics and Materials 820: 206-211.

Sarbu, I., and Sebarchievici, C. (2018) A comprehensive review of thermal energy storage. Sustainability 10(1): 1-32.

Socaciu, L.G. (2012) Thermal Energy Storage: An Overview. Acta Technica Napocensis, Series: Applied Mathematics and Mechanics, 55(4).