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Material-Level Experimental Evaluation of Soil-Based Thermal Energy Storage for Solar-Powered Adsorption Refrigeration System

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1. ABSTRACT

Integration of concentrating solar collectors with thermal energy storage systems, can enhance the performance of solar thermal adsorption refrigeration systems. In this research, soils sourced from the central rift valley of Ethiopia were investigated for thermal energy storage. Therefore, emphasis was on heat capacity and thermal diffusivity to assess thermal storage capacity and charging/discharging agility. The study analyses soil samples from representative locations (Koka, Bote, and Meki) and examines their thermophysical attributes across varying grain sizes. The results reveal associations between porosity, heat capacity, and thermal diffusivity, providing valuable insights for energy-efficient systems. The specific heat capacity ranges from 0.86 to 1.44 J/g°C, while thermal diffusivity varies between 0.38 and 0.54 mm²/s. These findings contribute to sustainable energy practices and inform soil-based thermal management strategies. It is observed that utilising soil as a low-cost sensible heat storage and integrating it with solar thermal collectors and photovoltaic panels to power adsorption refrigeration system, high solar fractions can be achieved. Soil appears to be a technically viable heat storage medium, facilitating extended operating periods and efficient early starts of the system.

2. INTRODUCTION

Understanding the thermal properties of soil is crucial for various engineering, agricultural, and environmental applications [1]. Thermal collectors and PV panels have been utilised to attain high solar fractions to meet the thermal and electric energy required by adsorption refrigeration system, which led to sustainable year-round operation for the cold room, when utilising adsorption refrigeration system. Li et al. [2] proposed storing solar energy in soil during the transition season for a solar-ground source double-effect LiBr-H_2O absorption heat pump. Soil-based energy storage was evaluated based on heat balance objectives. Their results indicate that soil heat imbalance can be mitigated using this approach. One of the key challenges hindering the widespread adoption of solar thermal driven adsorption cooling systems is their intermittent availability. Sunlight dictates system operation, limiting cooling to daytime hours. Conventional thermal storage solutions like water often struggle in solar thermal systems due to limitations in operating temperatures. The heat transfer fluid in solar collectors and the generator of the adsorption system typically exceed 90°C. Water's boiling point restricts its effectiveness at these high temperatures. This research proposes a groundbreaking solution: utilizing soil as a low-cost, sustainable thermal energy storage medium to achieve 24/7 operation and significantly advance the performance of these systems. Soil emerges as a highly viable

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alternative. Its inherent properties, including high heat capacity, favorable thermal diffusivity and abundant and cost-effective. This paper presents part of the outcome of research that focuses on studying the adsorption refrigeration system and integrating thermal energy storage using soil sourced from the Central Rift Valley of Ethiopia. By analyzing the thermal diffusivity and heat capacity of soil from this specific location, we aim to optimize the system's design and performance for the local context.

3. METHDOLOGY

When evaluating the thermal energy storage capacity of soil, three key parameters come into play: thermal conductivity, heat capacity, moisture content, density, porosity, and thermal diffusivity. These factors collectively determine how effectively the soil can absorb, store, and release thermal energy, crucial for various applications, such as thermal-driven cooling systems. Three representative locations were selected to collect representative samples, i.e. Koka, Bote and Meki. Soil samples were randomly collected from the fields, then dried, packed and shipped to UK to determine thermal properties. The soil grain size is then sorted using 4 different sieves, i.e. 1, 0.5, 0.425, 0.25 mm. The soil characterization primarily begins with thermogravimetric moisture content determination (TGA analysis). The principle of the thermogravimetric method of moisture content determination is defined as the weight loss of mass that occurs as the material is heated. The sample weight is taken prior to heating and again after reaching a steady-state mass subsequent to drying.

Then, the soil samples are examined to identify the heat capacity and thermal diffusivity using differential scanning calorimetry (DSC) and Laser Flash Analyzer (LFA), respectively. Thermal diffusivity (α) is a fundamental parameter that characterizes the ability of a material to conduct heat relative to its ability to store heat, which gives a direct representation to the rate of heat charging/discharging. It is defined as the ratio of thermal conductivity (k) to volumetric heat capacity (ρC_P), where ρ is the density and cp is the specific heat capacity. The formula for thermal diffusivity is:

$$\alpha = k/\rho C_P \quad (1)$$

4. RESULTS

The results of LFA test results on soil samples with grain size 0.25 mm are shown in Fig. 1. The DSC test results for grain size 0.25 mm in Fig. 2. Also, the average values of thermophysical properties of soil from each origin and with different grain sizes are listed in Table 1.

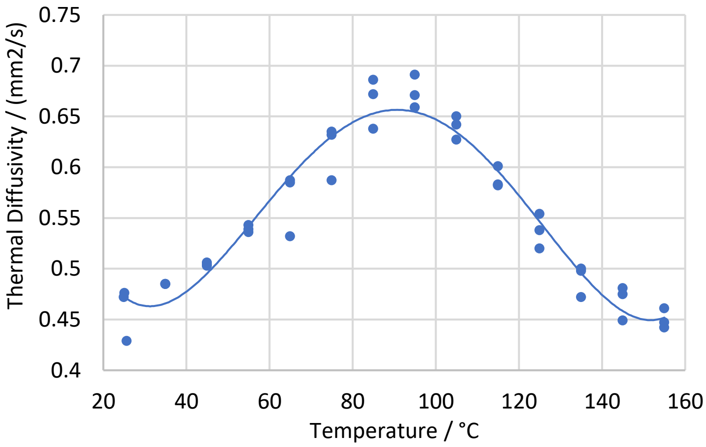

Fig. 1: Thermal Diffusivity of soil sample, Bote origin (grain size 0.250 mm), Average uncertainty 0.8%

The thermophysical attributes of soil samples obtained from diverse sources were analysed with the objective of investigating plausible associations between porosity, heat capacity, and thermal diffusivity. The tests were performed from 20 to 90 °C, representing the range of heat source temperature for adsorption refrigeration system. The density of the soil samples falls within the spectrum of 1.1 to 1.4 g/cm^3. Furthermore, the specific heat capacity spans from 0.86 to 1.44 J/g C, while the thermal diffusivity ranges between 0.38 to 0.54 mm^2/s. Based on the results, for an integrated adsorption chiller (10 TR) with parabolic trough solar collector, a soil thermal storage volume of 185 m^3 is required to ensure performance advancement during a year.

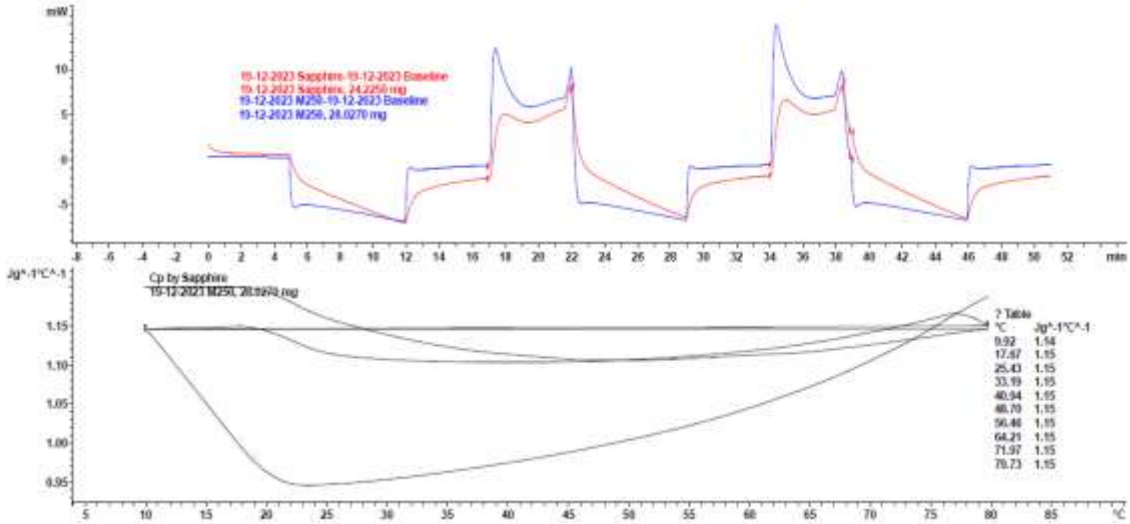

Figure 2: Heat Capacity of soil sample, Meki origin (grain size 0.25 mm)

Table 1: Thermophysical characteristics of soil samples averaged (B: Bote, K: Koka, M: Meki)

Sample #	B-250	B-500	B-1000	K-250	K-500	K-1000	M-250	M-500	M-1000
Weight (mg)	11.9	26.49	12.94	26.88	27.64	9.27	28.03	13.15	12.19
Grain size (mm)	0.25	0.5	1	0.25	0.5	1	0.25	0.5	1
Density (g/cm^3)	1.257	1.399	1.307	1.235	1.151	1.138	1.457	1.317	1.214
Specific Heat (J/g C)	0.875	1.44	1.21	0.908	0.91	1.42	1.15	0.86	0.93
Thermal diffusivity (mm^2/s)	0.54	0.47	0.44	0.47	0.45	0.42	0.41	0.39	0.38

5. CONCLUSIONS

In conclusion, the thermal properties of soil from samples collected areas are influenced by a variety of factors including soil type, moisture content, and organic matter. It is difficult to observe a clear effect of grain size but as a general understanding, more air-filled porosity leads to less thermal storage capacity and also less heat conductivity. It is hypothesized that variations in porosity may engender discernible effects on both heat capacity and thermal diffusivity, with higher porosity potentially augmenting heat capacity due to increased void space facilitating enhanced thermal energy absorption. Moreover, porosity alterations might also influence thermal diffusivity, thereby potentially altering the rate of heat propagation within the soil matrix. Considering these nuanced interrelationships, we find that soil from the Bote region is a promising candidate for efficient thermal storage, which can contribute to advancing solar thermal adsorption refrigeration systems.

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