Local Thermal Insulating Materials For Thermal Energy Storage

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Abstract

Thermal insulation is one of the most important components of a thermal energy storage system. In this paper the thermal properties of selected potential local materials which can be used for high temperature insulation are presented. Thermal properties of seven different samples were measured. Samples consisted of: clay, kaolin, ash, banana fibres, sugarcane fibres, sawdust and charcoal dust. The thermal properties measured were, thermal conductivity, thermal diffusivity and specific heat capacity.

The Quick thermal conductivity meter (QTM-500) was used to measure thermal conductivity at room temperature (approximately 25^{o}C). Thermal diffusivity was determined using the Transient heat pulse technique and the specific heat capacity was calculated using the thermal conductivity, thermal diffusivity and density of the samples.

The effect of particle size and compaction pressure on the thermal conductivity of the selected samples is also presented.

Key words : *Thermal conductivity, specific heat capacity, thermal diffusivity, thermal insulation, thermal energy storage systems.*

1. Introduction

It is necessary to use thermal insulating materials around thermal energy storage systems to minimize heat losses from the systems [1]. There are varieties of insulating materials which come in various forms like loose fill, rigid boards, pipe and foam. The thermal insulation is provided by embedding insulation materials at least on the roof areas and the vertical walls of the storage systems [2]. Poor thermal insulation of the heat storage systems leads to high heat losses [3].

Proper selection of the insulating material to be used is based on the thermal properties which include the thermal conductivity, specific heat capacity and thermal diffusivity.

The thermal conductivity (κ) of a material is a measure of the effectiveness of the material in conducting heat [4]. Good heat insulators should have low thermal conductivities, in order to reduce the total coefficient of heat transmission. It has been found to vary with: density, moisture content, temperature, direction of heat flow with respect to grain for fibrous materials, the presence of defects in the material and porosity.

Specific heat capacity is one of the important parameters for determining the insulation property of a material. It is the amount of heat required to raise the temperature of one kilogram of a material by one degree Celsius. A high specific heat capacity value means high ability of heat retention for an insulating material.

Thermal diffusivity measures the ability of a material to transmit a thermal disturbance. It indicates how quickly a material's temperature will change. Thermal diffusivity increases with the ability of a body to conduct heat.

The major insulating materials currently being used for insulation in TES systems include; calcium silicate, rock wool, expanded silica, or perlite, fibre glass, polyurethane, polystyrene and insulating cement. This is mainly due to their low thermal conductivity, high specific heat capacity and low thermal diffusivity presented in Table 1[5] leading to good thermal insulation. However, their application has been limited because these thermal insulators are expensive. There are also risks to human health as a result of exposure during handling especially those in fibrous form [6].

Table 1. Thermal properties of insulation materials commonly used in TES systems

Material	**Density/ kgm^{-3}**	**Thermal conductivity/ $Wm^{-1}K^{-1}$**	**Specific heat capacity/ $Jkg^{-1}K^{-1}$**	**Thermal diffusivity $x10^{-7}$/ m^2s**
Molded polystyrene	19	0.034	1280	14.8
Extruded polystyrene	28	0.032	1280	89.3
Injected polystyrene	20	0.034	1280	13.3
Polyurethane	28	0.023	1537	5.58
Insulating cement	551	0.120	882	3.19
Perlite	94	0.04	1090	5.27
Glass fiber	30	0.034	960	14.6
Rock wool	50	0.037	840	10.0

In Uganda there are many local materials available for consideration as thermal insulators. These local materials are either available naturally or are obtained as industrial wastes. Due to the environment concerns and the need to conserve energy, various research efforts have been directed towards the utilization of waste materials. The potential of these materials for thermal insulation is based on: the availability of the material, thermal and other properties of the material and environmental and health impacts

The locally available insulating materials that have been considered include clay, kaolin, ash, banana fibres, sugarcane fibres, sawdust and charcoal dust.

Clay is one of the common refractory used in furnaces and kilns for insulation in form of fire bricks.

Ash deposits largely reduce heat transfer rates in furnace walls, super heater tubes, and other heat transfer surfaces. Allen [7] reported that the thermal conductivity of ash deposits in situ is 0.14Wm $^{-1}$K^{-1}. Bagasse-based thermal insulation materials have been produced. It is reported that their thermal conductivity is in the range of 0.046 - 0.051 Wm^{-1}K^{-1}[8].

Paul et al. [9] in their observations on the effect of fiber loading on banana/polypropylene composite found that both the thermal diffusivity and thermal conductivity were decreasing on increasing fiber loading (i.e., from 0.24Wm^{-1}K^{-1} for neat polypropylene matrix to 0.217 and 0.157Wm $^{-1}$K^{-1} for 0.10 and 0.50 of volume fraction respectively).

Thermal properties of sawdust types depend on the varieties of wood from which it is obtained from. Ogunleye and Awogbemi [10] investigated the thermal and physical properties of eight varieties of sawdust and found them to be with different thermal conductivity values.

2. Methodology

Thermal conductivity measurement

Sample preparation

The clay and kaolin collected from the deposit were soaked in water and massive particles were separated by gravity sedimentation. Thereafter, the samples were sun dried for three days then placed inside the oven and further dried for a period of eight hours at a temperature of 50^{o}C. The dried samples were finally crushed down to smaller sizes.

The clay, kaolin, saw dust, ash and charcoal dust were sieved through a 500µm sieve to remove coarse particles and foreign materials which are larger than 500µm that might have been present in the samples.

Sieving by hand is difficult to perform because it is both time consuming and labor intensive and the results are somewhat subjective. A mechanical test sieve shaker or vibrator was preferred in the study. The particle sizes/ fibre diameters obtained were in the range <90µm, 90 -125µm, 125 - 150µm, 150 -180µm and 180 - 355µm.

According to the principle of hot wire method which is used by the Quick thermal conductivity meter, infinitely long and rectangular plates are desired for measurements. These samples should be large enough so that the heat from the hot wire is not lost through the surrounding hence leading to errors in measurement. Rectangular plates of the samples were achieved through compacting the samples in a rectangular mould using a manual hydraulic press. To study the effect of compaction pressure on the thermal conductivity, the samples were compacted at pressures of 18.2, 36.4, 54.6 and 72.9 MPa.

However when the charcoal dust sample was compacted, a weakly cohesive structure was formed so the sample was not removed from the mould since otherwise it would break. So thermal conductivity measurements were done when the sample was still in the mould. The study of effect of compaction pressure on the sample was not done.

Determination of thermal conductivity

The QTM-500 which uses the hot wire method was used in the measurement of thermal conductivity because it is a fast and accurate method for measurement of thermal conductivity of insulating materials. It involves placing the rectangular block sample in the probe box and then placing the sensor probe (PD-11) on the sample surface. The sensor probe consists of a constantan wire heater and a chromel- alumel thermocouple. The heating wire is used to supply heat to the test sample and the thermocouple monitors the heat flow rate. The measurement result is shown on display immediately after the measurement is finished (after 60s).

Sample preparation for measurement of thermal diffusivity

Samples were sieved to obtain particle sizes/ fibre diameter of <180 μm. In order to obtain large rectangular block samples to allow the heat pulse to propagate without reaching any boundary during the time of the measurement, the samples were mixed with water to form a solid mixture and poured in rectangular moulds.

A nichrome wire (heater) was embedded in the middle of the sample. The wire was selected as a heating element in the study because of it high resistivity and high melting point of about 1400^{o} C.

At the opposite sides of the embedded nichrome wire, holes were drilled at equal distances from the heater. During measurements the thermocouples were inserted in these holes to measure the temperature response of the samples to a transient heat pulse.

Samples were then dried in the oven at 100^{o}C for about 48h to remove all the moisture content. The samples were then removed from the oven, weighed and their masses were recorded. Also the dimensions of the samples were measured and used in calculating the volume. Using the values obtained for mass and volume of the samples the density was obtained.

Measurement of thermal diffusivity.

The transient heat pulse technique was used in the study. The advantages of the method include easy sample preparation, relatively simple data analysis and high sensitivity. This method is accurate in

determining thermal diffusivity of a material provided constant power is supplied. According to the transient heat pulse technique, two equivalent solutions to the diffusion equation for an infinite slab of thickness a, which is excited by an instantaneous input heat pulse are given below.

$$\delta T = \left(\frac{Q}{2\pi w\, C_\rho\, \alpha t}\right) exp - \frac{x^2}{4\alpha t} \quad (1)$$

$$\delta T = \left(\frac{Q}{2aw\, C_\rho \sqrt{(\pi \alpha t)}}\right) exp - \frac{x^2}{4\alpha t} \quad (2)$$

where Q is the total heat input, x is the distance between the heater and the thermocouple and t, w, α, C_ρ are the measurement time, width, thermal diffusivity and volumetric specific heat capacity of the sample respectively.

The sample was clamped at both ends to prevent movement of any kind. Thermocouples were then inserted in the holes drilled at the opposite sides of the heater.

An instantaneous heat pulse was introduced into the sample by energising the heater with a voltage pulse. After every 30s the temperature on the thermocouples was noted. This was done until a steady temperature was attained.

Graphs of lnδT vs $^1/_t$ were drawn for the samples and their slopes determined. The thermal diffusivities were calculated using the slopes.

$$\alpha = -\frac{x^2}{4slope} \quad (3)$$

Determination of specific heat capacity

During the measurement, heat losses could not be eliminated completely because the samples were not insulated hence volumetric heat capacity could not be obtained from the intercepts of the graphs of lnδT vs $^1/_t$ It was obtained from the thermal diffusivity and thermal conductivity of the samples,

$$C_\rho = \frac{\kappa}{\alpha} \quad (4)$$

2. Results and discussion

Thermal conductivity

The thermal conductivity/$W^{-1}K^{-1}$ values obtained ranged from 0.086 to 0.107 for sugarcane fibres, 0.297 - 0.301 for ash, 0.276- 0.338 for banana fibres, 0.185- 0.240 for saw dust, 0.466 - 0.554 for kaolin, 0.210 -0.308 for clay and 0.1840 - 0.219 for charcoal dust.

Only the thermal conductivity of clay and kaolin have so far been investigated in Uganda. The thermal conductivity values obtained for fired clay ranged from 0.13 -0.3$Wm^{-1}K^{-1}$ [11] and for fired kaolin the values obtained ranged from 0.3- 1.5$Wm^{-1}K^{-1}$[12].

Graphical analysis showed that the measured thermal conductivity:
• Increased with compaction pressure, P, according to the power law,$\kappa = \xi P^{\gamma}$ due to a decrease in porosity. The values for γ were approximately 0.05 for sugarcane fibres, 0.13 for ash, 0.04 for banana fibres, 0.08 for sawdust, 0.18 for clay and 0.08 for kaolin.
• Decreased with increasing particle size, S, according to the equation $\kappa = \varepsilon S^{\beta}$ because of the increase in porosity with increase in particle size. The values for β were approximately 0.04 for sugarcane fibres, 0.26 for ash, 0.10 for banana fibres, 0.06 for sawdust, 0.20 for clay, 0.15 for kaolin and 0.25 for charcoal dust.

Thermal diffusivity and specific heat capacity

Temperature responses to a heat pulse for the different samples were fitted using a Gaussian distribution and linearization of lnδT vs $1/t$ was used to determine the thermal diffusivity.

The values for thermal diffusivity and specific heat capacities obtained are presented in table 2 for the different samples.

Table 2. Thermal diffusivity and specific heat capacity of selected local insulating materials

Sample	**Thermal diffusivity $x10^{-7}/m^2s$**	**Specific heat capacity $/Jkg^{-1}K^{-1}$**
Sugarcane fibres	5.05	1125
Ash	3.67	900
Banana fibres	8.13	874
Sawdust	1.12	942
Clay	1.58	919
Kaolin	4.27	677
Charcoal dust	6.09	800

3. Conclusion

Among the materials studied, sugarcane fibres can provide the best thermal insulation for thermal energy storage systems (TES) since it has the lowest thermal conductivity and highest specific heat capacity.

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