INFLUENCE OF AIR TEMPERATURE, FLOW RATE AND SAND LAYER THICKNESS ON THE RATE OF CHARGING SAND

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A Thesis submitted to the Graduate school in partial fulfillment for the requirements of the Degree of Masters of Science in Engineering Systems and Management of Egerton University

EGERTON UNIVERSITY

APRIL, 2016

DECLARATION AND RECOMMENDATION

DECLARATION

I declare that this thesis is my original work and has not been presented before to this or any other University for similar or any other degree award.

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RECOMMENDATION

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DEDICATION

I dedicate this study to my dear wife Jane, children; Florence, Alice, Agnes and Naomi for the encouragement and unwavering support throughout the entire period of the study. God bless them mightily.

ACKNOWLEDGEMENT

Thanks to the Almighty God for blessing me with life and ability to do this study. Great appreciations to my supervisors Dr. Njue, M. of Egerton University and Prof. Mailutha J. T. of Jomo Kenyatta University of Agriculture and Technology for the humility, professional guidance and encouragement that ensured that I complete this research work. Am also grateful to Prof. Mutua, B. M., Mr. Kibiwot V. N. and Prof. Nyaanga D. M., all of Egerton University for the encouragement and unlimited suggestions during the undertaking of the work. It's unfair to forget Prof. Ogola W. of the Technical University of Kenya who encouraged me to pursue the study to the end. Acknowledged also is the support I received from the Faculty of Engineering and Technology of Egerton University where the experiments were carried out. Many other people assisted me in various ways and this is also highly appreciated.

ABSTRACT

Solar thermal energy storage technology has made solar energy a potentially viable supplement for fossil fuels in much of the developing world. However one of the challenges in adopting the technology is the low efficiency of the storage media. Many thermal energy storage materials have difficulties and limitations such as handling, containment, storage and cost. Sand which is abundant, cheap, easy to handle and contain, can be used to alleviate the difficulties. Research carried out on sand as thermal energy storage material has been concentrated on the amount that can be stored. Literature on factors that influence the rate of charging sand thermal energy storage media could not be accessed. There is no existing information on the rate of charging various types of sand. The objective of this research was to determine the influence of air temperature and flow rate on the rate of charging different types of sand of different layer thicknesses. Sieve analysis was done on the sands to grade them in terms of particle size distribution. Air at temperatures of 40, 50, 60 and 70^{o}C and flow rates of 0.0004, 0.0006, 0.0008 and 0.001m^{3}/s was passed through a thermal energy storage tank containing four types of sand which were collected from Machakos, Mombasa, Kisumu and Nakuru. However electric heater was used to heat the air instead of a solar heating system. The Taguchi experimental design approach was used. The temperature rise for sand at intervals of 2.5 minutes was recorded. Data analysis was carried out by use of Excel Statistical Analysis Software (SAS). The result of the study showed that the rate of charging sand increases as temperature of air increases. The result also showed that the rate of charging sand increases slightly as flow rate of charging air increases. The rate of charging was inversely proportional to the sand layer thickness. The four types of sand showed different rate of charging with sand from Mombasa having the greatest charging rate at 1.14^{o}C/min. This was followed by sand from Nakuru at a rate of 1.12^{o}C/min, sand from Kisumu at 1.01^{o}C/min and finally sand from Machakos at 0.9^{o}C/min. The most influential factors on the rate of charging were sand layer thickness and charging air temperature and contributed 86.93% and 10.00% of the variation in the charging rate respectively. The air flow rate and type of sand had little influence on charging rate and contributed 2.23% and 0.49% of charging rate variation respectively. The optimum factors for the charging process were observed to be charging air temperature of 70^{o}C, sand type from Mombasa, sand layer thickness

of 0.01cm and flow rate of $0.001m^3/s$. A confirmation experiment proved the result to be correct by registering a charging rate of $3.60^oC/min$.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
ETC	Energy Consulting Group
HTF	Heat Transfer Fluid
IES	Isabella Experimental Station
MOE	Ministry of Energy
NEP	Nottingham Energy Partnership
PCM	Phase Change Material
PID	Proportional with Integral and Derivative
SAS	Statistical Analysis Software
S/N	Signal to Noise ratio
TES	Thermal Energy Storage

LIST OF SYMBOLS

M_R	Mass of sand retained in sieve
M_T	Total mass of sand sample
Q	Heat Transferred
t	Time
T	Temperature
T_{ac}	Ambient Temperature during Charging
T_{ad}	Ambient Temperature during Discharging
T_c	Charging Temperature
T_{co}	Control Temperature
T_d	Discharging Temperature
T_s	Temperature of Sand
V	Volume
x	Thickness
$\dot{V}$	Flow Rate
α	Thermal Diffusivity
η	Efficiency

1. INTRODUCTION

1.1 Background

Thermal Energy Storage (TES) is defined as the temporary storage of thermal energy at high or low temperatures (Ataer, 2006). The earlier major use of thermal storage was to maintain dwelling places warm during cold winter nights. Large stones, blocks of cast iron, and ceramics were used to store heat from an evening fire for the entire night. The technology of thermal storage has been developed to a point where it has a significant effect on modern life. With the advent of the industrial revolution, TES was introduced as a by-product of the energy production. A variety of new techniques of TES have become possible in the past. Heat storage in some cases is in the form of steam or hot water and is usually for a short time. Other materials such as oils having very high boiling points are useful as heat storage substances for the electric utilities. Materials that have high heat of fusion at high temperatures are also used (Adeyanju and Manohar, 2009). A promising application of thermal energy storage is for solar heated structures, where almost any material such as dry earth materials, water and even air can be used (Kazemi, 2008). Currently, the existing or planned systems for solar power employ materials such as molten salts or heat transfer fluid (HTF) which are relatively expensive. Furthermore, the containers necessary to store fluids especially if the vapour pressure is high can be very expensive. Consequently, a less costly storage medium, especially one capable of high temperature operation, is desirable.

Developing efficient and inexpensive energy storage devices is sometimes as important as developing new sources of energy. Nallusamy *et al*. (2007) observed that effective use of time-dependent energy resources relies on appropriately energy storage methods to reduce the time and rate mismatch between supply and demand. Energy storage plays an important role in energy conservation and also improves the performance and reliability of a wide range of energy systems. Capital investments can also be reduced if energy storage is used to permit the use of smaller power generating systems. The smaller systems operate at or near the peak capacity, irrespective of the instantaneous demand for power by storing excess energy during reduced demand periods for subsequent use in meeting peak demand requirements (Ataer, 2006).

Kenya is a country which has a great potential of renewable energy sources. Solar energy is by far the most attractive alternative source for the future (Garg et al. 1985). Kenya lies at the equator and this makes it a good candidate for solar energy applications (Rabah *et al.*, 1995). Erickson (2009) reported the installation of a solar powered icemaker for milk preservation in two rural areas in the coast of Kenya. The project resulted in generation of rural incomes, rural jobs, and alleviation of poverty as well as contribution to food and energy security. This type of project is one among many which have contributed immensely toward the development of some part of the country which do not have electricity. Rabah (2005) observed that Kenya gets an annual average exposure to sunshine of about 10 hours per day in most regions and an annual mean radiation of 6.98 kWh/m^2. The problem is that the supply is periodic, intermittent, often unpredictable and diffused due to yearly and diurnal cycles. The demand for energy, on the other hand, is also unsteady due to yearly and diurnal cycles for both industrial and personal needs (Ataer, 2006). Therefore the need for thermal energy storage in the country is inevitable. The energy can then be used conveniently and continuously for purposes such as air-conditioning, water desalination, drying and other industrial or domestic needs. On the other hand, sand is in abundant supply in most areas of Kenya at very low cost.

Some of the important characteristics of a storage system are its volumetric energy capacity or amount of energy stored per volume and the rate at which the energy can be stored. The smaller the volume of the storage system the better (Adeyanju and Manohar, 2009). Again the higher the rate at which the energy can be stored the better. Losses may occur from the system by radiation, convection and conduction. This can be kept to minimum by proper insulation. The energy density of packed dry sand is 1396 $kJ/m^3\,^{o}C$ (IES, 2008). As was revealed by literature review, research on sand as TES material has only been carried on the amount of heat that can be stored but not on the process of charging. The research aimed at determining the influence that temperature and flow rate of heat transfer fluid have on the rate of charging some types of sands available in Kenya.

1.2 Statement of the Problem

Solar energy supply is periodic, intermittent and often unpredictable and the demand for energy for industrial and personal needs on the other hand is varied and irregular. In order to bridge the mismatch between supply and demand as well as maintain a continuous supply the energy is stored in various systems. Thermal energy has been stored in various media like water, air, concrete, bricks, stones and sand. Factors that influence the rate of charging sand as thermal energy storage medium have not been adequately investigated. Therefore there was need to determine how the air temperature and flow rate influence the rate of charging thermal energy in different sand media in Kenya.

1.3 Objectives

1.3.1 General Objective

The broad objective was to investigate how the rate of charging sand is influenced by the air characteristics of temperature and flow rate; and thickness of sand layer.

1.3.2 Specific Objectives

The specific objectives were:

i. To determine the influence of the air temperature, flow rate, sand type and sand layer thickness on the rate of charging some types of sand.
ii. To optimize the parameters for charging of sand.

1.4 Research Questions

i. How do the air temperature, flow rate, sand type and sand layer thickness influence the rate of charging some types of sand?
ii. What are the optimal values of the parameters for charging of sand?

1.5 Justification of the Study

The need for solar thermal energy storage is inevitable to reduce mismatch between energy supply and energy demand. Different solid materials such as concrete, stone, stones and sand have been used for thermal energy storage. Sand is abundant and cheap in most part of Kenya. There is need to investigate and document the influence of air temperature, flow rate and sand layer thickness on different sand media as thermal energy storage materials. The results of the study will contribute immensely towards energy development in the country.

1.6 Scope and Limitations

Generally where there is sand in abundance, there is a lot of solar energy. The study has examined the influence of charging air temperature, flow rate and sand layer thickness on some types of sand thermal storage media. The charging air temperature is limited to that which is possible with solar air heaters. Other factors such as colour of sand and ambient temperatures were not investigated. Sand samples were collected from only four locations within Kenya.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Energy Perspective in Kenya

The five major categories of energy sources in Kenya are biomass, fossil fuels, electricity, solar and wind all of which are at different levels of exploitation. At national level biomass account for 68% of the total primary energy consumption followed by petroleum at 22%, electricity at 9 % and others at about less than 1%. In rural areas the reliance on biomass is over 80%. Only about 15% of Kenyans have access to grid electricity (ETC, 2007). Abdullah and Jeanly (2011) carried a survey in Kenya and reported that connection costs are an impediment to electrification in rural areas. Although connectivity to households had greatly improved in the last six years, Ngui *et al*. (2011) reported that there was still need for strategic move to reduce initial cost of connection to electricity. Rabah (2005) observed that majority of the Kenyan population still depends on biofuel as their major source of fuel with consequent adverse effect on health and productivity. In their study on energy access among the urban poor in Kenya, Karekezi *et al.* (2008) reported that kerosene is the most important modern energy option for the poor for both lighting and cooking. Investments in power sector have lagged behind growth in demand with the effect of this undesirable situation being felt throughout the Kenyan economy, largely in the form of lost production due to inadequate power supply (Osawa, 2004). Kiplagat *et* al. (2011) reported that in Kenya the local energy produced as percentage of total energy consumed was 10.9% in 2007. For Kenya to achieve its overall national development objectives which is accelerated economic growth, quality energy services is required in a sustainable, cost-effective and affordable manner to the people amongst others. According to ETC (2007), the level and intensity of commercial energy is a key indicator of economic growth and development. This is currently low and calls for intensified action for the development and use of energy services that are reliable, affordable and readily available.

2.2 Solar Energy in Kenya

According to MOE (2002), Kenya receives good solar insolation coupled with moderate to high temperatures all year round. Rabah (2005) observed that Kenyans gets an annual average exposure to sunlight of about 10 hour per day in most regions and annual of 6.98 kWh/m^2, which if harnessed efficiently could contribute to improved quality of life in rural and poor urban sector. Solar energy is the most meaningful option of renewable energy for rural sector, particularly in terms of lighting, refrigeration, energizing small appliances and provision of hot water to house-holds and institutions (Rabah, 2005). The potential for development of stand alone solar power system in Kenya is enormous, but there is complete lack of incentive for the development of this benign energy resource.

Erickson (2009) reported of a project that involved the installation of a solar powered icemaker for milk preservation in two rural areas in the coast of Kenya. The project resulted in generation of rural income, rural jobs, and alleviation of poverty as well as contribution to food and energy security.

2.3 Solar Energy Technology

The Sun is the source of all energy on Earth: whether they are fossil fuels or renewable. Harnessing this abundant energy source is crucial to renewable energy technologies (NEP, 2007.) Garg *et al*. (1985) observed that solar energy is by far the most attractive alternative energy source for the future. Solar energy is free; environmentally clean, and is therefore recognized as one of the most promising alternative energy resources options. Designers, engineers, architectures and material providers must consider solar energy installations as a sustainable energy development (Mekhilef *et al*., 2011). The main problem of solar energy is its intermittent nature; there is no sun at night. Its total availability value is seasonal and is dependent on the meteorological conditions of the location (Bal *et al.* 2010). Therefore the need for solar energy storage is paramount for the improvement on the availability and efficiency of solar energy systems. Solar air heaters are the cheapest and extensively used solar energy collection devices. Since the heaters have low thermal efficiencies, use of packing of porous materials have been proposed for the enhancement of their thermal performance (Prasad *et al.* 2009).

Hazami *et al*. (2009) investigated a solar energy system and concluded that the amount of solar energy collected depended on solar radiation. Water was used as the heat collecting media and its temperature increased to a maximum value of 50^{o}C at 14:00 pm in the noon and remained constant for some time before it started to decrease later in the afternoon. Sharma *et al.* (2009) reported that the performance evaluation of a natural convection solar air heater with phase change material energy storage has been successfully undertaken. The daytime performance of the system under no-load conditions was tested under natural environmental conditions involving ambient temperature variations in the range 19 – 41°C and daily global irradiation in the range 4.9 – 19.9 MJ/ m^2. Peak temperature rise of the heated air was about 15K. The peak cumulative useful efficiency was about 50%. The use of solar cookers is much needed in many regions with good solar radiation intensity throughout the world. This is due to the economical, ecological, social, medical and others which improve the quality of life (Schwarzer and Silva, 2008). Mawire and McPherson (2008) investigated a thermal storage system of a proposed solar cooker and found that the cooker could be used at any time of the day, the cooking speed is fast and the cooking capacity could be maximized.

2.4 Thermal Energy Storage Technology

Thermal energy storage has been developed to a point where it can have significant impact on modern technology. It can contribute significantly in meeting society's need for more efficient, environmental benign energy use in building for heating and cooling, aerospace power and utility applications. Dincer and Rosen (2002) observed that the use of energy storage often results in such significant benefit as reduction of energy cost, reduction of energy consumption, improved indoor air quality, and increased flexibility of operation and reduced initial and maintenance cost. Thermal energy storage is essential in solar circuits, in order to take maximum advantage of the solar resource and control difference between demand and solar radiation availability (Chidambaram et al., 2011). Sunliang (2010) observed that different criteria lead to various categories of thermal energy storage technologies as shown in Figure 2.1.

If the criterion is based on the temperature level of stored thermal energy, the thermal storage solutions is divided into "heat storage" and "cold storage''; if based on the time length of stored thermal heat, it is divided into "short term'' and "long term"; if based on the state of energy storage material, it is divided into "sensible heat storage" and "latent heat storage '' and" thermal-chemical heat storage".

The efficiency of thermal energy storage system can be defined as the ratio of the energy extracted from the storage system to the energy stored into it (Adeyanju and Manohar, 2009). This is represented by Equation 2.1.

$$\eta = \frac{(T - T_0)}{(T_\infty - T_0)} \qquad (2.1)$$

Where T and T_0 are the maximum and minimum temperatures of the storage during discharging respectively and T_∞ is the maximum temperature at the end of charging period.

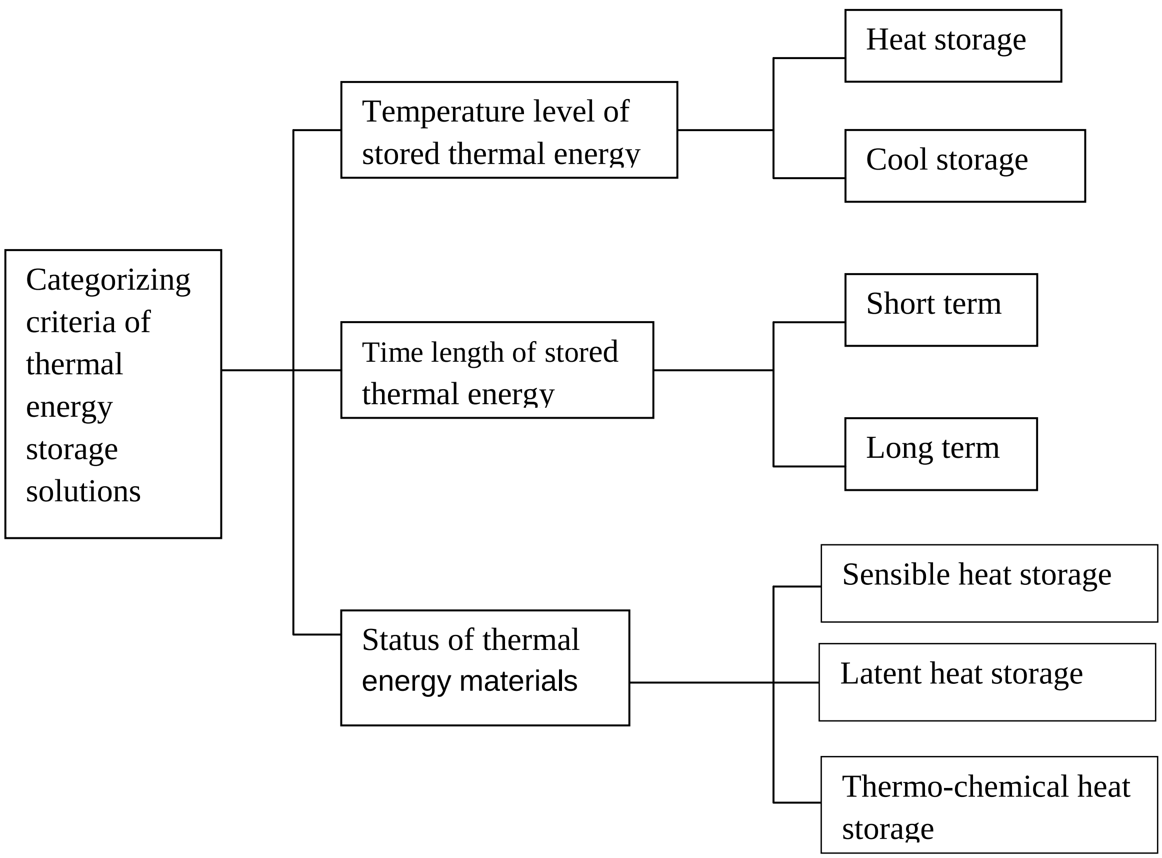

Figure 2.1 Categories of Thermal Storage Solutions (Sunliang, 2010)

Some of the considerations, which determine the selection of the method of storage and its design, are:

- The temperature range, over which the storage has to operate.
- The storage capacity. This has a significant effect on the operation of the rest of the system. A smaller storage unit operates at a higher mean temperature. This result in a

reduced heat transfer equipment output as compared to a higher one having a larger storage unit.

- Heat losses from the storage have to be kept to a minimum.
- The rate of charging and discharging.
- Cost of the storage unit. This includes the initial cost of the storage medium the containers and insulation and the operating cost.

Other considerations include the sustainability of materials used for the container, the means adopted for transferring the heat to and from the storage and the power requirements for these purposes. Bayon *et al*. (2010) while reviewing seasonal heat storage in large basins reported that specific hot-water storage costs in constructed large tanks are rather high. Gravel-water heat storage seems to reduce the cost since no structural frame is necessary. Due to lower heat capacity of gravel the storage volume will be bigger. Hasnain (1998) noted that for a short-term storage unit, the time period would be a few days, while for a long-term storage unit it could be a few months or even one year. For a well-designed short-term storage unit, the value of the efficiency should generally exceed 80%.

Ataer (2006) compared various types of energy storage techniques and reported that the main problem with water storage systems is the corrosion as a result of long operation periods. Another disadvantage of water storage systems is that volume of the storage may be very large for large heat quantities and therefore the whole system becomes very heavy. With large units there is also stratification problem and hence controls are required. With packed-bed storage there is no corrosion or scale forming problem but volume of the system might increase with an increase in cost. By use of a phase change storage systems, large volumes required by the other two types are eliminated. However phase change systems are the most expensive. They are the most compact types having least using periods because of the materials deformation and degradation problems. Because of their compactness, their total initial costs are small. Farid *et al*., (2004) in a review on phase change energy storage; materials and applications reported that organic and inorganic compounds are the two most common groups of phase change materials. Most organic phase change materials are non-corrosive and chemically stable, exhibit little or no sub cooling, are compatible with most building materials and have a high latent heat per unit weight and low vapour pressure. Their disadvantages are low thermal conductivity, high changes in volume on phase change and flammability. Inorganic compounds have a high latent heat per unit volume and high thermal conductivity and are non-flammable and low in cost in comparison to organic compounds. However, they are corrosive to most metals and suffer from decomposition and sub cooling, which can affect their phase change properties. A PCM with an easily adjustable melting point would be a necessity as the melting point is the most important criterion for selecting a PCM for passive solar applications. On weight and volume basis, bond storage has a greater capacity than other systems (Ataer, 2006).

2.5 Sensible Heat Storage

According to Fernadez *et al*. (2010) sensible heat storage materials are defined as a group of materials that undergo no phase change in the temperature range of the storage process. It is desirable for the sensible heat storage medium to have high specific heat capacity, long term stability under thermal cycling, compatibility with its containment and most importantly, low cost (Hasnain, 1998). Sensible heat storage may be classified on the basis of the heat storage media as liquid media storage (like water, oil based fluids, molten salts etc) and solid media storage (like rocks, metals and others)

Typical data of some relevant properties of heat storage materials used in thermal stores are given in Table 2.1.

Table 2.1 Comparison of Various Heat Storage Media

	Heat storage material			
	Sensible heat storage		Phase Change Materials	
Property	Rock	water	organic	inorganic
Latent heat of fusion (kJ/kg)	*	*	190	230
Specific heat (kJ/kg)	1.0	4.2	2.0	2.0
Density (kg/m^3)	2240	1000	800	1600
Storage mass for storing 10^6 kJ (kg)	67000	16000	5300	4350
Relative mass**	15	4	1.25	1.0
Storage volume for storing 10^6 kJ (m^3)	30	16	6.6	2.7
Relative volume	11	6	2.5	1.0

(Stored Energy = 10^6kJ = 300kWh: Δ T=15K)

*Latent heat of fusion is not of interest for sensible heat storage

** Relative mass and volume are based on latent heat storage in inorganic phase change materials

(Adapted from Hasnain, 1998).

2.6 Solid Media Storage

Nallusamy *et al.* (2007) found that the HTF temperature from a conventional solar air heater can reach a value of 70^{o}C. For both low and high temperature thermal energy storage, solid materials such as rocks, metals, concrete, sand, bricks etc. can be used (Hasnain, 1998). These materials will not freeze or boil at these temperatures. The difficulties of the high vapour pressure of water and other limitations of other liquid can be avoided by storing thermal energy as sensible heat in solids. Organics oils, molten salts and liquid metals do not exhibit the same pressure problems but their use is limited because of their handling, containment, and storage capacity and cost

(Ataer, 2006). Garg *et al.* (1985) carried out an experimental study on a storage system using a rock bed and observed that solid materials for thermal energy storage are easily available and cheap. Laing *et al.* (2011) carried experiments on concrete cubes and concluded that concrete could serve as a high temperature sensible heat storage material for up to 500^0C in parabolic trough power plants. Direct contact between the solid storage media and a heat transfer fluid is necessary to minimize the cost of heat exchange in a solid storage medium.

2.7 Packed-bed Energy Storage Systems

Adeyanju and Manohar (2009) when comparing various types of energy storage techniques found that the various difficulties and limitations such as handling, containment, storage and cost of phase change materials and liquids thermal energy storage media can be avoided by use of solid materials. Energy can be stored in rocks, pebbles, grits etc. packed in insulated vessels. The type of storage is often used for temperatures up to 100^oC in conjunction with solar air heaters. Alkilani *et al*. (2011) noted that the performance of heat storage in a rock bed is affected by various design and operational parameters. Such parameters are rock size and bed, air mass flow rate, void fraction within rock bed, thermal and physical properties of rock. According to Pinel *et al.* (2011), certain simplified models of rock bed and HTF system assume a very high coefficient between HTF and the rocks. This result in both phases being at the same temperature and therefore being treated as a single phase: i.e. with only one energy balance equation. The efficiency of heat storage system depends on thermal and physical properties of the heat storage material (specific heat, thermal conductivity, and density), heat storage temperature, geometry of heat exchanger, and system configuration (Ozuturk and Bascentincelik, 2003). The system arrangement is simple in design and relative inexpensive. Mawire et al., (2009) reported that for solar thermal/pebble-bed systems, a large temperature difference along the height of the storage satisfies the requirement of a good degree of thermal stratification for efficient energy storage. Table 2.2 shows the properties of some solid materials that can be used in the packed-bed storage.

Table 2.2 Solid Media Properties for Sensible Heat Storage

Medium	Density (kg/m^3)	Specific heat capacity (J/kg/K)	Heat capacity $\rho c x10^6$ (J/m^3/K)	Thermal conductivity (W/m/K)	Thermal diffusivity $\alpha=k/\rho c\ 10^6 (m^2/s)$
Aluminium	2707	896	2.4255	204 at 20^oC	84.100
Aluminium oxide	3900	840	3.2760	-	-
Aluminium sulphate	2710	750	2.0325	-	-
Brick	1689	840	1.4263	0.69 at 29^oC	0.484
Brick magnesia	3000	1130	3.3900	5.07	1.496
Concrete	2240	1130	2.5310	0.9-1.3	0.356-0514
Cast iron	7900	837	6.6123	29.3	4.431
Pure iron	7897	452	3.5581	73.0 at 20^oC	20.450
Calcium chloride	2510	670	1.6817	-	-
Copper	8954	383	3.4294	385 at 20^oC	112.300
Earth (wet)	1700	2093	3.5581	2.51	0.705
Earth dry	1260	795	1.0017	0.25	0.250
Potassium chloride	1980	670	1.3266	-	-
Potassium sulphate	2660	920	2.4472	-	-
Sodium carbonate	2510	1090	2.7359	-	-
Stone, granite	2640	820	2.1648	1.73to3.98	0.799-1.840

Stone, limestone	2500	900	2.2500	1.26to1.33	0.560-0.591
Stone, marble	2600	800	2.0800	2.07to2.94	0.995-1.413
Stone sandstone	2200	710	1.5620	1.83	1.172

(Adapted from Adeyanju and Manohar, 2009).

2.8 Charging of Packed-bed Storage Systems

The charging process is implemented by making the heat transfer fluid (such as air or water) flowing through the granules to exchange the thermal energy. A typical packed-bed storage unit is normally composed of a container, a screen to support the storage material, supports beneath the screen, openings and ducts for the heat transfer fluids. The packed-bed storage materials parameters which need to be considered are size, shape, density, thermal properties, packing densities etc (Sunliang, 2010). Mawire *et al.* (2008) compared the constant-temperature charging method and constant-flow rate charging method of the oil-pebble bed TES. The former was reported to result to a larger degree of thermal stratification and energy storage than the latter.

Garg *et al.* (1985) experimentally investigated inexpensive solar collector cum storage system, i.e. a solar air heater with an augmented integral rock system for agricultural uses [Figure 2.2(a-c)]. For a given rock bed thickness and small value of mass flow rate, where appreciable rise of temperature above the ambient occurs, the use of two glass covers is recommended as the use of single or double glass covers depends on the compromise of optical and thermal losses. Storage in the integrated rock storage and collection system was effective normally up to 3.30 pm irrespective of mass flow rate. The performance of the system was promising showing a satisfactory overall efficiency improvement as compared either to commonly used conventional solar air heater or with the integrated rock storage and collection system. Barasa (2011) carried a study on the performance of a solar air heater incorporated with rock- bed energy storage system. He found that the performance was improved by 75% in terms of heat retention and heat emission in the absence of sunshine when compared with that of a conventional solar air heater.

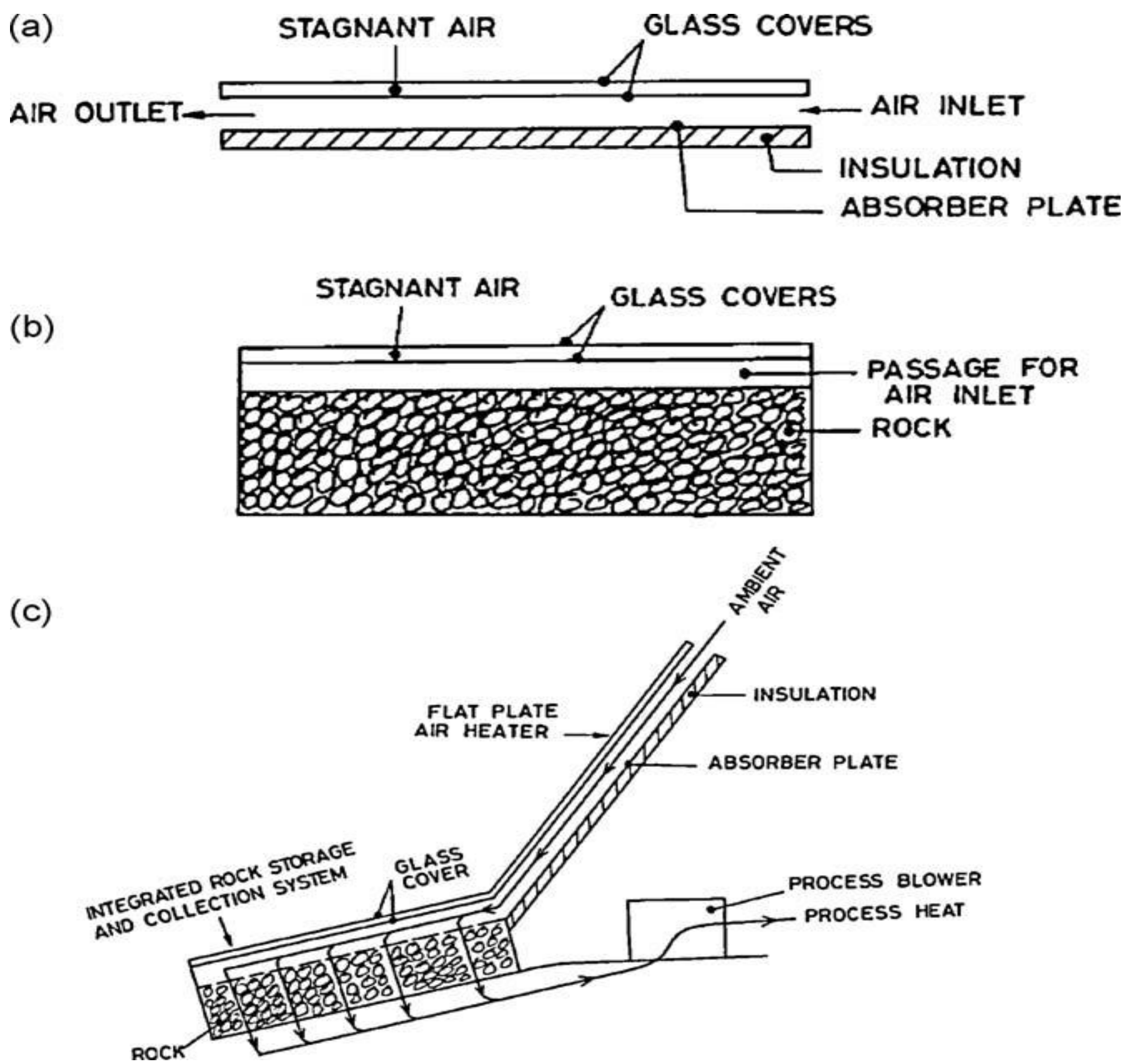

Figure 2.2 (a) Flat Plate Air Heater. (b) Integrated Rock Storage and Collection System.

(c) Augmented Integrated Rock System. (Adapted from Garg *et al*. 1985)

2.9 Sand as Thermal Energy Storage Medium

The free online dictionary define sand as a sedimentary material consisting of a small, often rounded grains or particles of disintegrated rock , smaller than granules and larger than silt. The diameter of the particle ranges from 0.0625 to 2mm. Sand often consists of some other mineral or rock fragments as well. The energy density of packed dry sand is 1396 kJ/m^3 ^{o}C (IES, 2008).The use of rocks for thermal energy has advantages that rocks are not toxic and non-flammable. Rocks are also inexpensive and act both as heat transfer surface and storage medium.

Finally the heat transfer between air and a rock bed is commendable due to the very large surface (Adeyanju and Manohar, 2009). Warerkar *et al.* (2011) reported that sand is suitable as a thermal storage medium due to its high thermal stability, specific heat capacity and low-cost availability. Singh *et al.* (2010) reported that energy can be stored up to 800^{o}C in sand. The use of sand promises to reduce the costs of energy storage.

Jeter and Stephens (2010) in the development of a novel thermal energy storage system using sand as the medium investigated the heat transfer coefficient for two types of sand; the fine grained olivine sand and course silica sand. The olivine sand was experimentally measured to have a mean diameter of 78 μm with a standard deviation of 30 μm. The silica sand was found to have a mean diameter of 550 μm with a standard deviation of 320 μm. Of the factors that affect heat transfer coefficient, particle size was found to have the dominant effect. The specific heat of olivine sand was found to be higher than for silica sand. Silica sand was used as representative of course grain natural material and olivine sand as representative of fine grain processed material.

Hazami *et al*. (2009) experimentally investigated the energy and exergy efficiency of a daily heat storage unit for building heating using sand in a wooden case of 5m length, 1m width and 1m depth. It was observed that at the upper zone of about 0.2 m, the sand temperature fluctuates seriously with external climatic conditions. Under this depth the sand temperature does not oscillate with external climatic conditions. Thus, more than 0.2 m-depth is considered to be a long term thermal storage section.

Hazami *et al.* (2005) investigated the thermal performance of a solar heat storage accumulator used for greenhouses condition. By analyzing soil temperature variation they noticed that the superior layers of soil undergoes easily with the external climatic variation. Beyond a certain depth, the soil temperature does not vary between the day and the night. The soil accumulator can be divided into two zones; upper and lower. The thickness of the upper zone depends on the temperature of the heating media. It is about 0.2 m when soil accumulator is heated by water at temperature of 45^{o}C. They results also indicated that the soil moisture increases the heat storage capacity in the long-term storage zone and facilitates the heat extraction from short-term storage zone to the greenhouse inside air at night. The amount of thermal energy in the accumulator decreased with the decreasing of difference between the inlet and outlet temperatures during the charging periods. It also depends on the outside temperature. A good thermal insulation of the accumulator area has great effects on temperature distribution in the soil and on the energy thermal losses.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Research Setup

The research was conducted at Egerton University, Department of Agricultural Engineering workshops and laboratories. The experiment setup is shown in Figure 3.2. Sieve analysis was carried out on the sands. The average prevailing ambient temperatures during experimentation was 23^{o}C.

3.1.1 Sources of Sand

Sand samples were collected from Machakos, Mombasa, Kisumu and Nakuru. The approximate locations of these places are Machakos at 1^{o}31’S 37^{o}16’E, Mombasa at 04^{o}02’S 39^{o}43’E, Kisumu at 00^{o}03’S 34^{o}45’E and Nakuru at 00^{o}15’S 36^{o}03’E. The locations in Kenya are shown in Figure 3.1. The choice of the locations was based on the fact that where there is a lot of sunlight, there is usually a lot of sand.

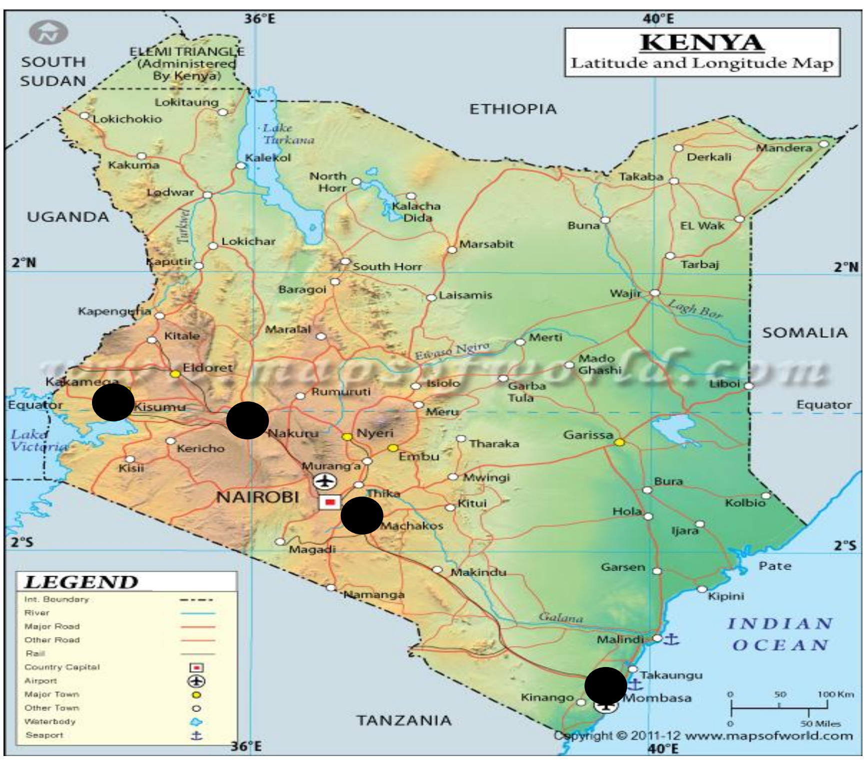

Figure 3.1: Map of Kenya Showing the Locations Where Sand Samples were Collected (Kisumu, Nakuru, Machakos and Mombasa). (Source: World Map, 2016)

3.1.2 Sieve Analysis

The sieve analysis was carried on sands from Machakos, Mombasa, Kisumu and Nakuru. Sand being a product of disintegration of rocks has its properties influenced by the different types of parent rocks and weather conditions of different areas. Sieve analysis was carried out on each sand medium to assess its particle size distribution grading. Dry sieving was carried out since it's the most suitable for sands and gravels which do not contain any clay. The dry sieving method was used as per BS 1377: Part 2:1990. First, all the sands were carried through equal treatment by being passed through a 300µm sieve. The aim was to improve on their permeability. The available sizes of the sieves for the analyses which were also found to be satisfactory were: 4760 µm, 2000 µm, 850 µm, 595 µm, 425 µm, 297 µm, 250 µm and 75 µm.

All the sieves were arranged into a column with one having the biggest opening placed at the top and the one with the smallest at the bottom. At the base a round pan called the receiver was put into place to collect the particles which passed the lowest sieve. The column was placed in a mechanical shaker. Each sample was shaken for a period of 10 minutes. After this, the sample on each sieve was weighed and recorded. The weight of each sample sieve was then divided by the total weight to give a percentage amount retained on each sieve.

$$\% \text{ Retained} = \frac{M_R}{M_T} \tag{3.1}$$

The size of the average particle on each sieve was then analysed to get a cut-off point or specific size range. The results of this test were provided in graphical form to identify the type of gradation of the sand. Unified soil classification system was used. The sand was classified as either coarse grained or medium grained. The data collected after the sieve analysis is as shown in Table A.1 in Appendix A.

3.2 Influence of Air Temperature, Flow Rate, Sand Layer Thickness and Sand Type on the Charging Rate

Experiments were conducted to investigate how the charging air temperature, flow rate and thickness of sand layer influence the rate of charging and discharging thermal energy in various sands.

3.2.1 Experimental Design

The Taguchi experimental design approach was used to carry out the investigation. The design was opted for because it significantly reduced the number of experiments to be carried out, thereby speeding up the work with great saving in cost. The experiments were reduced from 268 to 16. The design also enabled the experiments to be arranged in a way that all the parameters could be investigated simultaneously. The research involved four parameters namely charging fluid temperature, flow rate, sand layer thickness and sand type. The parameters were each experimented at four levels. The four levels for temperature were 40^oC, 50^oC, 60^oC, and 70^oC. The levels for flow rates were $0.0004m^3/s$, $0.0006m^3/s$, $0.0008m^3/s$ and $0.001m^3/s$. The sand layer thickness was at levels of 0.01 m, 0.02 m, 0.03 m and 0.04 m which translate to approximately 300g, 600g, 900g and 1200g of sand respectively. Sand types were Machakos, Mombasa, Kisumu and Nakuru. Taguchi method of orthogonal arrays was used to get the 16 experiments as shown in Table 3.1.

Table 3.1 The Taguchi Experimental Design

Experiment No.	**Temperature(^{o} C)**	**Sand Type**	**Flow Rate (m^3/S)**	**Sand Layer Thickness(m)**
1	40	Machakos	0.0004	0.01
2	40	Mombasa	0.0006	0.02
3	40	Kisumu	0.0008	0.03
4	40	Nakuru	0.001	0.04
5	50	Machakos	0.0006	0.04
6	50	Mombasa	0.0004	0.03
7	50	Kisumu	0.001	0.02
8	50	Nakuru	0.0008	0.01
9	60	Machakos	0.0008	0.02
10	60	Mombasa	0.001	0.01
11	60	Kisumu	0.0004	0.04
12	60	Nakuru	0.0006	0.03
13	70	Machakos	0.001	0.03
14	70	Mombasa	0.0008	0.04
15	70	Kisumu	0.0006	0.01
16	70	Nakuru	0.0004	0.02

3.2.2 Experimental Set-up

A schematic diagram of the main experimental set-up is shown in Figure 3.2. This consisted of insulated rectangular section tank which housed a container for holding sand to be investigated at any one time. Other items included a flow meter for measuring air flow rate, a compressor to supply the air, an air heater fitted with an electric heating element of 6.5 kW rating, flow control valve and type T thermocouples connected to a PID temperature controller for setting the appropriate temperature. The container for sand shown in Figure 3.2 was filled with sand when type T thermocouples were already placed in position as shown in Figure 3.3. The other ends of the thermocouples were connected to a data logger shown in Figure 3.4. The sand container was centrally placed in the insulated rectangular tank and then an insulated top cover placed in position. Air from the air heater at the appropriate set temperature was then blown smoothly through the tank. Plenum chambers, one at the entry and the other at the outlet of the tank were provided to make uniform flow of the air. The tank was insulated with Styrofoam to reduce heat losses. Air was used as the HTF due to its low specific heat capacity and is less prone to corrosion as compared to water.

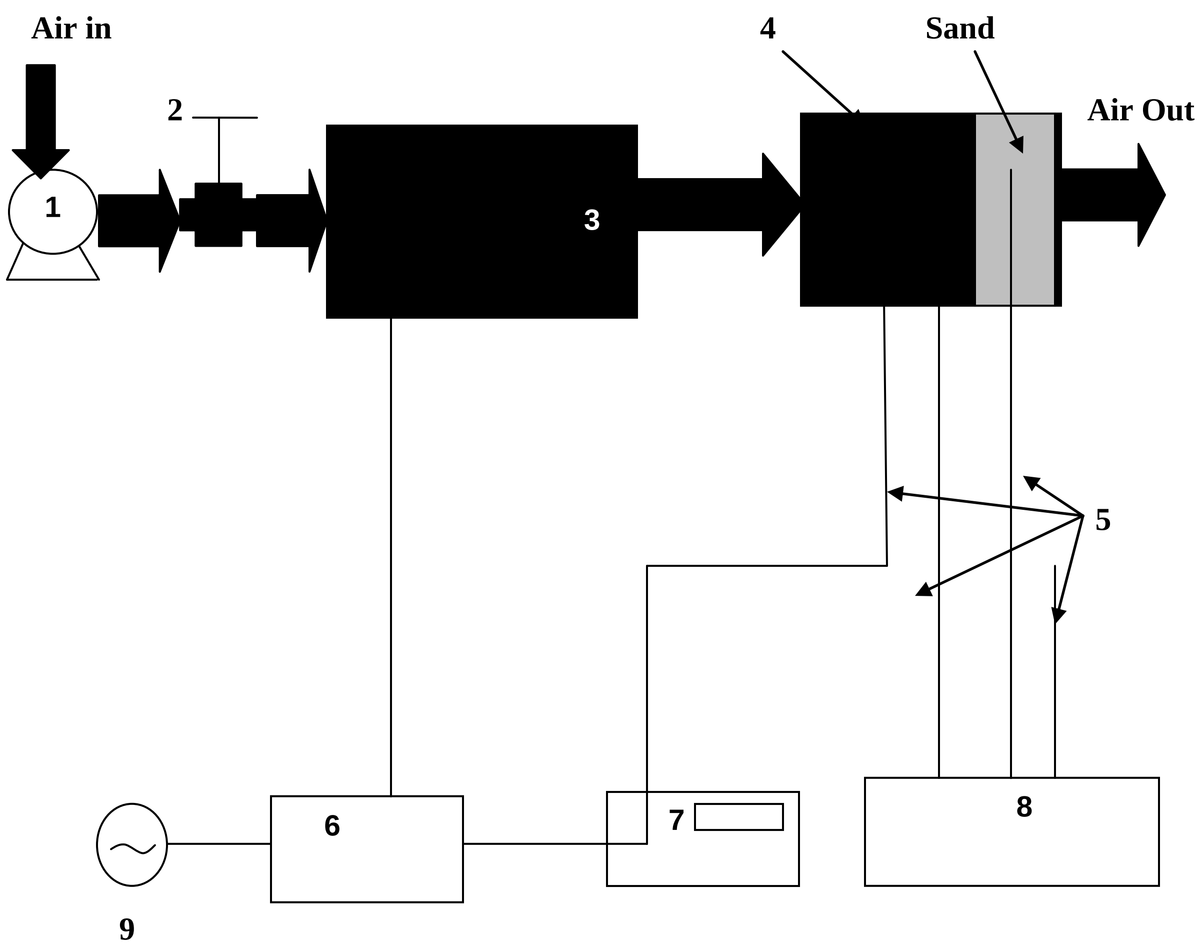

Figure 3.2: Experimental Set-up (Not to Scale)

Where:

1 – Air compressor 2- Air flow control valve

3- Air heater 4- TES tank

5- T- type thermocouples 6- Solid state relay

7- Temperature controller 8- Data logger

9- Electric power source

The container for holding the sand was made from sheet of steel of 0.0012m thickness and was made of size; 0.04m width, 0.196m length and 0.194m height.

The container is shown in Figure 3.3.

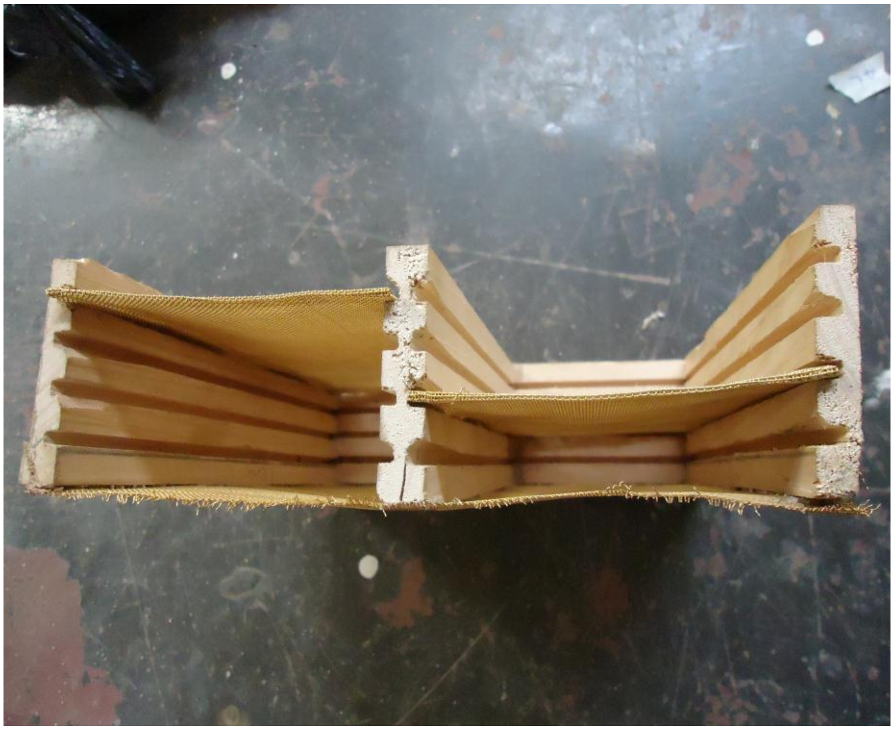

Figure 3.3 Container for Holding the Sand

Figure 3.4 shows the container filled with sand and the thermocouples placed into position. It was divided into two equal sections along the heights. This ensured that two sets of readings were obtained for each sample and then the mean evaluated. The rectangular section tank that housed the sand container was made from sheet of steel of 0.0012m thickness and was of size; 0.24m length, 0.2m width and 0.2m height.

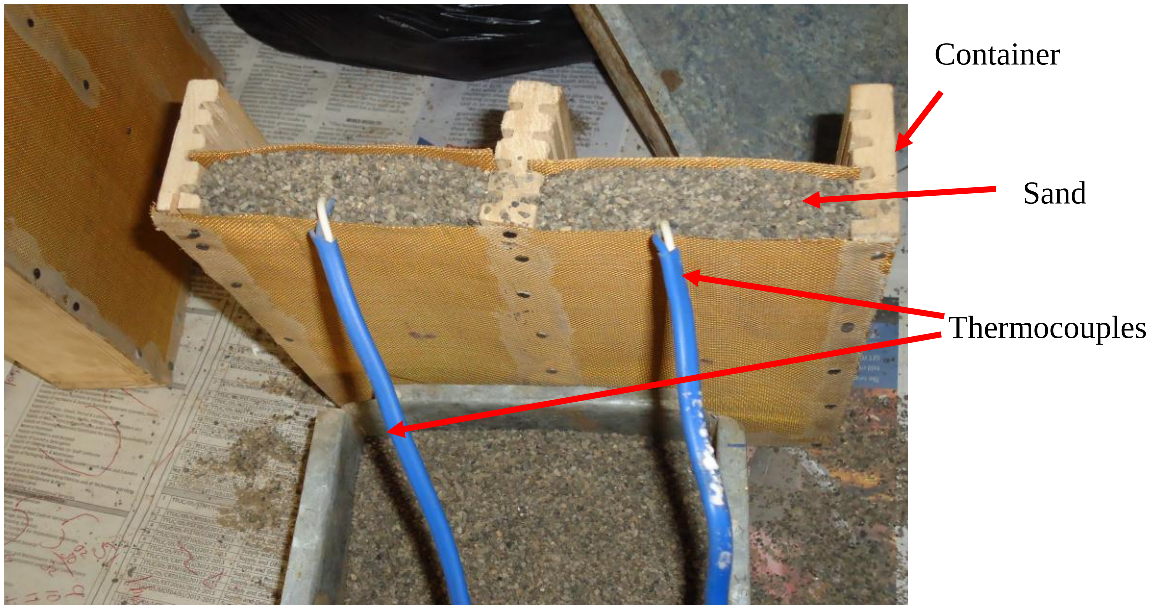

Figure 3.4 Container for Holding the Sand with Thermocouples in Position

The tank that accommodated the sand container is shown in Figure 3.5 as the container was fitted in. After the container was inserted into the tank an air tight cover was placed over the opening.

Figure 3.5 Fitting the Sand Container into the Insulated Rectangular Section Tank

The other end of the theromcouples were connected to a data loger shown in Figure 3.6. The data logger which recorded readings automatically is as shown in Figure 3.6.

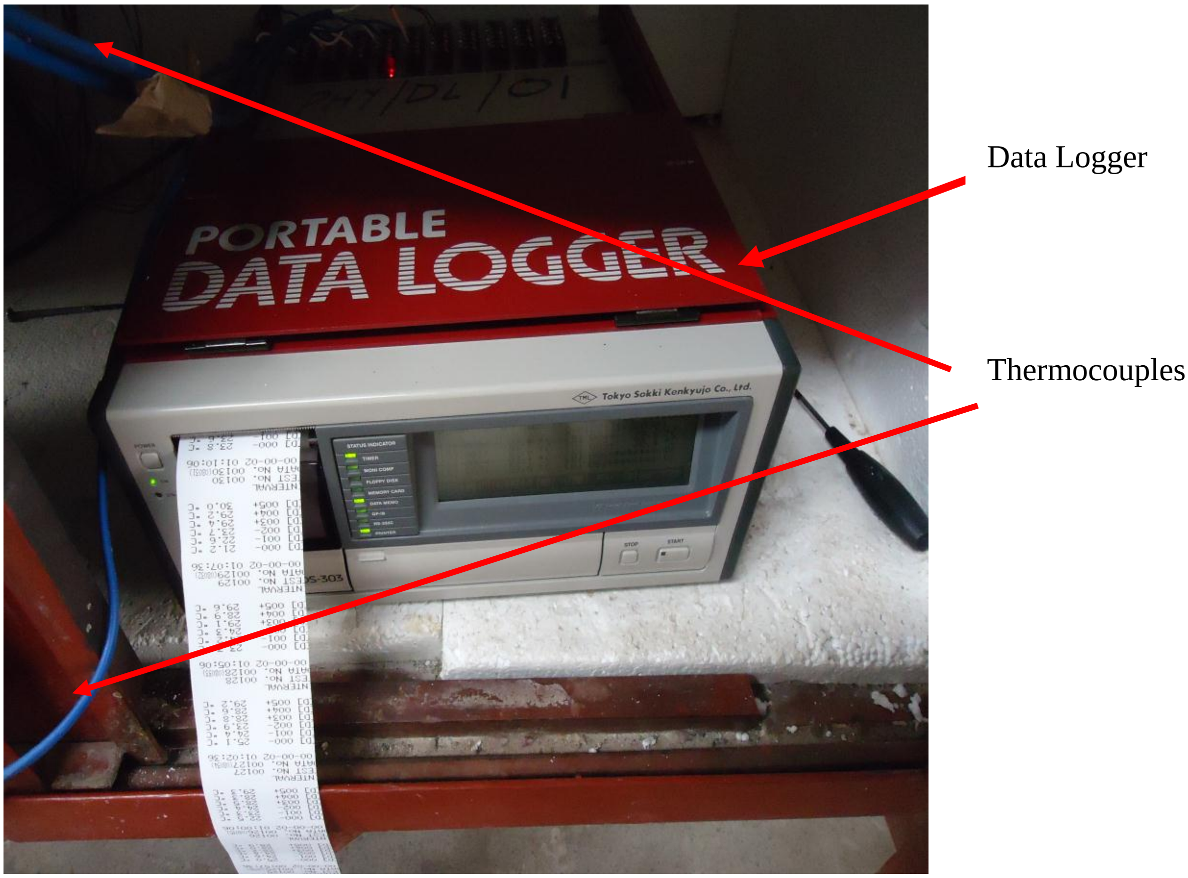

Figure 3.6 The Data Logger with Thermocouples Connected

3.2.3 Experimental Procedure

The sand holder was set at a thickness of 0.01 m. The tips of the thermocouples were positioned at the mid-point of the space for sand in the container. The container was then filled with Machakos sand at a layer thickness of 0.01 m and then placed in the TES tank. The range of layer thickness of 0.01 m, 0.02 m, 0.03 m and 0.04 m was selected based on the greatest layer of 0.04 m which would allow air passage through the sand without excessive resistance. The heat transfer fluid was set to inlet TES tank temperature of 40^{o}C. This was arrived at when the highest possible temperature of 70^{o}C with solar air heaters was considered. This highest temperature had been reduced gradually to attain a temperature range of 40^{o}C, 50^{o}C, 60^{o}C and 70^{o}C. Again there was need to maintain lowest temperature for the experiment that would enable sufficient temperature gradient from that of the ambient expected. The fluid was circulated continuously through the tank at a flow rate range of 0.0004 m^3/s, 0.0006 m^3/s, 0.0008 m^3/s and 0.001 m^3/s. The range of flow rate was found suitable for similar experiment under literature review. Temperature of the sand was recorded at an interval of 2.5 minutes with the use of a data logger. The interval was determined through trial experiments. The experiment was continued until when the charging rate was 0.08^{o}C/min or less which was considered to be insignificant. After the charging process, discharging of heat from the sand was carried out and temperatures recorded at interval of 2.5 minutes until when discharging rate was 0.08^{o}C/min or less. The discharging process was undertaken under the prevailing ambient conditions. The experiment was replicated three times using different samples of the same sand. The second experiment was carried out using Mombasa sand at a layer of thickness of 0.02 m with air at temperature of 40^{o}C and 0.001 m^3/s flow rate. The rest of the experiments were carried out under parameters values as indicated in Table 3.1.

3.3 Optimization of the parameters for charging sand

Graphs of the average charging rate values against each parameter levels were drawn. The optimum factor levels were obtained from the graph by using the quality characteristics of the bigger the better. Confirmation experiment was carried out to ascertain the obtained results.

3.4 Data Analysis

Data was analysed using Excel and Statistical Analysis Package (SAS). Analysis of S/N ratio was used to determine the optimum conditions for high robustness based on the quality characteristic of the bigger the better. Analysis of variance (ANOVA) was performed on the S/N ratios at $\alpha = 0.05$. This was to test the level of significance of all the main factors and also determine the percentage contribution of each to the charging rate of sand. Correlation analysis was carried out to establish whether there were significant correlation between charging rate of sand storage media and air temperature, flow rate and sand layer thickness. Multiple regression analysis was used to determine the relationship between the dependent variables of air temperature, flow rate and sand layer thickness and the charging rate of various sands.

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1: Classification of Sand using Sieve Analysis

Table 4.1 shows the results of the sieve analysis. The classification of the sands was done as per the British Standard range of particle sizes and the results are as follow

1. Machakos sand = Coarse / Medium Grained Sand (Cc=0.58)
2. Mombasa sand = Medium Grained Sand (Cc =0.95)
3. Kisumu sand = Coarse / Medium Grained Sand (Cc=0.57)
4. Nakuru sand = Medium Grained Sand (Cc=1.88)

According to these results, Machakos sand was similar to Kisumu sand and Mombasa sand was similar to Nakuru sand in terms of particle sizes. However, all the sands were found to be different in terms of coefficient of gradation. This would result to different porosity and bulk density in the sands and probably lead to different heat transfer characteristics. The sands showed a uniformity coefficient (Cu) greater than 5 indicating they were all well graded according to British soil classification (BS 5930:1999). This was also supported by the obtained values of coefficient of gradation (Cc) which were between 0.5 and 2.0.

Table 4.1: Particle Size distribution of Sand

Sand Type	**D_{10} (µm)**	**D_{30} (µm)**	**D60**	**Cu** D_{60}/D_{10}	**Cc** $(D_{30})^2/(D_{60}\times D_{10})$	**% Gravel**	**% Sand**	**% Fine**
Machakos	2	17	0.25	125.00	0.58	9.5	46.4	44.1
Mombasa	8	40	0.21	26.25	0.95	15.0	70.2	14.8
Kisumu	2	17	0.25	125.00	0.57	9.4	46.4	44.2
Nakuru	5	40	0.17	34.00	1.88	12.0	70.0	18.0

The results were obtained by considering mass of container and the mass of container together with sand retained shown in Table A.1 in Appendix A. It is from this data that the amount of sand retained and the percentage passing through each sieve were determined for each type of sand. The results were presented on semi logarithmic graphs of particle size against percentage passing by weight and are as shown in Figures 4.1, 4.2, 4.3 and 4.4. The graphs were used for the gradation of the sands.

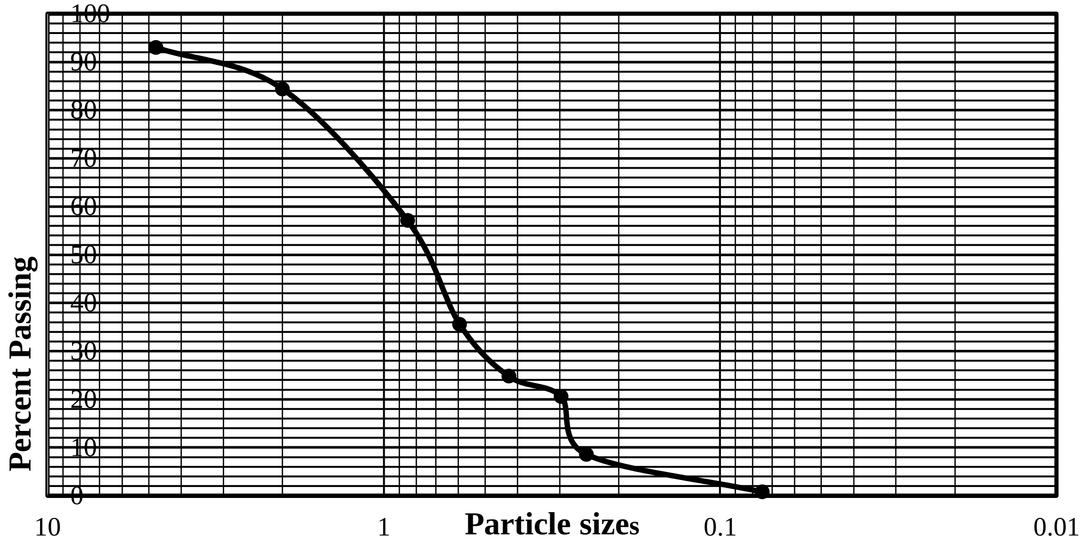

Figure 4.1: Semi Logarithmic Graph for Sand from Machakos

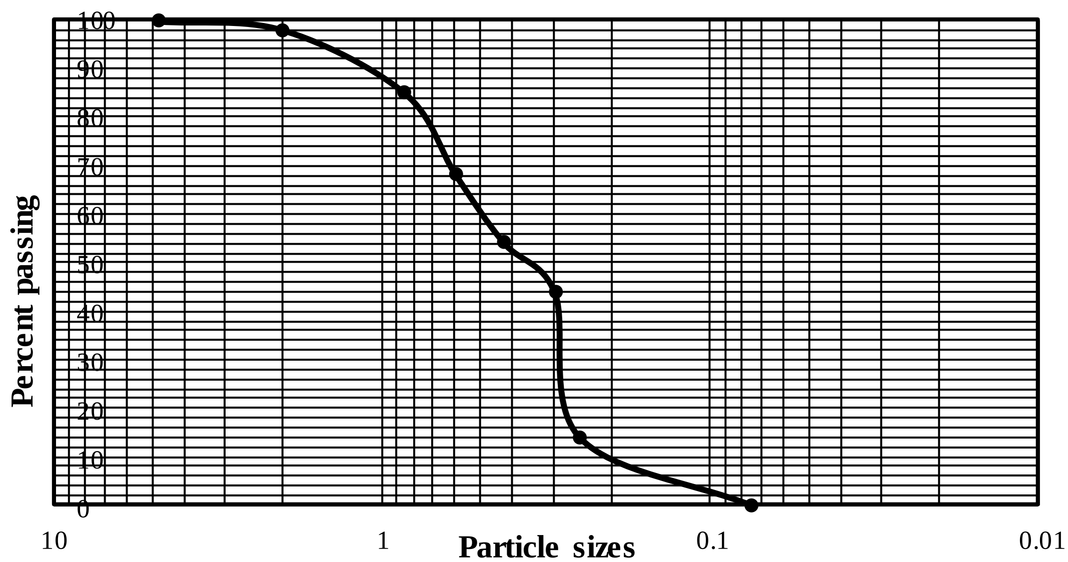

Figure 4.2: Semi Logarithmic Graph for Sand from Mombasa

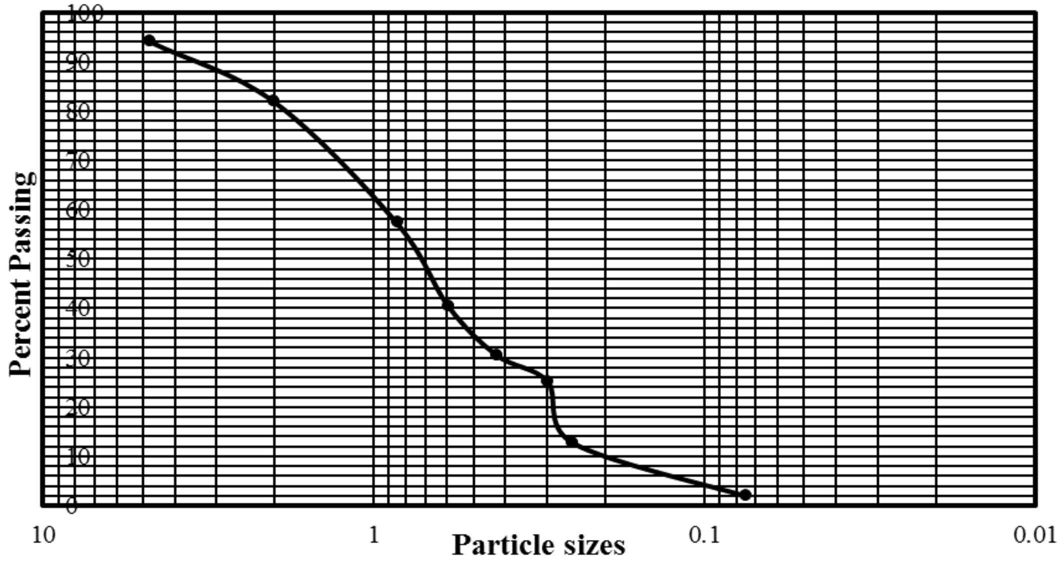

Figure 4.3: Semi Logarithmic Graph for Sand from Kisumu

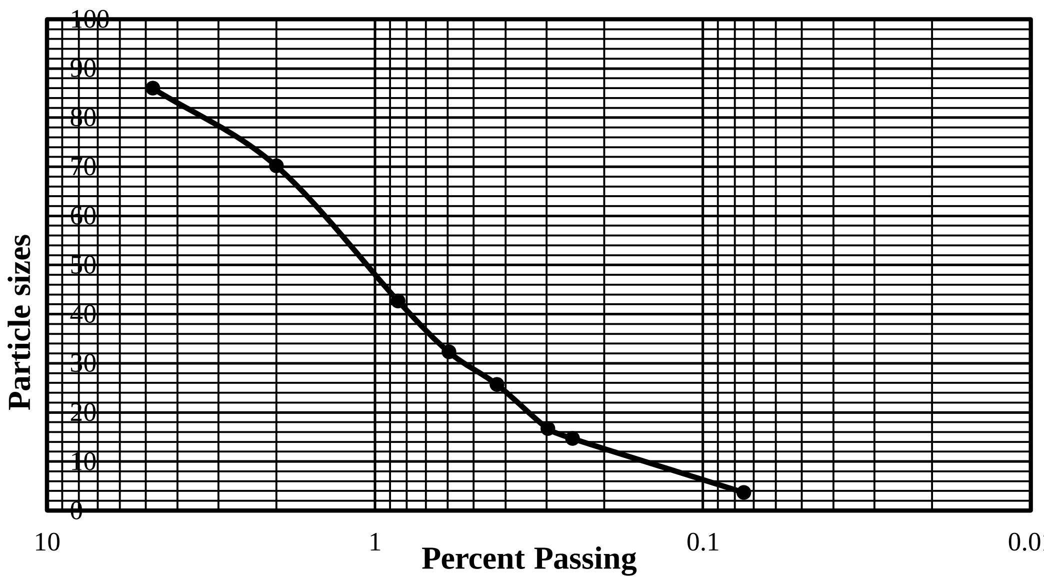

Figure 4.4: Semi Logarithmic Graph for Sand form Nakuru

4.2: Influence of Air Temperature, Flow rate, Sand Type and Sand Layer Thickness on the Rate of Charging Sand

4.2.1: Influence of Air Temperature on the Rate of Charging Sand

The average rates of charging sand at various temperatures are shown in Table 4.2.

Table 4.2: Rate of Charging Sand at Different Temperatures

Temperature (^oC)	Average Rate of Charging (^oC/min)
40	0.82
50	0.97
60	1.21
70	1.22

The rates were computed from Table B.2 in Appendix B. The average rate of charging sand as a function of temperature is shown in Figure 4.5. Results from the graph show that the rate of charging increased as temperature of air increased. This was attributed to the increasing temperature difference between the charging air and the sand. The increase of rate of charging was not constant since at high sand temperature there would be more heat transferred to the surrounding due to higher temperature difference between the two. However if the experiment was done under controlled condition the charging rate increase would be expected to be constant.

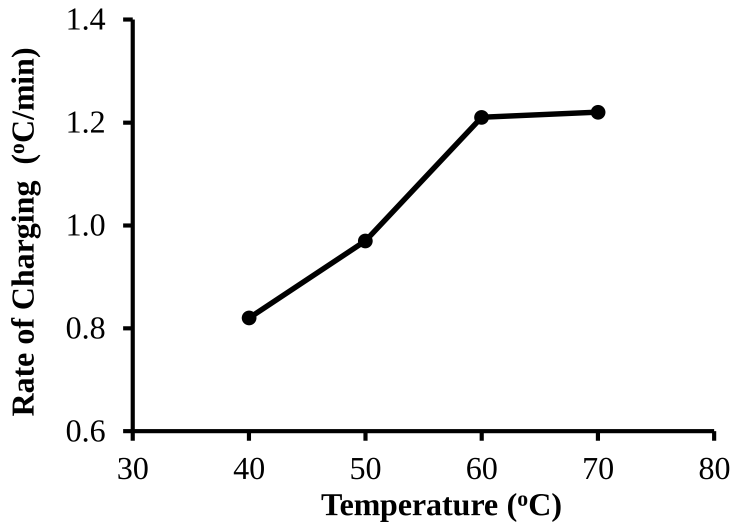

Figure 4.5: Rate of Charging Sands at Different Temperatures

4.2.2: Influence of Air Flow Rate on the Rate Charging of Sand

The average rates of charging sands at flow rates under consideration are shown in Table 4.3.

Table 4.3: Rate of Charging Sand at Different Flow Rates

Flow Rate (m^3/s)	Average Rate of Charging ($^oC/min$)
0.0004	0.91
0.0006	1.06
0.0008	1.06
0.001	1.20

Figure 4.6 shows the influence of flow rate on the rate of charging sand. It was noted that the rate of charging sand increased slightly as the flow rate increased. The rate of charging sand at 0.0004 m^3/s was 0.91 $^oC/min$ and that at 0.001 m^3/s was 1.20 $^oC/min$. This was attributed to more heat supplied at high flow rate at 0.001m^3 compared to 0.0004m^3. The increase of the rate of charging was not uniform as high flow rates also meant reduced time of heat transfer from air to sand.

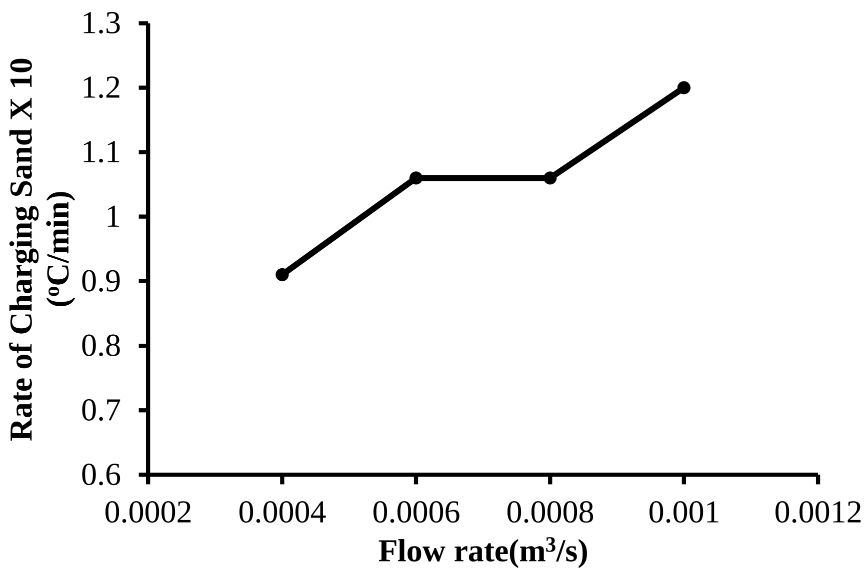

Figure 4.6: Rate of Charging Sands at Different Flow Rates.

4.2.3: Influence of Sand Layer Thickness on the Rate of Charging Sand.

The average rates of charging sands at various layer thicknesses are shown in Table 4.4.

Table 4.4; Rate of Charging Sand at Different Sand Layer Thicknesses

Sand Layer Thickness(m)	**Average Rate of Charging ($^oC/min$)**
0.01	1.87
0.02	1.06
0.03	0.72
0.04	0.59

Figure 4.7 shows the rate of charging sand at different sand layer thickness. It was observed that the rate of charging sand was inversely proportional to the sand layer thickness. Sand at layer thickness of 0.01m showed the highest rate of charging sand at 1.87 $^oC/min$. This could be attributed to the small amount of sand (300g) relating to the small layer thickness. Big layer thickness of sand would obviously mean more sand and hence lower rate of charging due to the high amount of thermal energy required to change the temperature of sand. This was emphasized by the charging process of sand at a thickness of 0.04m with an approximate amount of 1200g of sand with a rate of 0.59 $^oC/min$.

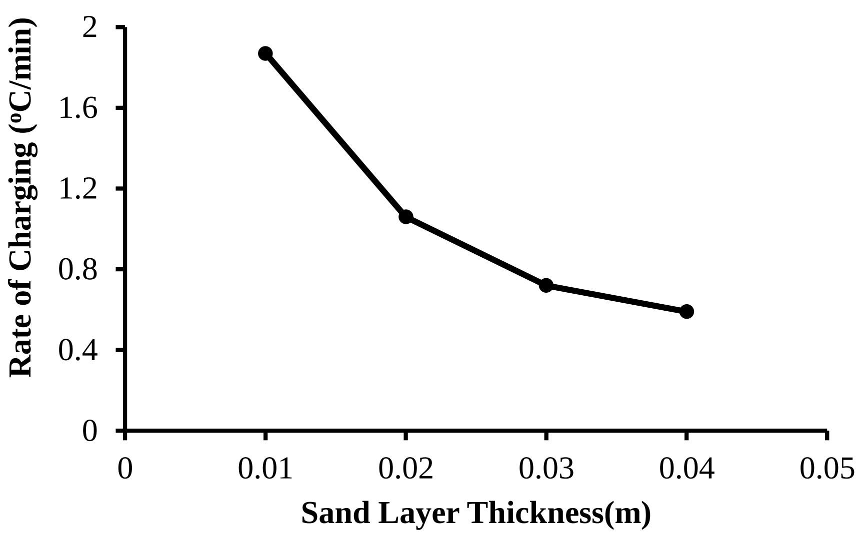

Figure 4.7: Rate of Charging Sands at Different Sand Layer Thicknesses

4.2.4: Influence of Sand Type on the Rate of Charging Sand

The average rates of charging some types of sands are shown in Table 4.5.

Table 4.5: Rate of Charging Some Types of Sand.

Types of Sand	Average Rate of Charging (^{o} C/min)
Machakos	0.97
Mombasa	1.14
Kisumu	1.12
Nakuru	1.01

It was observed from Figure 4.8 that Mombasa sand had the greatest rate of charging at 1.14^{o}C/min. The rate of charging Kisumu, Nakuru and Machakos sands were 1.12, 1.01 and 0.97^o C/min respectively. It was noted that though Machakos sand was similar to Kisumu sand and Mombasa sand was similar to Nakuru sand in terms of particle sizes distribution the results of charging rates were different. The charging rate of Machakos sand was similar to that of Nakuru while that of Mombasa sand was similar to that of Kisumu. This could be attributed to chemical composition of the sand. However the differences in the charging rates are not statistically significant. This was obtained by correlation analysis between charging rate and sand type which resulted to a p-value of 0.936 ($p>0.05$) shown in Table 4.8. The physical properties of the sands as displayed in Table 4.1 show that Machakos sand and Kisumu sand have same properties. There is no connection between uniformity, gradation as well as percentage constituents of sand and changing rate established. The difference realised on the rate of charging Machakos and Kisumu sands with thermal energy could have been brought about by the differences in their chemical properties. Generally according to the results, the particle size distribution did not contribute to charging of thermal energy to the sands. Mombasa and Kisumu sands showed great rate of charging as compared to the other two types. The optimum factors levels for the charging process were determined from the graphs as air temperature of 70^{o}C, Mombasa sand, sand layer thickness of 0.01 m and flow rate of 0.001m^3/s. The particular experiment was not in the Taguchi design and therefore a confirmation experiment was carried out.

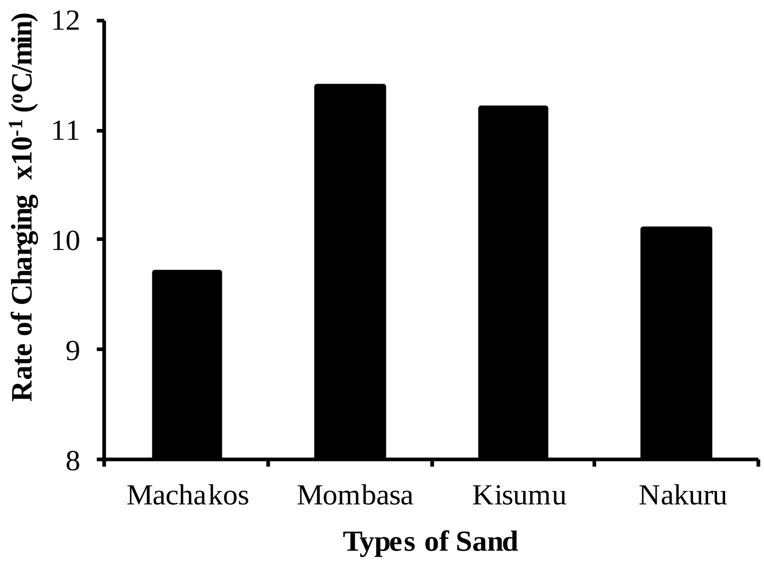

Figure 4.8: Rate of Charging Some Types of Sand.

4.3: Optimization of the Parameters for the Charging Rate of Sand

4.3.1: Signal to Noise Ratios

Signal to Noise (S/N) ratio represents the ratio of sensitivity of a process or a product to variability. It means that the higher the S/N ratio the better the quality of process or product. The idea is to maximise the S/N ratio thereby reducing the effect of random noise factors which has significant impact on the process performance. Since for the charging process the higher the rate of charging the better, then, S/N ratio was determined based on the quality characteristic of the bigger the better which leads to Equation 4.3.

S/N = -10 log {mean of sum squares of reciprocal of measured data}

$$S/N = -10 \log \left\{ \frac{\Sigma(1/y_i^{\ 2})}{n} \right\} \qquad (4.3)$$

Where; y_j = charging rate for experiments number j n = number of samples

A response table as shown in Table 4.6 was generated in which the average S/N ratio obtained for all levels are as indicated.

Table 4.6: S/N Ratio Values for Sand Charging Rate by Factor Level

Level	Temperature	Sand Type	Flow Rate	Thickness
1	-2.34	-0.86	-1.38	5.17
2	-1.21	-0.28	-0.90	0.34
3	0.35	-0.29	-0.13	-2.97
4	0.93	-0.85	0.14	-4.81
Delta	3.27	0.58	1.52	9.98
Rank	2	4	3	1

NB: The levels are: Temperatures - 40, 50, 60 and 70^oC; Sand Type - Machakos, Mombasa, Kisumu and Nakuru; Flow Rate - 0.0004, 0.0006, 0.0008 and 0.001m^3/s; Thickness - 0.01, 0.02, 0.03 and 0.04m.

According to Taguchi design of experiment, the effect of these factors was then calculated by determining the range represented by delta in the Table 4.6 which was determined by using Equation 4.4.

$$\text{Delta} = \text{Max} - \text{Min} \tag{4.4}$$

The factor with the biggest range had the greatest effect and one with the lowest had the least effect. Therefore thickness had the largest effect on the rate of charging sand with thermal energy and the sand type had the smallest effect on the rate of charging.

The factor S/ N ratios averages at various levels of charging air temperature, flow rate, sand type and sand layer thickness were plotted on graphs shown in Figures 4.9, 4.10, 4.11 and 4.12. The graphs were used to get optimal factors combination values for the charging process. Results from the graphs show that optimum conditions for the charging process are temperature of 70^oC, Mombasa sand, sand layer thickness of 0.01m and flow rate of 0.001 m^3/s. This was based on the experimental results for maximizing the rate of charging as the quality characteristic used was the bigger the better.

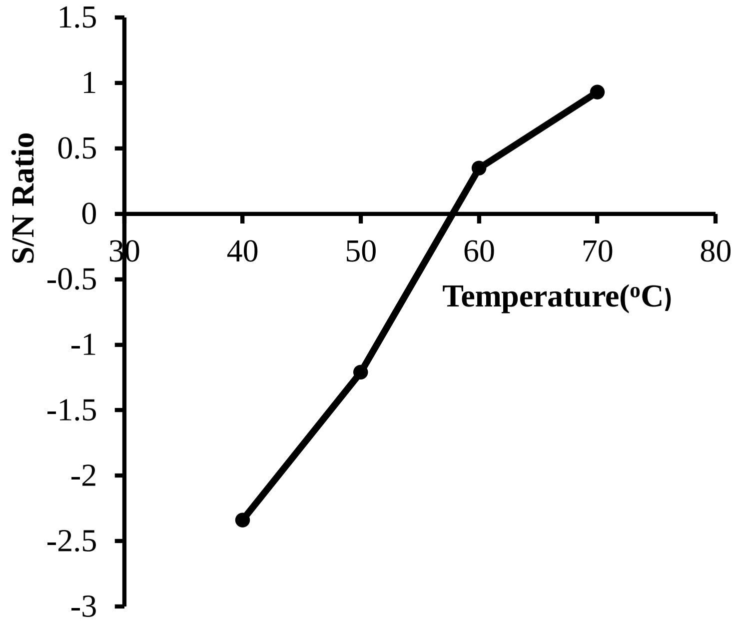

Figure 4.9: S/N Ratio Averages for Charging Air Temperatures.

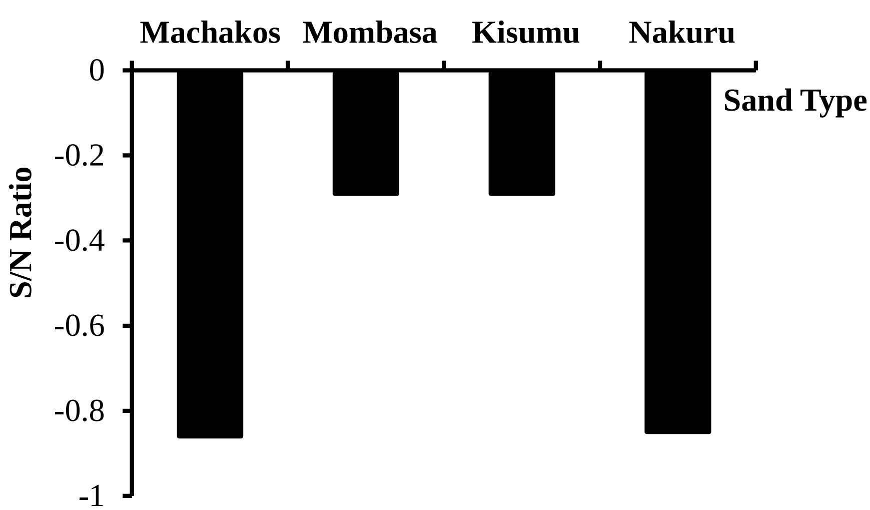

Figure 4.10: S/N Ratio Averages for Sand Types

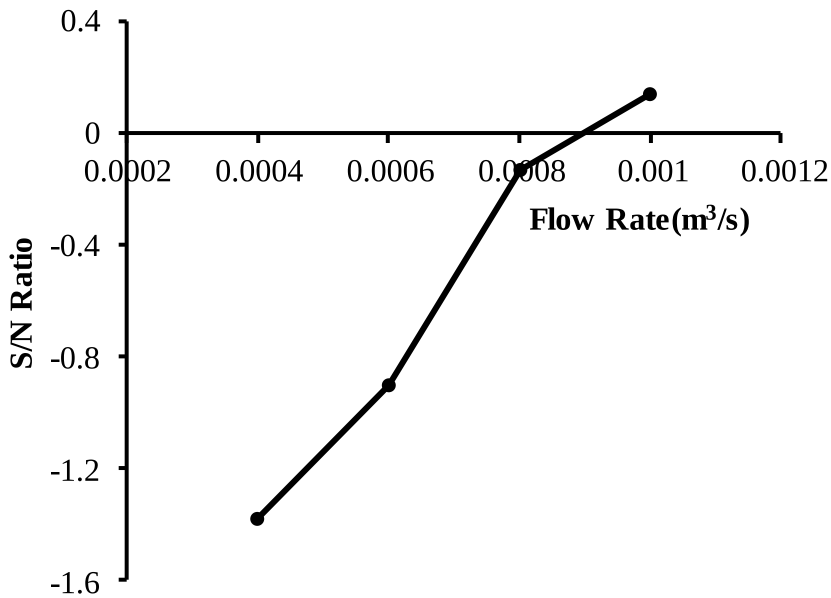

Figure 4.11: S/N Ratio Averages for Charging Air Flow Rates.

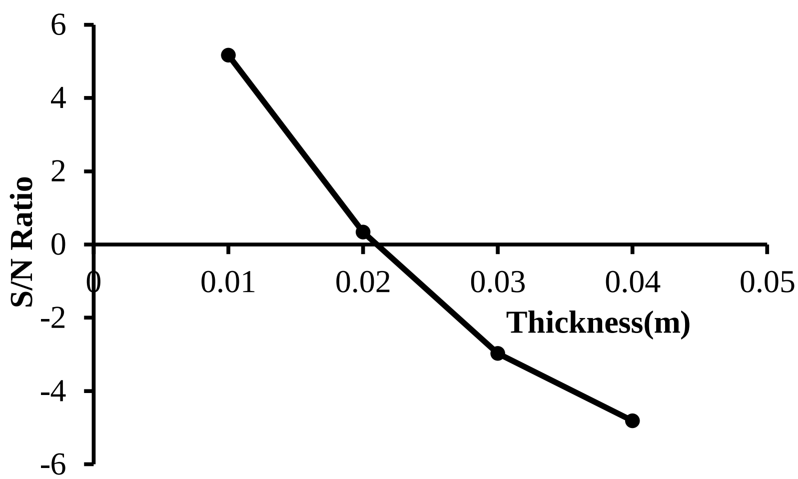

Figure 4.12: S/N Ratio Averages for Sand Layer Thicknesses.

The average S/N ratios for each factor at different levels are shown in Table B 3 in Appendix B.

4.3.2: Results of Charging Process of the Confirmation Experiment

The variation of charging rate with time for the confirmation experiment is shown in Figure 4.13. The charging rate was found to be high at the start and reduced with time. This was attributed to the reducing temperature gradient between the charging air and the sand with time. This was also attributed to the increasing temperature of the sand and the TES tank that resulted to higher heat loss to the environment.

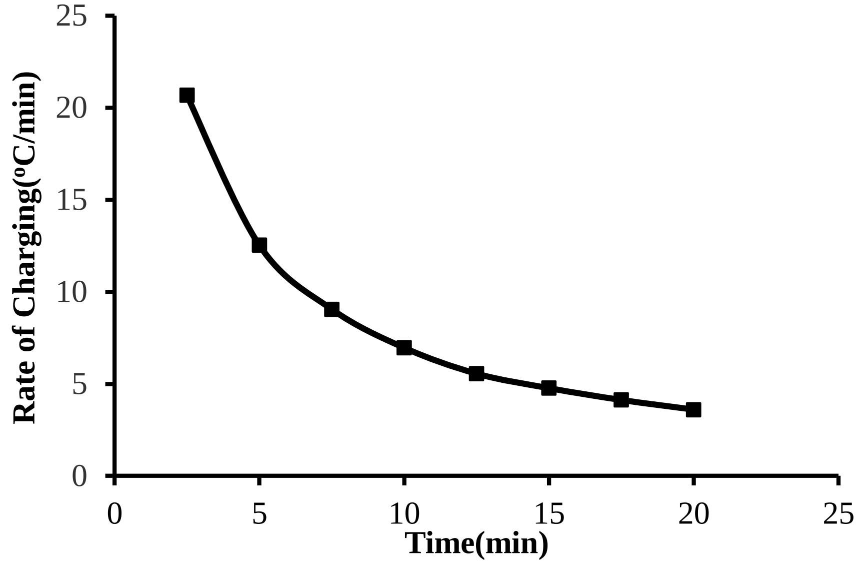

Figure 4.13: Rate of Charging Sand for Confirmation Experiment

Figure 4.14 shows the confirmation experiment results when compared to results of other 4 experiments selected to consist among others ones with lowest and highest charging rate of all the 16 carried out. The rate of charging for the different conditions appeared to be the same after about 30 minutes. This was attributed to the resultant small temperature difference between the charging air and the sand. It was observed that the confirmation experiment results had the highest charging rate of 3.60 ^{o}C/min as noted from Table B.2 in Appendix B. This confirmed the optimum parameter values obtained under Taguchi experimental design which were temperature of 70^{o}C, Mombasa sand, and sand layer thickness of 0.01m and flow rate of 0.001m^3/s.

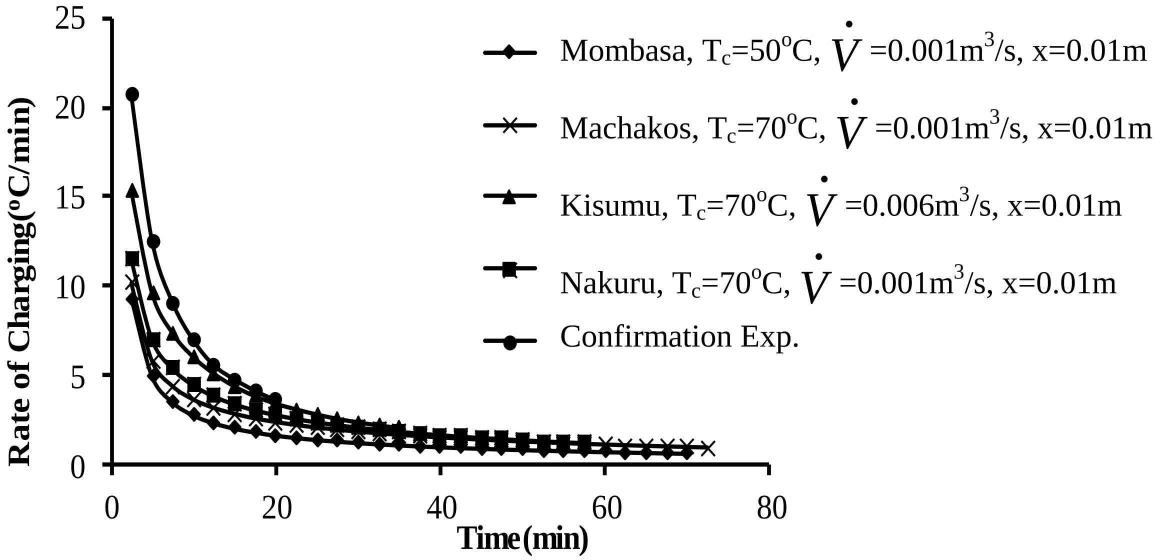

Figure 4.14: Rate of Charging Sand for Different Experiments

4.4: ANOVA

The analysis was carried out to determine exactly how each factor influences the rate of charging sands. The results of the analysis are shown in Table 4.7 and the contribution for each factor to the charging process are as shown in percentages. The calculated values of F for temperature and thickness are greater than the critical values and therefore the factors are significant to the charging process. On the other hand the calculated values of F for sand type and flow rates are less than the critical values, an indication that the factors are insignificant to the charging process.

Table 4.7: ANOVA Table

Source	Optimum Level	$F_{cal.}$	$F_{crit.}$	% Contribution to Charging Rate
Temperature (^{o}C)	70	27.5	9.28	10.00
Sand Type	Mombasa	1.34	9.28	0.49
Flow Rate (m^3/s)	0.001	6.13	9.28	2.23
Thickness (m)	0.01	239.19	9.28	86.93
Error	-	-	-	0.36
Total	-	-	-	100

It can be observed from Figure 4.15 that thickness (representing amount of sand), temperature, flow rate and sand type contributed 86.93%, 10%, 2.23% and 0.49% respectively to the charging rate. Therefore it can be concluded that sand layer thickness and air temperature are the most influential on the charging rate. Air flow rate and type of sand have very little influence on the rate of charging sand. This could be due to the fact that high air flow rate mean more thermal energy exposed to the sand but at less time resulting to the same effect. At the same time the sands used in the study had no major difference in terms of physical characteristics determined.

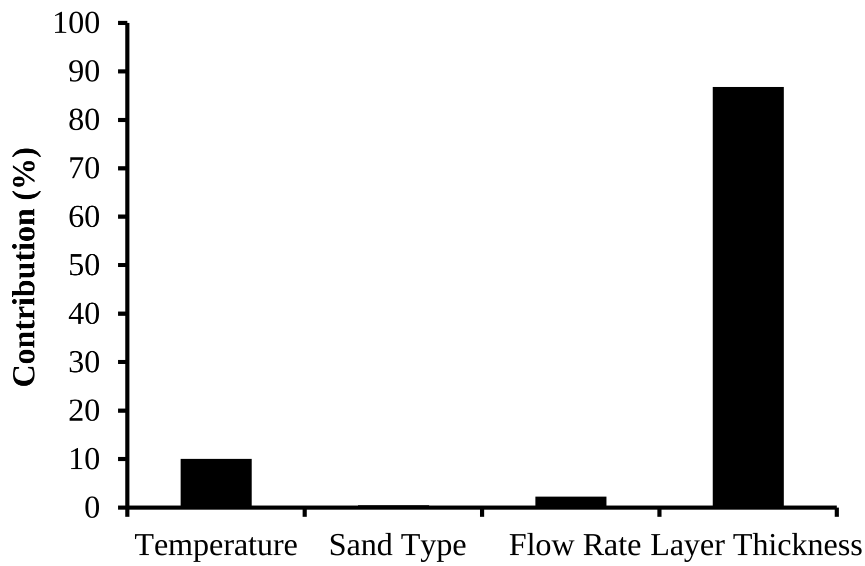

Figure 4.15: The Contribution of Each Factor

4.5: Results of the Discharging Process

Figures 4.16, 4.17, 4.18 and 4.19 show the variation of the rates of discharging with time for the four types of sand when charged at air temperatures of 40^{o}C, 50^{o}C, 60^{o}C and 70^{o}C. From these results it was observed that the higher the temperature of charged sand, the higher the rate of discharging. The sand charged at air temperature of 70^{o}C discharged thermal energy at highest rate and for a longer period when compared with others. The sand charged at 40^{o}C showed the least rate of discharging and for a shorter period. This could be attributed to temperature difference between the charged sand and the sink (the ambient conditions) during the discharging process.

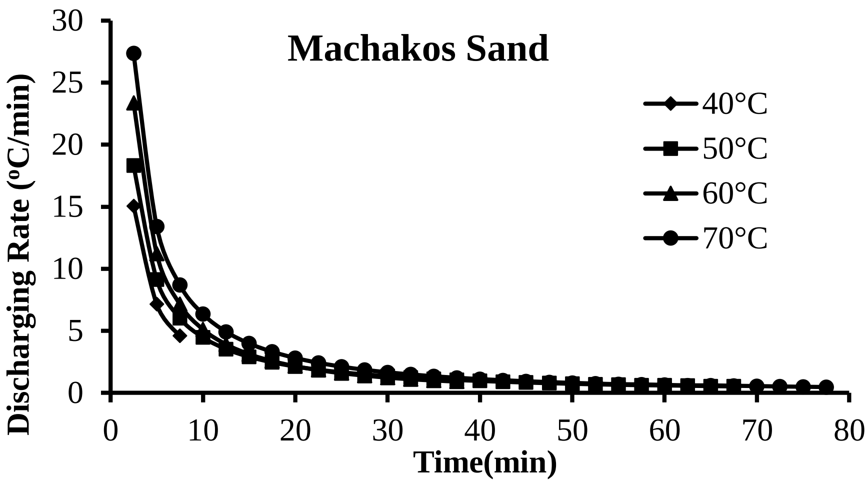

Figure 4.16: Rate of Discharging Machakos Sand Previously Charged at Different Air Temperatures.

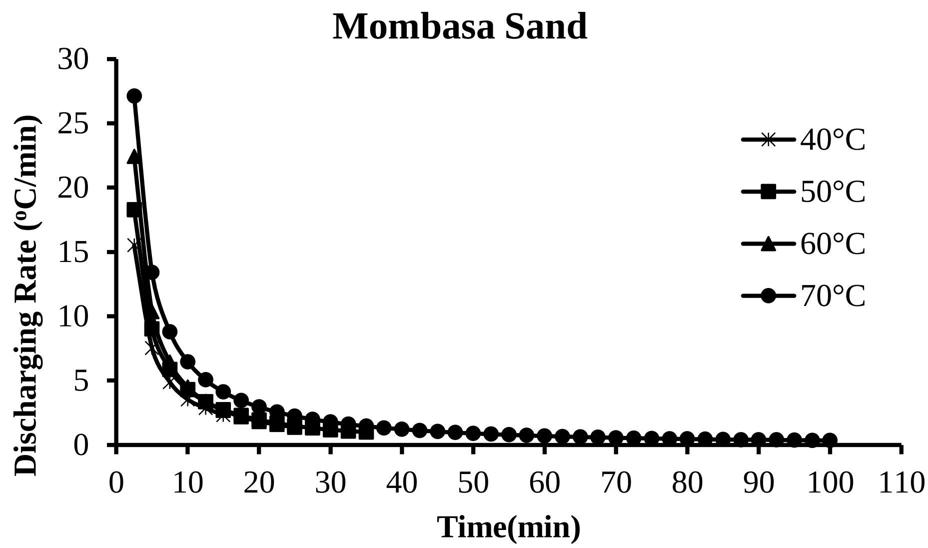

Figure 4.17: Rate of Discharging Mombasa Sand Previously Charged at Different Air Temperatures.

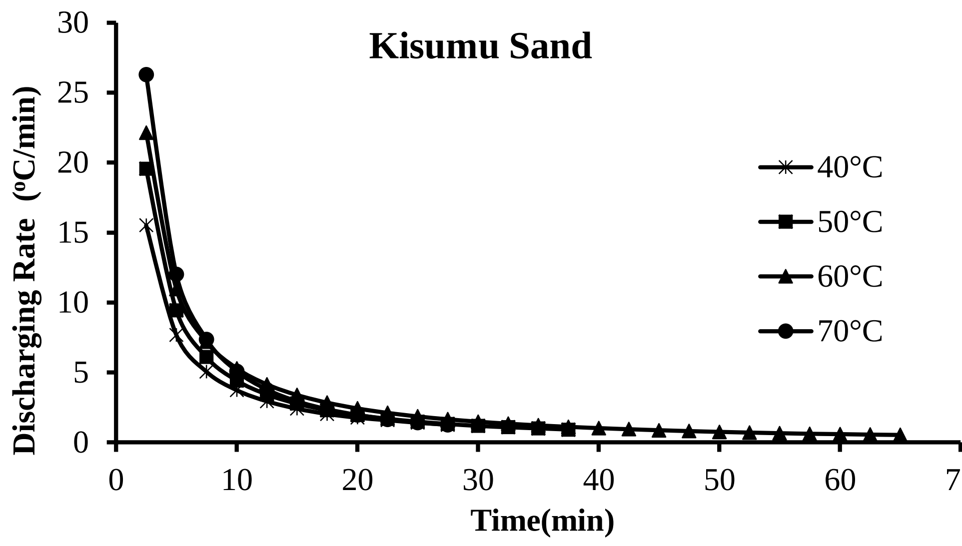

Figure 4.18: Rate of Discharging Kisumu Sand Previously Charged at Different Air Temperatures.

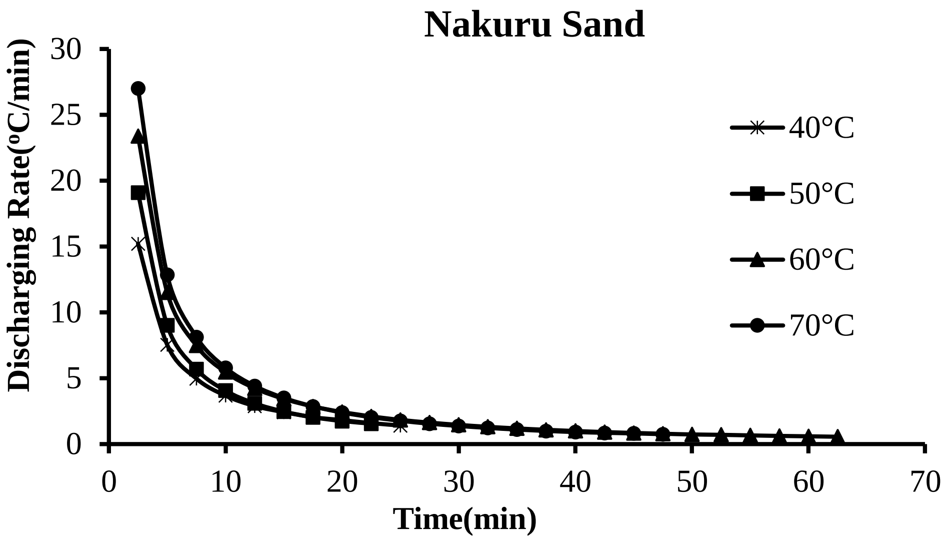

Figure 4.19: Rate of Discharging Nakuru Sand Previously Charged at Different Charging Fluid Temperatures.

4.6: Results of the Discharging Process of the Confirmation Experiment

Results of the discharging process of the confirmation experiment is as shown in Figure 4.20. The results was compared with those of other discharging processes of Mombasa sand under different charging air temperatures as shown in Figure 4.21. It was observed that the confirmation experiment has the highest rate of discharging. This could be attributed to the sand layer thickness of 0.01m which was the smallest for all these experiments.

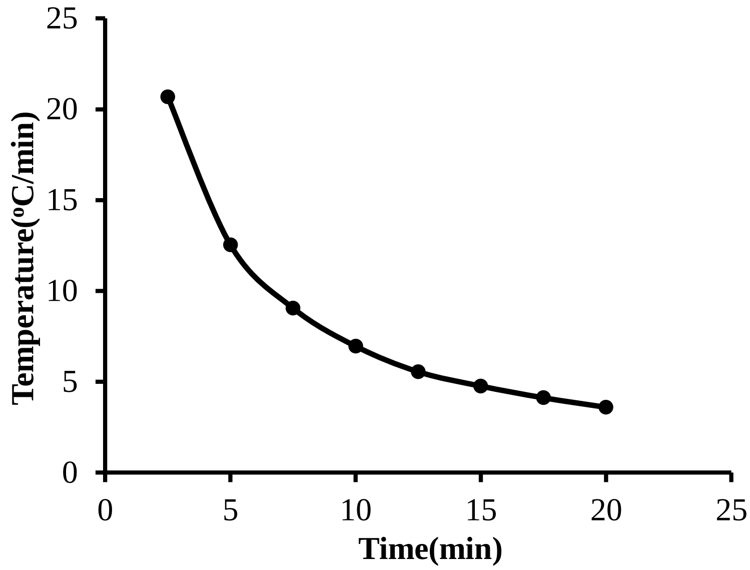

Figure 4.20: Rate of the Discharging sand for the Confirmation Experiment

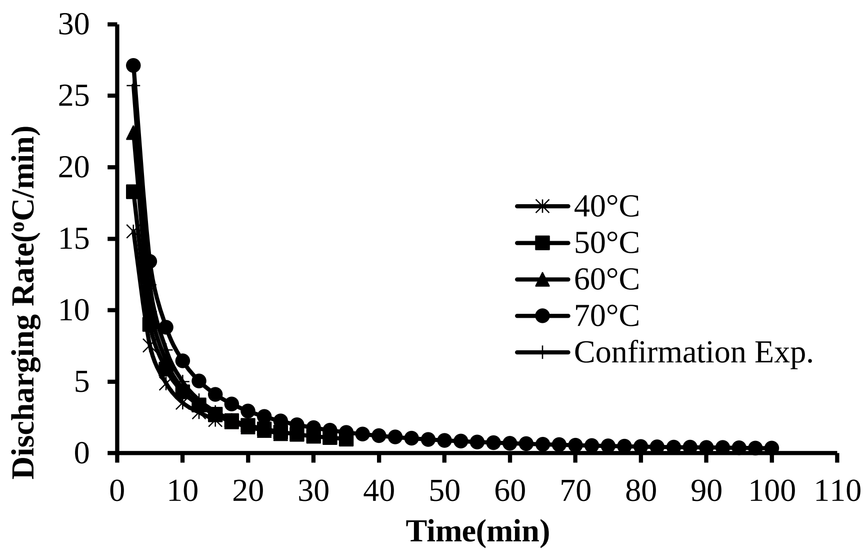

Figure 4.21: Rate of Discharging Mombasa Sand Charged at Different Temperature and for the Confirmation Experiment

4.7: Correlation Analysis

The study sought to establish the relationship that exist between charging rate of sand storage media and air temperature, flow rate, sand type and thickness. In addition, the study also sought to establish the relationship between sand type and discharging rate. In this study, Pearson correlation was used to explore relationships between the variables, specifically to assess both the direction (positive or negative) and strength of the relationship between the variables.

4.8: Relationship between Charging Rate and Air Temperature, Flow rate, Sand Type and Thickness

Results of correlation analysis between charging rate and air temperature, flow rate, sand type and thickness are shown in Table 4.8.

Table 4.8: Pearson Product-Moment Correlation between Charging Rate and Air Temperature, Flow Rate and Thickness.

No.	Correlation variables	Pearson's correlation coefficient (r)	P-value
1	Charging rate & Air temperature	0.296	0.266
2	Charging rate & Air flow rate	0.177	0.512
3	Charging rate & Thickness	-0.854	0.000
4	Charging rate & Sand type	0.022	0.936

NB: Correlation is significant at the 0.01 level (2-tailed).

There was a strong and negative correlation between charging rate (dependent variable) and thickness which was statistically significant ($r = -0.854$, p-value<0.01) in Table 4.8. This is an indication that thickness negatively influences charging rate. The correlation coefficient (r) between charging rate and air flow rate was 0.177, however the relationship was not statistically significant ($p=0.512$). Similarly, there was a very weak and positive correlation between charging rate (dependent variable) and sand type which was not statistically significant ($r = 0.022$, $p=0.936$). The relationship between charging rate and air temperature was also not statistically significant ($r = 0.296$, $p=0.266$). The relationship was however positive, which is an indication that as air temperature increases, charging rate increases.

4.9: Relationship between Discharging Rate, Sand Type and Thickness

Results of correlation analysis between discharging rate of sand storage media, thickness and sand type are shown in Table 4.9. Results of this study indicate that there was a strong and negative correlation between discharging rate (dependent variable) and thickness which was statistically significant (r = -0.589, p-value<0.05). This is an indication that thickness negatively influences discharging rate. The correlation coefficient (r) between charging rate of sand and sand type was -0.233; however the relationship was not statistically significant (p=0.386).

Table 4.9: Pearson Product-Moment Correlation between Discharging Rate, Thickness and Sand Type

No.	Correlation between	Pearson's Correlation coefficient (r)	P-Value
1	Discharging Rate & thickness	-0.589	0.016
2	Charging Rate & Sand Type	-0.233	0.386

4.10: Regression Analysis

4.10.1: Prediction of the Charging Rate from Operating Variables

To establish a prediction model, regression analysis was performed using the experimental data in Table 4.3. In this analysis, the charging rate was the dependent variable while the operating variables (air temperature, flow rate, sand type and thickness) were considered as the independent variables. The regression model is given by equation 4.5 and the dependent variable, is shown as a linear function of all operating variables. The multiple regression model produced R^2 = .849, $F (4, 11) = 15.457$, $p<0.05$. The value of the determination coefficient (R^2) of the model is 0.849, an indication that the independent variables explain 84.9% of the variance in the charging rate. The overall model reveals a statistically significant relationship ($p<0.05$) an indication that the operating variables significantly influence sand charging rate.

$$Y = 0.976 + 0.014X_1 + 433.750X_2 - 0.418X_3 + 0.011 X_4 + \varepsilon \qquad (4.5)$$

where, Y is the charging rate (^oC/min), X_1 is the air temperature (^oC), X_2 is the flow rate (m^3/s), X_3 is thickness (m), X_4 is sand type and ε is error term.

Table 4.10: Statistical Results of the Regression Model for Predicting Charging Rate

Independent variables	Coefficient(β)	Standard error	t-value	Significance
(Constant)	0.976	0.430	2.268	0.044
Air temperature (^oC)	0.014	0.006	2.523	0.028
Flow rate (m^3/s)	433.750	286.874	1.512	0.159
Thickness (m)	-0.418	0.057	-7.290	0.000
Sand type	0.011	0.057	0.187	0.855

NB: Dependent variable: Charging rate

In the analysis, the t-test was used to examine the significance of each variable in the model, while the F-test was used for the whole model significance at a 95 per cent significance level. The statistical results of the model are given in Table 4.6 in detail. As shown in the Table 4.10, air temperature ($\beta = 0.014$, $t=2.523$, p= value 0.028) and thickness ($\beta = -0.418$, $t= -7.290$, p = value<0.05) are significant predictors of charging rate. Flow rate of air (m^3/s) and sand type are not however significant predictors of charging rate (p-value>0.05).

4.10.2: Prediction of the Discharging Rate from Thickness and Sand Type

To establish a prediction model, regression analysis was performed using the experimental data in Table B.4. In this analysis, the discharging rate was the dependent variable while thickness and sand type were the independent variables. The regression model is given by Equation 4.6 and the dependent variable, is shown as a linear function of the two independent variables. The multiple regression model produced $R^2 = .401$, $F(2, 13) = 4.351$, $p=0.036$. The value of the determination coefficient (R^2) of the model is 0.401, an indication that the independent variables explain 40.1% of the variance in the discharging rate. The overall model reveals a statistically significant relationship ($p<0.05$) an indication that thickness and sand type significantly influence discharging rate.

$$Y = 6.091 - 1.070X_5 - 0.423X_6 + \varepsilon \qquad (4.6)$$

where, Y is the discharging Rate ($^oC/min$), X_5 is thickness (m), X_6 is sand type and ε is error term.

Table 4.11: Statistical Results of the Regression Model for Predicting Discharging Rate

Independent variables	Coefficient (β)	Standard error	t-value	Significance
(Constant)	6.091	1.446	4.214	0.001
Sand layer thickness	-1.070	0.390	-2.744	0.017
Sand type	-0.423	0.390	-1.084	0.298

NB: Dependent variable: Discharging rate

As shown in Table 4.7, thickness is a significant predictor of sand discharging rate (t = -2.744, p-value<0.05). Sand type is however not a significant (t = -1.084, p=0.298) predictor of discharging rate

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1: Conclusions

The study showed that the rate of charging sand increased as temperature of charging air increased. However the charging rate was not constant since it reduced with time as the temperature difference between charging air and sand reduced. Charging temperature contributed 10.00% to the variation of the charging rate.

The rate of charging sand was found to increase slightly as the flow rate increased. Flow rate showed little influence on charging rate contributing 2.23% to the variation of the charging rate. The charging rates at air flow rate of 0.0004 m^3/s, 0.0006 m^3/s, 0.0008 m^3/s and 0.001m^3/s were 0.91 $^oC/min$, 1.06 $^oC/min$, 1.06 $^oC/min$ and 1.20 $^oC/min$ respectively. The increase of charging rate is not constant since increased flow rate also meant reduced time of heat transfer from air to sand.

There was indication of a strong and negative correlation between the charging rate and sand layer thickness. The charging rate decreased greatly as the sand layer thickness increased. The average rate of charging at thicknesses of 0.01m, 0,02m, 0.03m and 0.04m were 187 $^oC/min$, 1.06 $^oC/min$, 0.72 $^oC/min$ and 0.59 $^oC/min$ respectively. Thickness was the most influential factor and contributed 86.93% to the variation of the charging rate.

The charging rate was found to change slightly with change of type of sand. Type of sand had the least influence and contributed 0.49% to the variation of charging rate. Despite the similarity between Machakos and Kisumu sands, and Mombasa and Nakuru sands in terms of particle sizes grading, in terms of charging, Machakos sand was similar to Nakuru sand while Machakos sand was similar to Kisumu sand.

The optimum conditions for the charging process were found to be air temperature of 70^oC, Mombasa sand, and thickness of 0.01m and flow rate of 0.001 m^3/s. Confirmation experiment was carried out. The rate of charging was determined to be 3.60$^oC/min$. This was found to be higher than any other rate for the 16 experiments carried out under this research.

5.2: Recommendations

To broaden the understanding of charging process of sand media, the following further investigations need to be carried out:

1) Influence of the colour of sand on the thermal charging process of various types of sand.

2) The effect of thermal cycling sands on the charging process.

3) The effect of use of different range of flow rates than the one considered under experimentation.

REFERENCES

Abdullah, S. and Jeanly, P. W. (2011). Willingness to pay for renewable energy: Evidence from a contingent valuation survey in Kenya. *Journal of renewable and sustainable energy reviews.* Vol. 15, no. 6, pp. 2974-2983.

Adeyanju, A. A. and Manohar, K. (2009). Comparison of thermal energy storage techniques. *Journal of engineering and applied sciences.* Vol. 4, no. 3, pp.221-231.

Alkilani M. M., Sopian K., Alghoul M. A., Sohif M. and Ruslan M. H. (2011). Review of solar air collectors with thermal storage units. *Journal of renewable and sustainable energy reviews.* Vol. 15, no. 3, pp. 1476-1490.

Ataer, O. E. (2006). *Storage of thermal energy.* Encyclopaedia of life support systems. Eolss publishers, Oxford, UK.

Bal, L. M., Satya S. and Naik S. N. (2010). A review of solar dryer with thermal energy storage systems for drying agricultural food products. *Journal of renewable and sustainable energy reviews.* Vol. 14, pp. 2298-2314.

Barasa, H. M. (2011). *Performance of a solar air heater incorporated with a rock-bed energy storage system.* A master's thesis. Masinde Muliro University, department of mechanical and industrial engineering.

Bayon, J. R., Castro-Fresno D. and Rodriguez-Hernandez J. (2010). Review of seasonal heat storage in large basins: Water tanks and gravel-water pits. *Journal of applied energy.* Vol. 87, no. 2, pp. 390-397.

Chidambaram, L. A., Ramana, A. S., Kamaraj, G. and Velraj, R. (2011). Review of solar cooling methods and thermal storage options. *Journal of renewable and sustainable energy reviews.* Vol. 15, no. 6, pp. 3220-3228.

Dincer, I. and Rosen, M. (2002). *Thermal energy storage: Systems and applications.* John Wiley and sons Ltd. Chic ester, England, pp. 23-50.

Erickson, c. (2009). Rural milk preservation with ISAAC solar icemaker. *Journal of energy for sustainable development.* Vol. 13, no. 4, pp. 287-291.

ETC (Energy Consulting Company) Group (2007). A feasibility study on promoting biogas systems in Kenya.

Farid, M. M., Khudhair, A. M., Razack, S. A. K. and Al-Hallaj S. (2004). A review on phase change materials and applications. *Journal of energy conversion and management.* Vol. 45, pp. 1597-1615

Fernadez, A. I., Martinez, M., Segar ra M., Martorell, I. and Cabeza L. F. (2010). Selection of materials with potential in sensible thermal energy storage. *Journal of solar energy materials and solar cells.* Vol. 94, pp. 1723-1729.

Garg, H. P., Sharmar V. K., Mahajan, R. B. and Bhargave, A. K. (1985). Experimental study of an inexpensive solar collector cum storage system for agricultural uses. *Journal on solar energy*. Vol. 35, no. 4, pp. 321-331.

Hasnain, S. M. (1998). Review on sustainable thermal energy storage technologies, Part 1: Heat storage materials and techniques. *Journal of energy conversion and management.* Vol. 39, no. 2, pp. 185-200.

Hazami, M., Kooli, S., Lazaar, M., Farhat, A. and Belghith, A. (2005). Thermal performance of a solar heat storage accumulator used for greenhouses conditioning. *American journal of environmental sciences.* Vol. 1, no. 4, pp. 270-277.

Hazami, M., Kooli, S., Lazaar, M., Farhat, A. and Belghith, A. (2009). Energy and exergy efficiency of a daily heat storage unit for building heating. *Journal of renewable energy.* Vol. 12, no. 2, pp. 185-200.

IES (Isabella Experiment Station) (2008). Solar thermal energy system – zero energy home challenge.

Jeter, S. and Stephens, J. (2010). *Development of a novel thermal energy storage system using sand as the medium.* American solar energy society.

Karekezi, S., Kimani, J. and Onguru, O. (2008). Energy access among the urban poor in Kenya. *Journal of energy for sustainable development.* Vol. 12, no. 4, pp. 38-48.

Kazemi, H. (2008). Greenbuilding] EPDM Lined Tanks – vs Thermal Sand Storage. http://listserv.repp.org/pipermail/greenbuilding_listserv.repp.org/2008-August/007692.html Accessed on 10th, January, 2011.

Kiplagat, J. K., Wang, R. Z. and Li, T. X. (2011). Renewable energy in Kenya: Resourse potential and status of exploitation. *Journal of renewable and sustainable energy reviews.* Vol.15. no. 6, pp. 2960-2973.

Laing, D., Bahl, C., Bauer, T.,Lehmam, D. and Steinmann, D. (2011). Thermal energy storage for direct steam generation. *Journal of solar energy.* Vol. 85, no. 4, pp. 627-633.

Li, P.,Lew, J. V., Karaki, W., Chan, C., Stephens, J. and Wang, Q. (2011). Generalised charts of energy storage effectiveness for thermocline heat storage tank design and calibration. *Journal of solar energy.* Vol. 85, no. 9, pp. 2130-2143.

Mawire, A. and McPherson, M. (2008). Experimental characterization of a thermal energy storage system using temperature and power controlled charging. *Journal of renewable energy*. Vol. 33, pp. 682-793.

Mawire, A., McPherson, M. and Heet Kamp, van den R. R. J. (2008). Simulated energy and exergy analyses of the charging of an oil pebble bed thermal energy storage system for a solar cooker. *Journal of solar energy materials and solar cells.* Vol. 92, pp. 1668-1676.

Mawire, A., McPherson, M., Heet Kamp, van den R. R. J. andMlatho, S. J. P. (2009). Simulated performance of storage materials for pebble bed thermal energy storage (TES). *Journal of applied science.* Vol. 86, no. 7-8, pp. 1246-1252.

Mekhilef, S., Saidur, R. and Safari, A. (2011). A review on solar energy use in industries. *Journal of renewable and sustainable energy reviews*. Vol. 15, no. 4, pp. 1777-1790.

MOE (Ministry of Agriculture) (2004). *Sessional paper, no. 4 on energy.* Government printer, Nairobi.

Mekhilef, S., Saidur, R. and Safari, A. (2011). A review on solar energy use in industries. *Journal of renewable and sustainable energy reviews*. Vol. 15, no. 4, pp. 1777-1790.

NEP (Nottingham Energy Partnership) (2007). *Thermal energy storage.*

Nallusamy, N., Sampath, S. and Velraj, R. (2007). Experimental investigation on a combined sensible and latent heat storage system integrated with constant/varying (solar) heat sources. *Journal of renewable energy*. Vol. 32, pp. 1206-1227.

Ngui, D., Mutua, J., Osiolo, H. and Aligula, E. (2011). Households' energy demand in Kenya: An application of the linear approximate almost ideal demand system (LA-AIDS). *Journal of energy policy.* Vol. 39, no. 11, pp. 7084-7094.

Osawa, B. (2004). Cogeneration in Kenya: Opportunities and implications? *Refocus.* Vol. 5, no. 5, pp. 34-37

Ozuturk, H. H. and Bascentincelik, A. (2003). Energy and exergy efficiency of a packed bed heat storage unit for greenhouse heating. *Journal of biosystems engineering.* Vol. 86, no.2, pp.231-245.

Pinel, P., Cruickshank, C. A., Beausoleil-Morrison, I. and Wills, A. (2011). A review of available methods for seasonal storage of solar thermal energy in residential applications. *Journal of renewable and sustainable energy reviews.* Vol. 15, no. 7, pp. 3341-3359.

Prasad, S. B., Saini, J. S. and Singh, K. M. (2009). Investigation of heat transfer and friction characteristics of packed solar air heaters using wire mesh as packing materials. *Journal of solar energy.* Vol. 83, no. 5, pp. 773- 783.

Rabah, K. V. O. (2005). Integrated solar energy systems for rural electrification in Kenya. *Journal of renewable energy.* Vol. 30, no. 1, pp. 23-42.

Rabah, K. V. O., Ndjeli, L. and Raturi, A. K. (1995). Review of photovoltaic energy development in Kenya for rural electrification. International centre for theoretical physics, Trieste, Italy.

Sawhney, A. K. and Sawhney, P. (2005). *A course in electrical and electronic measurements and instrumentation.* Dhanpat Rai & Co. (P) Ltd. Delhi, India.

Schwarzer, K. and Silva, M. E. V. (2008). Characterisation and design methods of solar cookers. *Journal of solar energy.* Vol. 8, pp. 157-163.

Sharma, A., Tyagi, V. V., Chen, C. R. and Buddhu, D. (2009). Review on thermal energy storage with phase change materials and applications. *Journal of renewable and sustainable energy reviews.* Vol. 13, no. 2, pp. 318-345.

Singh, H., Saini, R. P. and Saini, J. S. (2010). A review on packed bed solar energy storage systems. *Journal of renewable and sustainable energy reviews.* Vol. 14, no. 3, pp. 1059-1069.

Sunliang, C. (2010). *State of the art thermal energy storage solutions for high performance buildings*. A master's thesis. University of Jyvaskyla, department of physics.

Warerkar, S., Schmit, S., Goettsche J., Hoffschmidt, B. and Reiβel, M. (2011). Air-sand heat exchanger for high-temperature storage. *Journal of solar energy engineering.* Vol. 133, no. 2, (7 pages)

World Map (2016). Kenya latitude and longitude map,www.Mapsofworld.com/lat_long/Kenya-lat-long.html, Retrieved on 3rd march 2016.

APPENDICES

Appendix A Sand Sieve Analysis

Table A.1 Data Collected on Mass of Sieve/Can and of Sand Retained During the Sieve Analysis

	Machakos Sand		Mombasa Sand		Kisumu Sand		Nakuru Sand	
Sieve size (µm)	Mass of empty can (g)	Mass of can + sand retained (g)	Mass of empty can (g)	Mass of can + sand retained (g)	Mass of empty can (g)	Mass of can + sand retained (g)	Mass of empty can (g)	Mass of can + sand retained (g)
4760	515	550	27	28	27	53	514	584
2000	440	483	26	35	26	87	440	519
850	441	577	27	92	27	150	441	578
595	404	511	25	109	25	109	403	455
425	330	384	25	95	25	75	329	362
297	454	475	26	78	26	53	454	499
250	350	410	28	96	28	90	378	388
75	285	324	27	175	27	81	314	369
Pan	346	349	346	348	345	355	346	363

Table A.2 Amount of Sand Retained and the Percentage Passing

Sieve Size (µm)	Machakos Sand		Mombasa Sand		Kisumu Sand		Nakuru Sand	
	Mass Retained (g)	Percent Passing	Mass Retained (g)	Percent Passing	Mass Retained (g)	Percent Passing	Mass Retained (g)	Percent Passing
4760	35	93	1	99.8	29	94.2	70	86
2000	43	84.4	9	98	61	82	79	70.2
850	136	57.1	65	85	123	57.4	137	42.7
595	107	35.6	84	68.2	84	40.6	52	32.3
425	54	24.8	70	54.2	50	30.6	33	25.7
297	21	20.6	52	43.8	27	25.2	45	16.7
250	60	8.6	68	14.1	62	12.8	10	14.7
75	39	0.8	148	13.7	54	2	55	3.7
Pan	3	0	2	0	10	0	17	0

Appendix B Experimental and Statistical Data Analysis

Figure B.1 The Researcher and Supervisor, Dr Njue Discussing the Connection of Thermocouples to the Tank.

Table B.1 The Rate of Charging Thermal Energy in Sands

Exp. No.	Temperature (°C)	Sand type	Flow Rate (m^3/s)	Thickness (cm)	Charging Rate (°C/min)
1	40	Machakos	0.0004	1.0	1.31
2	40	Mombasa	0.0006	2.0	0.82
3	40	Kisumu	0.0008	3.0	0.66
4	40	Nakuru	0.001	4.0	0.49
5	50	Machakos	0.0006	4.0	0.52
6	50	Mombasa	0.0004	3.0	0.62
7	50	Kisumu	0.001	2.0	1.09
8	50	Nakuru	0.0008	1.0	1.66
9	60	Machakos	0.0008	2.0	1.17
10	60	Mombasa	0.001	1.0	2.36
11	60	Kisumu	0.0004	4.0	0.58
12	60	Nakuru	0.0006	3.0	0.74
13	70	Machakos	0.001	3.0	0.86
14	70	Mombasa	0.0008	4.0	0.75
15	70	Kisumu	0.0006	1.0	2.14
16	70	Nakuru	0.0004	2.0	1.14

Table B.2 The S/N Ratio for Each Experiment

Exp. No.	Temperature (^oC)	Sand Type	Flow Rate (m^3/s)	Thickness (cm)	S/N Ratio
1	40	Machakos	0.0004	1	2.31
2	40	Mombasa	0.0006	2	-1.79
3	40	Kisumu	0.0008	3	-3.65
4	40	Nakuru	0.001	4	-6.21
5	50	Machakos	0.0006	4	-5.70
6	50	Mombasa	0.0004	3	-4.20
7	50	Kisumu	0.001	2	0.71
8	50	Nakuru	0.0008	1	4.37
9	60	Machakos	0.0008	2	1.33
10	60	Mombasa	0.001	1	7.44
11	60	Kisumu	0.0004	4	-4.74
12	60	Nakuru	0.0006	3	-2.65
13	70	Machakos	0.001	3	-1.37
14	70	Mombasa	0.0008	4	-2.57
15	70	Kisumu	0.0006	1	6.54
16	70	Nakuru	0.0004	2	1.11

Table B.3 The Rate of Discharging Thermal Energy in Sands

Exp. No.	Temperature (^oC)	Sand Type	Flow Rate (m^3/s)	Thickness (m)	Discharging Rate ($^oC/min$)
1	40	Machakos	0.0004	0.01	9.45
2	40	Mombasa	0.0006	0.02	3.95
3	40	Kisumu	0.0008	0.03	2.04
4	40	Nakuru	0.001	0.04	2.41
5	50	Machakos	0.0006	0.04	0.77
6	50	Mombasa	0.0004	0.03	1.58
7	50	Kisumu	0.001	0.02	1.62
8	50	Nakuru	0.0008	0.01	2.88
9	60	Machakos	0.0008	0.02	1.84
10	60	Mombasa	0.001	0.01	2.78
11	60	Kisumu	0.0004	0.04	0.94
12	60	Nakuru	0.0006	0.03	1.07
13	70	Machakos	0.001	0.03	1.09
14	70	Mombasa	0.0008	0.04	0.76
15	70	Kisumu	0.0006	0.01	2.93
16	70	Nakuru	0.0004	0.02	1.67

Table B.4 Confirmation Experiment Raw Data on Charging and Discharging of Sand

Sand	T(^oC)	$\dot{\upsilon}$ (m^3/s)	t(cm)	Sample	Tc(^oC)	Td(^oC)	Tco(^oC)	Tac(^oC)	Tad(^oC)
Mombasa	70	0.001	1	1	37.2	70.1	69.8	23.9	25.1
Mombasa	70	0.001	1	1	56.3	63.5	76.3	23.7	25.2
Mombasa	70	0.001	1	1	67.2	57.8	77.7	24	25.6
Mombasa	70	0.001	1	1	71.4	52.9	75.8	24.1	25.2
Mombasa	70	0.001	1	1	72	49	72.5	24	25.3
Mombasa	70	0.001	1	1	71	45.6	71.4	23.9	25.4
Mombasa	70	0.001	1	1	72.5	42.8	74.9	24.5	25.2
Mombasa	70	0.001	1	1	73.6	40.4	73.9	24.8	25.2
Mombasa	70	0.001	1	1	72.8	38.4	71.4	25	24.8
Mombasa	70	0.001	1	1	_	36.6	_	_	24.6
Mombasa	70	0.001	1	1	_	35	_	_	24.6
Mombasa	70	0.001	1	2	31.7	70.1	68.4	25.1	24.3
Mombasa	70	0.001	1	2	47.5	63.6	74.5	25.2	23.7
Mombasa	70	0.001	1	2	59.3	58.6	77.5	25.6	23.3
Mombasa	70	0.001	1	2	66.2	54.1	76.5	25.2	22.8
Mombasa	70	0.001	1	2	69.4	49.9	73.9	25.3	22.7
Mombasa	70	0.001	1	2	69.8	46.5	70.8	25.4	22.5
Mombasa	70	0.001	1	2	70.8	43.5	73.8	25.2	21.8
Mombasa	70	0.001	1	2	71.9	40.8	74	25.2	22
Mombasa	70	0.001	1	2	71.9	38.4	71.9	24.8	22
Mombasa	70	0.001	1	2	71.5	36.3	72.4	24.6	21.8
Mombasa	70	0.001	1	2	72.4	34.6	74	24.6	21.7
Mombasa	70	0.001	1	2	72.4	_	72.2	24.5	_
Mombasa	70	0.001	1	3	33.3	71.3	70.9	24.3	21.5
Mombasa	70	0.001	1	3	51.3	65.8	75.6	23.7	21.8

Mombasa	70	0.001	1	3	61.5	60.3	75.3	23.3	22
Mombasa	70	0.001	1	3	66.1	55.3	73	22.8	22.1
Mombasa	70	0.001	1	3	67.4	50.9	71.1	22.7	22
Mombasa	70	0.001	1	3	67.5	46.9	74.3	22.5	21.7
Mombasa	70	0.001	1	3	71.2	43.7	73.4	21.8	21.6
Mombasa	70	0.001	1	3	71	40.8	71	22	21.3
Mombasa	70	0.001	1	3	71.3	38.4	73.9	22	21.1
Mombasa	70	0.001	1	3	72.3	36.1	73.5	21.8	20.9
Mombasa	70	0.001	1	3	71.8	34.1	71.1	21.7	20.6