Influence of Charging Fluid Temperature, Flow Rate and Sand Layer Thickness on Rate of Charging Sand

George Njuguna Gichichi, Doctor Musa Njue, Professor Joseph T. Mailutha

Abstract— **Solar thermal energy storage technology has made solar energy a potentially viable substitute 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. Factors that influence the rate of charging sand thermal energy storage media have not been adequately investigated. There is no existing information on the rate of charging various types of sand. The research objective was to determine the influence of heat transfer fluid temperature and flow rate on rate of charging different types of sand of different layer thicknesses. Air at different temperatures and flow rates was passed through a thermal energy storage tank containing four types of sand. The Taguchi experimental design approach was used. Result showed that the rate of charging decreases as temperature of charging air increases. The rate increases slightly as flow rate of charging air increases. The rate was inversely proportional to sand layer thickness. The four types of sand showed different rate of charging. The most influential factors on charging rate were sand layer thickness and air temperature which contributed 86.93% and 10.00% of the variation in charging rate respectively. The charging fluid flow rate and type of sand have little influence on charging rate and contributed 2.23% and 0.49% of charging rate variation respectively which is not statistically significant. The study has provided documented information on the influence of charging fluid temperature and flow rate on the charging process of sand media with thermal energy.**

Index Terms— **Charging rate, Sand, solar energy, Thermal energy storage.**

I. INTRODUCTION

Thermal energy storage (TES) is the temporary storage of thermal energy at high or low temperature [1]. Earlier major uses of thermal storage was to maintain dwelling places warm during cold winter nights. The technology of thermal storage has been developed to a point where it has a significant effect on modern life. 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 [2]. 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*. [3] 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 [1].

Kenya lies at the equator and this makes it a good candidate for solar energy applications [4]. Erickson [5] 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. Rabah [6] 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 [1]. Therefore the need for thermal energy storage in the country is inevitable. On the other hand, sand is in abundant supply in most areas of Kenya at very low cost.

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 influence of charging fluid temperature, flow rate and sand layer thickness on rate of charging some types of sands available in Kenya.

II. REVIEW OF THERMAL ENERGY STORAGE

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 [7]. For Kenya to achieve its overall national development objectives which is accelerated

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economic growth, quality energy services is required in a sustainable, cost-effective and affordable manner to the people amongst others. This is currently low and calls for intensified action for the development and use of energy services that are reliable, affordable andreadily available.

According to [8] Kenya receives good all year round solar insolation coupled with moderate to high temperatures. Rabah [6] 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 [6]. The potential for development of standalone solar power system in Kenya is enormous, but there is complete lack of incentive for the development of this benign energy resource.

Garg *et al*. [9] 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 [10]. 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 [11]. 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 [12]. 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 [13]. Mawire and McPherson [14] 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.

Nallusamy *et al.* [3], found that the HTF temperature from a conventional solar air heater can reach a value of 70°C. For a low as well as high temperature thermal energy storage, solid materials such as rocks, metals, concrete, sand, bricks etc. can be used [15]. 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. Garg *et al.* [9] 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.

Adeyanju and Manohar [16] when comparing various types of energy storage techniques found that the various difficulties and limitations such as in handling, containment, storage and cost of phase change materials and liquids thermal energy storage media can be avoided by use of solid materials as sensible heat. 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°C in conjunction with solar air heaters. Alkilani *et al.* [17] 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. The charging and discharging processes are implemented by making the heat transfer fluid (such as air or water) flowing through the granules to exchange the thermal energy.

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 $kJ/m^3\,{}^0C$ (IES, [18]. 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 [16]. Warerkar *et al.* [19] 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.* [20] reported that energy can be stored up to 800°C in sand. The use of sand promises to reduce the costs of energy storage.

III. MATERIALS AND METHODS

A. Study area and materials

The research was conducted at Egerton University, Department of Agricultural Engineering workshops and laboratories. Sand samples were collected from Machakos, Mombasa, Kisumu and Nakuru. Machakos is located at 1°31'S 37°16'E, Mombasa at 04°02'S 39°43'E, Kisumu at 00°03'S 34°45'E and Nakuru at 00°15'S 36°03'E. The locations of these places in Kenya are shown in Fig. 1. The choice of the locations was meant to test whether sands from different places in Kenya would portray different physical properties. Sieve analysis was carried out on the sands. Experiment was set up and data collected. The data was then analyzed. The average prevailing ambient temperatures during experimentation was 23°C.

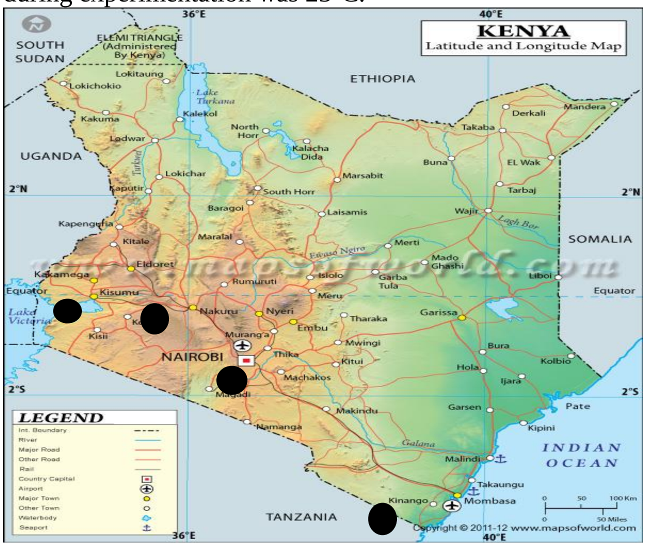


Fig. 1 Map of Kenya Showing the Location of Machakos, Mombasa, Kisumu and Nakuru

B. Experimental Set-up

A schematic diagram of the main experimental set-up is shown in Fig. 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 setting up air flow rate, a compressor to supply the air, an air heater fitted with an electric heating element of 6.5 kW, flow control valve and T-type thermocouples connected to a temperature controller of the on/off type for setting the appropriate temperature. The container for was filled with sand when T- type thermocouples were already placed in position. The other ends of the thermocouples were connected to a data logger. 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.

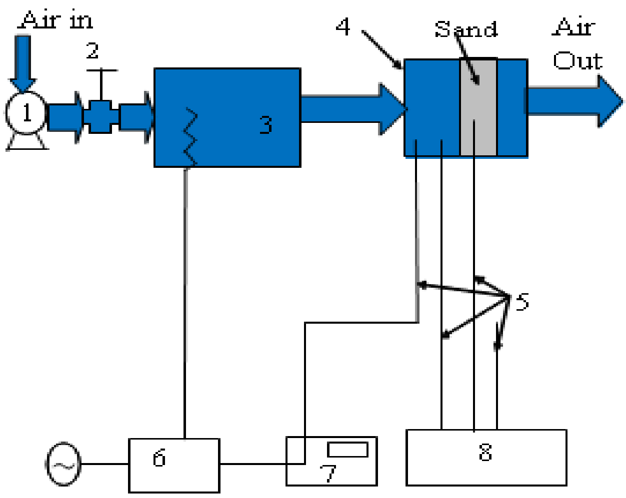


Fig. 2 Experimental Set-up

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

C. The 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°C, 50°C, 60°C, and 70°C. 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 A, B, C and D. Taguchi method of orthogonal arrays was used to get the appropriate 16 experiments as shown in Table I.

Table I**:** The Taguchi Experimental Design

Experiment No.	Temperature (°C)	Sand Type	Flow Rate (m3/S)	Sand Layer Thickness (m)
1	40	A	0.0004	0.01
2	40	B	0.0006	0.02
3	40	C	0.0008	0.03
4	40	D	0.001	0.04
5	50	A	0.0006	0.04
6	50	B	0.0004	0.03
7	50	C	0.001	0.02
8	50	D	0.0008	0.01
9	60	A	0.0008	0.02
10	60	B	0.001	0.01
11	60	C	0.0004	0.04
12	60	D	0.0006	0.03
13	70	A	0.001	0.03
14	70	B	0.0008	0.04
15	70	C	0.0006	0.01
16	70	D	0.0004	0.02

D. Experiments Procedure

The container for holding the sand 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 sand A at a layer thickness of 0.01 m and then placed in the TES tank. The layer thickness of 0.01 m was selected based on the greatest layer of 4 m which would allow air passage through the sand without excessive resistance. It is from this consideration that four levels of sand layer thickness of 0.01m, 0.02 m, 0.03 m and 0.04 m were arrived at. The heat transfer fluid was set to inlet TES tank temperature of 40°C. This was arrived at when the highest possible temperature of 80°C with solar air heaters was considered. This highest temperature was reduced gradually to attain four levels of temperature which are 40°C, 50°C, 60°C and 70°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 of 0.0004 m^3/s. The flow rate was in the range found suitable for similar experiment under literature review. Other levels of flow rates adopted are 0.0006 m^3/s, 0.0008 m^3/s and 0.001 m^3/s. 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 the rise in temperature of sand was 0.2°C 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 fall in temperature fall in sand is 0.2°C or less. The experiment was replicated three times using different samples of the same sand. The second experiment was carried out using sand B at a layer of thickness of 0.02 m with heat transfer fluid at temperature of 40°C and 0.001 m^3/s flow rate. The rest of the experiments were carried out under parameters values as indicated in Table I.

E. Data Analysis

Data analysis was carried out to determine the influence of charging fluid temperature, flow rate and sand layer thickness on rate of charging some types of sands available in Kenya. Analysis of S/N ratio was based on the quality characteristic of the bigger the better. Analysis of variance (ANOVA) was performed on the S/N ratios at α = 0.05. This was to test the level of significance of the factors and also determine the percentage contribution of each to the charging process of sand.

IV. RESULTS AND DISCUSSIONS

A. Influence of Charging Fluid Temperature on the Rate of Charging Sand.

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

Table II: Rate of Charging Sand at Different Temperatures

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

The average rate of charging sand as a function of temperature is shown in Fig. 3. Results from the graph shows that the rate of charging increases as temperature of heat transfer fluid increases.

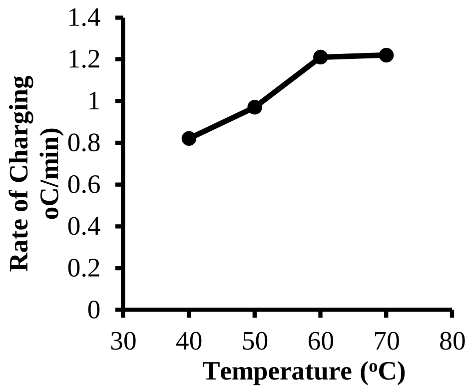


Fig. 3 Rate of Charging Sands at Different Temperatures

B. Influence of the Charging Fluid Flow Rate on the Rate of Charging Sand.

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

Table III: Rate of Charging Sand at Different Flow Rates

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

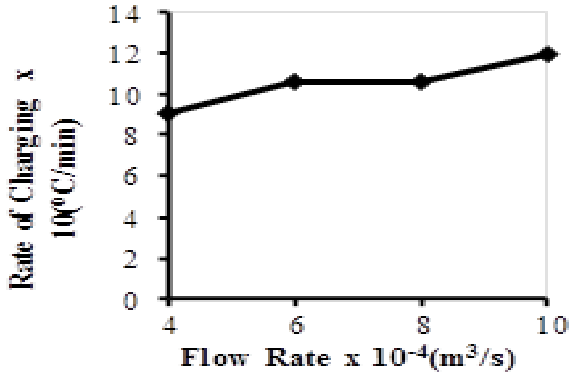


Fig. 4 Rate of Charging Sands at Different Flow Rates.

Fig. 4 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.

C. Influence of the Sand Layer Thickness on the Rate of Charging Sand.

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

Table IV: Rate of Charging Sand at Different Sand Layer Thicknesses

Sand Layer Thickness(m)	Average Rate of Charging (°C/min)
0.01	1.87
0.02	1.06
0.03	0.72
0.04	0.59

Fig. 5 shows the rate of charging sand at different sand layer thickness. It was observed that the rate of charging sand is inversely proportional to the sand layer thickness. Sand at layer thickness of 0.01m showed the highest rate of charging sand at 1.87 °C/min. This could be contributed by 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 is 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 ^{o}C/min.

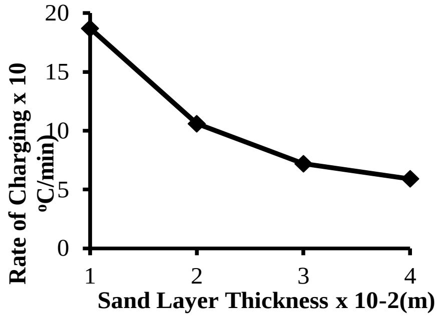


Fig. 5 Rate of Charging Sands at Different Sand Layer Thicknesses.

D. Determination of Rate of Charging Some Types of Sand

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

Table V: Rate of Charging Some Types of Sand.

Types of Sand	Average Rate of Charging (^{o} C/min)
A	0.97
B	1.14
C	1.12
D	1.01

It was observed from Fig. 6 that sand B has the greatest rate of charging at 1.14^{o}C/min. The rate of charging sands B, C and D are 1.12, 1.01 and 0.97^{o} C/min respectively. However the differences in the charging rates are not statistically significant.

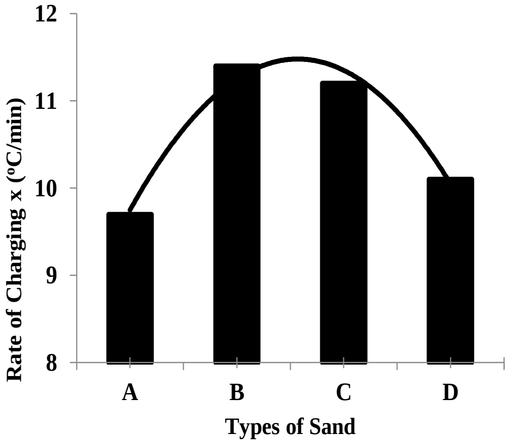


Fig. 6 Rate of Charging Some Types of Sand.

E. Signal to Noise Ratios

S/N ratio represent 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 Eq. (1).

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

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

Where; y_j = charging rate for experiments number j

n = number of samples

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

Table VI. S/N Ratio Values for Sand Charging Rate by Factor Level

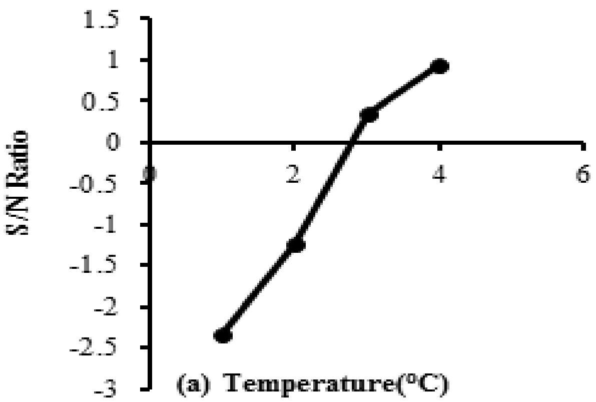
Level	Tempe-rature	Sand Type	Flow Rate	Thick-ness
1	-2.34	-0.86	-1.38	5.17
2	-1.21	-0.28	-0.9	0.34
3	0.35	-0.29	-0.13	-2.97
4	0.93	-0.85	0.14	-4.81
Delta	3.27	0.58	1.52	9.98
Rank	2	4	3	1

According to Taguchi design of experiment, the effect of these factors is then calculated by determining the range represented by delta in the table which is determined by using Eq. (2).

$$\text{Delta} = \text{Max} - \text{Min} \qquad (2)$$

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

The factor S/ N ratios averages at various levels were plotted on graphs (a), (b), (c) and (d) shown in Fig. 7. Results from the graphs show that optimum conditions for the charging process are charging fluid temperature of 70^{0}C, sand type B, sand layer thickness of 0.01m and flow rate of 0.001 m^{3}/s.



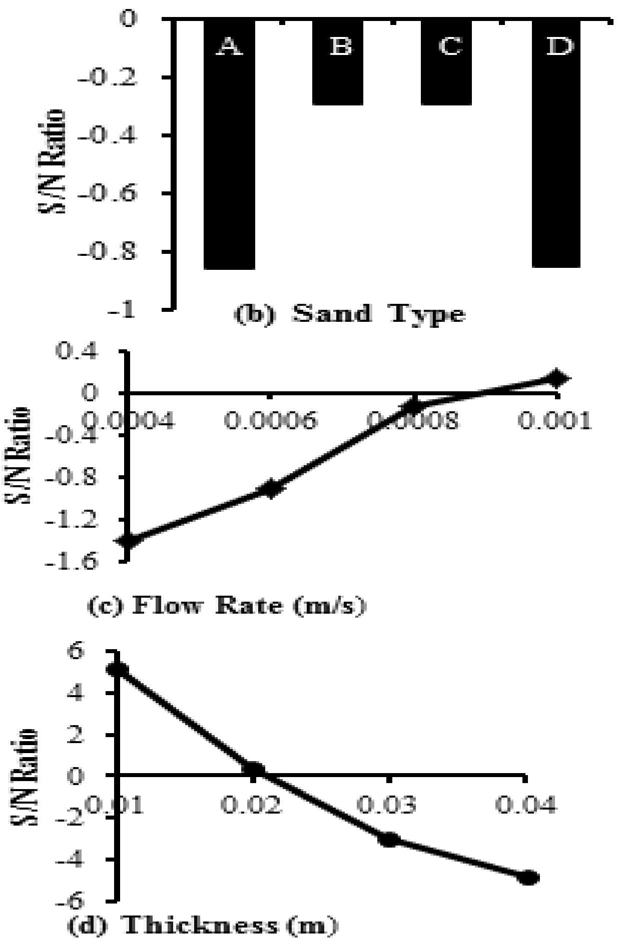


Fig. 7 S/N Ratio Averages for the Four Parameters

F. Analysis of variance

The analysis was carried out to determine exactly how each factor influences the rate of charging sands. The analysis is carried out using Table VII 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 VII: Analysis of variance

Source	DOF	SS	MS	F_{cal}	$F_{crit.}$	% Contri-bution
Tempe-rature	3	26.39	8.8	27.5	9.28	10
Sand Type	3	1.29	0.43	1.34	9.28	0.49
Flow Rate	3	5.87	1.96	6.13	9.28	2.23
Thick-ness	3	229.61	76.54	239.19	9.28	86.93
Error	3	0.96	0.32	-	-	0.36
Total	15	264.12	-	-	-	100

It can be observed from Fig. 8 that thickness (representing amount of sand), temperature, flow rate and sand type contributed 86.93%, 10%, 2.23% and 0.49% respectively on the charging process. Therefore it can be concluded that sand layer thickness and charging fluid temperature are the most influential on the charging rate of sand. Charging fluid 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 charging fluid 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 different physical characteristics.

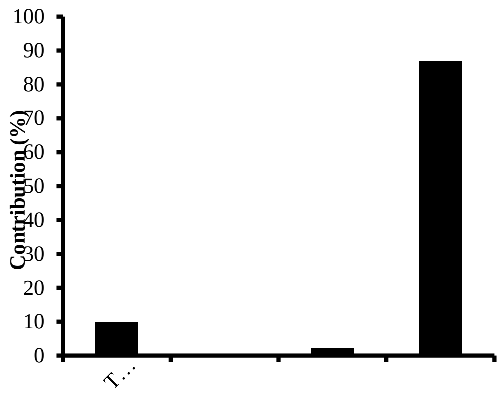


Fig. 8 Contribution of Each Factor

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