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Design and Fabrication of Solar Thermal Battery using Molten Salt

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ABSTRACT

Abundant use of fossil fuels to meet ever increasing global energy requirements has put question marks upon the sustainable future of human beings because of the environmental concerns. Research and development of new and renewable energy resources is mainly focused by researchers in recent decades. Solar Thermal Energy is one of the major technologies esteemed to replace the fossil fuels. Purpose of this research is to design and fabricate solar thermal battery to utilize natural solar resource for generation of electricity instead of fossil fuel. This paper proposes the design and fabrication of Solar Thermal Battery. To achieve the desired objective, the work is divided into two parts. In first part, all the materials regarding Solar Thermal Battery i.e. stainless steel, molten salts, insulation materials, suction creation, temperature and pressure gauges have been analyzed and characterized in detail. Heat storage materials have been experimentally characterized for insulation stability. Sodium Nitrate ($NaNO_3$) and Potassium Nitrate (KNO_3) are described in context of efficiency. In second part, designing and fabrication of Solar Thermal Battery has been discussed in detail. In designing process, stainless steel sheets are rolled and welded through organ welding plant to create vacuum suction. For heat preservation, glass wool, asbestos cloth, polyurethane and fiber glass sheets are found good for insulation. Results for different combinations of molten salts are obtained and discussed. In the end results of battery's charging and discharging time is discussed.

INDEX TERMS— Solar thermal battery, Heat storage capacity, Charging and discharging

1. INTRODUCTION

Recent increase in global warming and other climatic changes has forced us to rethink about our strategy of producing bulk electricity using fossil fuels. It is not a reliable and sustainable because of increasing fuel prices and limited declining supplies. These afore mentioned reasons have compelled to have an effort to effectively utilize other sources of renewable energy. Researchers are having an extensive effort to efficiently exploit the renewable energy sources and also to develop energy storage devices which are dually important. Solar thermal energy has emerged as a reliable source of energy. Sun is a natural and abundant source of thermal energy which can be easily converted into other forms of energy. Production of electricity is one of the bigger uses of this solar thermal energy. Thermal energy is under a lot of research to solve considerable global problems. Presently, more than 90% of sun energy is going to worn out on daily basis.

Earth surface receives electromagnetic radiations emitted by Sun with an average irradiance of 1353 W/m^2 [1-2]. If we are able to harvest this huge amount of energy, there would be enough energy to meet the current energy demand of the world [3]. The challenge to the scientists and researchers is to store this energy in the suitable form, which then can easily be converted into other forms of energy. The reliability and performance of the energy system will improve and reduce the mismatch between demand and supply [4]. There are two basic choices when it comes to solar energy. First is Photovoltaic (PV) and other is Solar Thermal. In PV, energy is directly converted from solar radiation to electricity. In solar thermal system, solar energy is stored in some thermodynamic system and then converted energy into electricity or some other form of energy. Solar thermal is further divided into solar thermal non-electric and solar thermal electric. Solar thermal non-electric includes applications like solar water heater, solar air heater etc. [5]. Solar thermal electric uses solar heat to produce steam and then electricity. This is also known as concentrated solar power (CSP) and four types of CSPs are available in market [6]. Solar thermal energy can be stored using different techniques [7]. Technical options associated with the storage of thermal energy have a wide range [8]. Presently, there is a lot of work carried in a phase change materials. Temperature distribution of a phase change material was achieved by Stritih [9]. Canbazoglu *et al*. [10] calculated the midpoint temperature with sodium thiosulphate pentahydrate. Aghbalou *et al*. [11] works on exegetic optimization of solar thermal system. Paraffin wax was used as PCM by Mettawee and Assassa [12]. Varol *et al*. [13] introduces an efficient method for calculation of useful energy. Arivizu *et al*. [14] studied and addressed issues related with solar energy. Efficiency of solar thermal system is higher compared to the photovoltaic systems. In photovoltaic systems efficiency is between 10 to 20% and it is about 30% for solar thermal system [15-16].

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Purpose of the research is to design and fabricate solar thermal battery. This paper will explains how solar energy is exploited by using solar thermal battery. Solar thermal battery is renewable device that stores heat for longer period of time to derive sterling engine or steam turbine. Salt is used to store heat, in molten form. Heat storage capacity of molten salt is very good as compared to other materials used to store heat.

Using battery to store energy is not new. Batteries fall into two categories, primary batteries and secondary batteries. Primary Batteries, also named as single use or throw-away batteries since these are disposed of when they become empty [17]. Secondary batteries, also named as rechargeable batteries as they can be used again and again after recharging. Solar thermal battery belongs to family of secondary type of batteries.

In this paper solar thermal energy is stored as a change in internal energy of the material. This paper proposes the design and fabrication of Solar Thermal Battery. To achieve the desired objective, the work is divided into two parts. In first part, all the materials regarding Solar Thermal Battery i.e. stainless steel, molten salts, insulation materials, suction creation, temperature and pressure gauges have been analyzed and characterized in detail. Heat storage materials have been experimentally characterized for insulation stability. Sodium Nitrate (NaNO3) and Potassium Nitrate (KNO3) are described in context of efficiency. In second part, designing and fabrication of Solar Thermal Battery has been discussed in detail. In designing process, stainless steel sheets are rolled and welded through organ welding plant so to create vacuum suction. For heat preservation, glass wool, asbestos cloth, polyurethane and fiber glass sheets are found good for insulation. Results for different combinations of molten salts are obtained and discussed. In the end results of battery's charging and discharging time is discussed.

2. PROPOSED MODEL OF SOLAR THERMAL BATTERY

A. Design Basis

Solar thermal battery works on the principle of first law of thermodynamics which states that, the change in system's internal energy is equal to difference of heat added to the system and work done by the system [18].

Mathematically,

$$\Delta U = Q - W \qquad (1)$$

ΔU is the change in internal energy, Q is the heat added to the system and W is the work done by the system. If we are not driving our engine then work done is zero so the internal energy will increase.

B. Detailed Design

Three non-magnetic, stainless steel cylinders of different sizes are used in the design of solar thermal battery. Inner two cylinders are of 4 mm thickness while outer cylinder is 1.5 mm thick. Molten salt is inhaled in the inner cylinder, middle cylinder generates suction and these two are inside the third cylinder. Between the outer and middle cylinder there is an insulating material. Dimension of the cylinders are given in Table I.

TABLE I
Dimension of the Cylinders

Cylinder	Length (m)	Diameter (m)	Radius (m)	Volume (m^3)
	H	D	R	$V = \pi r^2 h$
Inner	0.6096	0.3048	0.1524	0.0445
Middle	0.7112	0.4064	0.2032	0.0914
Outer	0.8636	0.5080	0.2540	0.1750

Stainless-steel sheets are used in the making of cylinders. These sheets are folded into cylinders by rolling machine. Both edges of sheets are joined by organ welding in order to make solar thermal battery water proof. All three cylinders are combined together such that distances between inner to middle and middle to outer cylinders are approximately 0.101 m (3.98 inches). All the cylinders are attached by four supporting rods to each other. Cylinders have their own diameter size lids joined by organ welding. Lids attached to cylinders have holes with their own functional characteristics.

Three different gauges are used in the arrangement. Temperature Gauge, to measure internal temperature of solar thermal battery. It is attached to inner cylinder. Pressure Gauge is used to measure pressure of the molten salt present in the inner cylinder of solar thermal battery. Suction Gauge which is connected to the middle cylinder of battery for pressure reduction measurement. Suction is created through vacuum pump up to -16 psi to increase backup time.

Pipes used in solar thermal battery are of 0.5 inch diameter. Molten salt inlet pipe is connected to the inner cylinder of the battery. Molten salt is inhaled into inner cylinder through this pipe and manually operating valve is connected at its outer side. This inlet pipe opens in the middle cylinder and is connected to the vacuum pump to remove air. It has no-return valve, which connects it to vacuum pump. Pressure Release value is connected to inner cylinder for maintenance of the battery. 32Psi is the set point; beyond this range pressure release valve operates.

Spiral copper pipe is passed through the inner cylinder of the battery. Before entrance of this pipe into the battery no-return valve is fixed so that high pressure steam may not move back. Other side of pipe opens to operate steam turbine or stirling engine. To recharge battery via artificial heat source, two pipes are connected to the battery on the upper and lower side of thermo syphon, linked to the inner cylinder. Hot molten salt flows inside of battery through the upper pipe and cold molten salt comes out through the lower pipe to thermo syphon to complete cycle. Schematic diagrams of the battery are shown in Figures 1 to 4 as following:

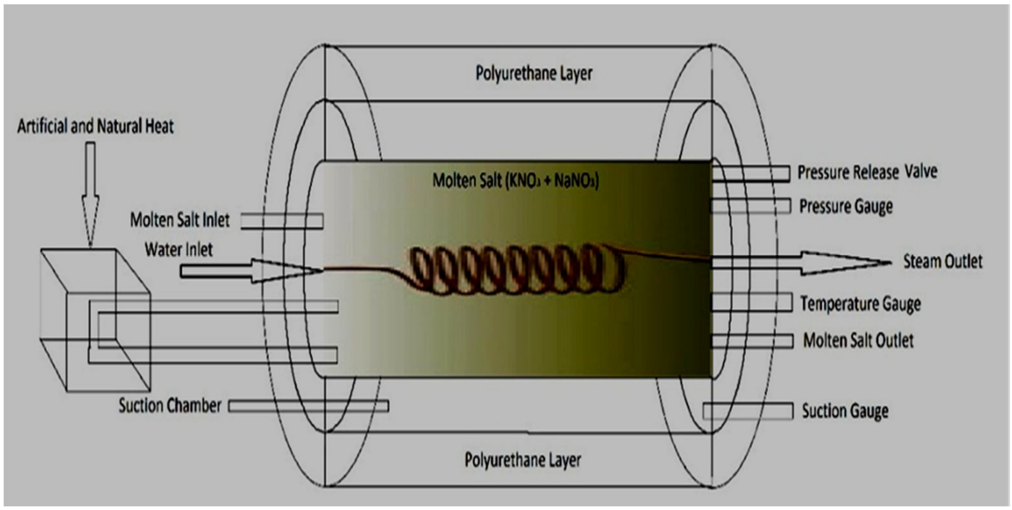

Fig.1. Schematic Diagram of Solar Thermal Battery (Overview)

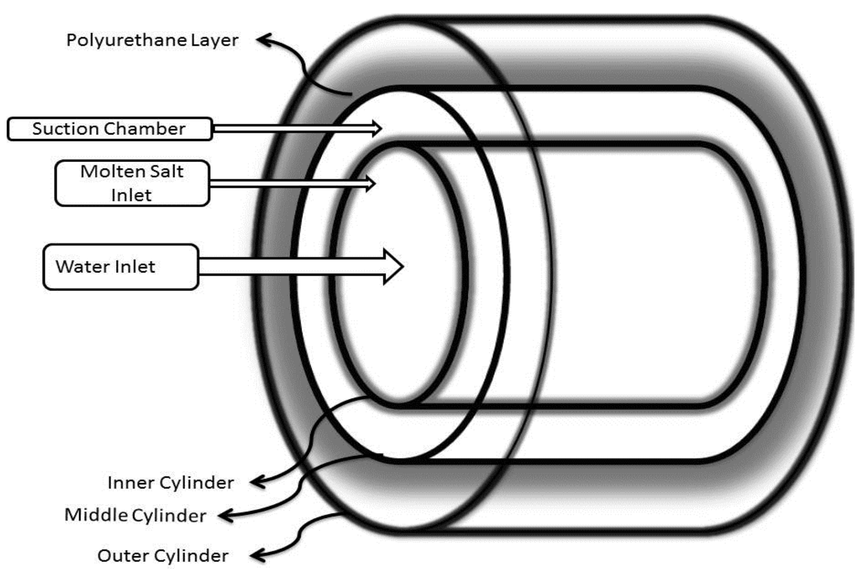

Fig. 2. Conceptual Diagram (Front View)

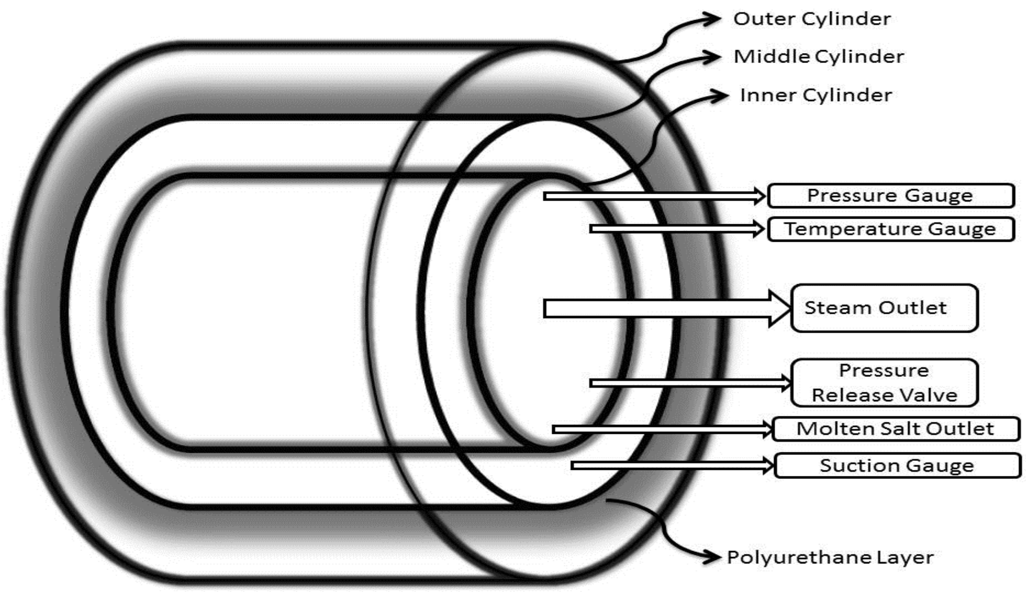

Fig. 3. Conceptual Diagram (Back View)

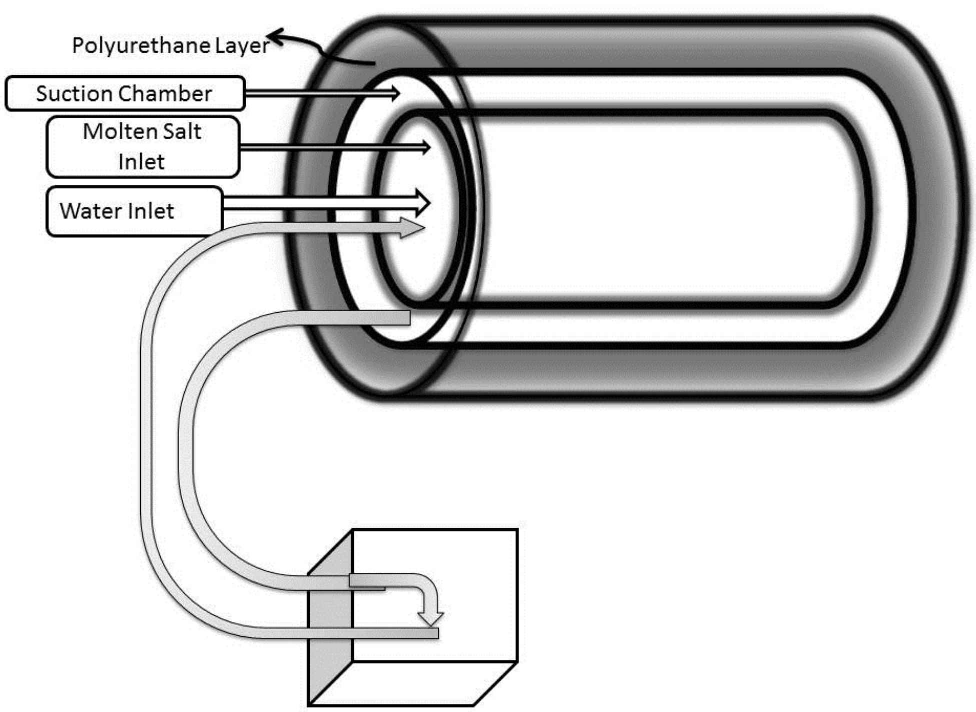

Fig. 4. Battery with Heat Absorber

C. Insulation Layers

Four different types of layers have been used in this battery, which are Asbestos Cloth, Cloth Wool, Ceramic Fiber Glass, Polyurethane. These insulation layers are used to save heat and increase backup time. Dimensions of insulation layers are in Table 2. Asbestos Cloth, it is the outer-most insulation layer covering the outer most cylinder. Cloth Wool, it is the second insulation layer form outside, on outer cylinder. Ceramic Fiber Glass, it is the third insulation layer situated under cloth wool on outer cylinder. Polyurethane, it is the mixture of diiscocyante and diol liquids. This insulation layer is inside of outer cylinder. Battery with insulation layers and gauges is shown in Fig. 5 and complete hardware with artificial heat source is shown in Fig. 6.

TABLE II
Dimension of Insulation Layers

No.	**Insulation Layer**	**Working Temperature (C°)**	**Sheet Width (m)**	**Sheet Length (m)**	**Area (m^2)**	**Volume (m^3)**
1	Asbestos Cloth	480-550	1.600	0.863	1.381	Nil
2	Cloth Wool	Nil	1.524	0.863	1.315	Nil
3	Ceramic Fiber Glass	650	1.524	0.863	1.315	Nil
4	Polyurethane	Nil	Nil	Nil	Nil	0.08356

Fig. 5. Battery with Insulation and Guages

Fig. 6. Battery with Artificial Heat Source

D. Heat Storage Medium

Molten salt is a heat storage material in solar thermal battery. It is a combination of Sodium Nitrate ($NaNO_3$) and Potassium Nitrate (KNO_3). Chemicals are not costly and effortlessly accessible in local markets. Table 3 shows the characteristics of the chemicals. Volume of molten salt is calculated in term of m^3 according to dimensions of inner cylinder as given in Table 1. It is 0.0445m^3 which is nearly equal to 44 kilograms. Ratio of $NaNO_3$ and KNO_3

is 7:4, which means 28 kg and 16 kg of salts are added, respectively. High temperature of salt will give longer time, for this purpose different experiments are performed on the basis of molten salt ratios.

TABLE III
Properties of Salt

Chemicals	M.P (C˚)	B.P (C˚)	Product Code	Flammability	Specific Gravity	pH
$NaNO_3$	308	380	3770	Zero	2.26	Aqueous
KNO_3	333	400	3190	Zero	2.10	7

E. Heat Storage Capacity

Heat storage material is salt. Efficiency of solar thermal battery is directly related to heat storage capacity of used mixture. Heat stored in material is calculated by formula as:

$$Q = V\rho C_p dT \qquad (2)$$

Where, Q is heat stored in material/thermal energy of solar thermal battery (J or BTU), V is the volume of the material (m3), ρ is the density of material (kg/m3), Cp is specific heat capacity of material (J/kgC˚), dT is temperature change (C˚). For solar thermal battery, density of the molten salt is 1000 kg/m3 while Cp and dT are given in Table 4. So by using values of V, ρ, Cp and dT for different ratios of NaNO3 and KNO3, heat storage capacity of molten salt can be calculated.

TABLE IV
Ratios of Molten Salt, Temperature Change and Heat Storage Capacity

No.	$NaNO_3$ (%age)	KNO_3 (%age)	C_p (J/KgK)	M. P. T_1 (C˚)	B. P. T_2(C˚)	$dT=T_2-T_1$ (C˚)	Q=CρCpdT (KWh)
1	40	60	1572	213	450	237	4.60
2	45	55	1560	217	490	273	5.26
3	50	50	1550	223	500	277	5.31
4	55	45	1539	230	525	295	5.61
5	60	40	1529	238	555	317	6.00
6	65	35	1520	242	590	348	6.53

Figure 7 shows graph between percentages of molten salts. It is clear from figure that NaNO3 is increasing and KNO3 is decreasing by ratios.

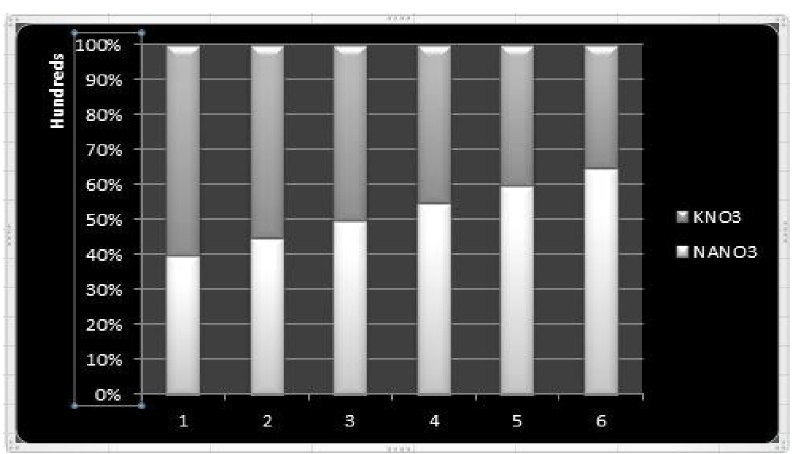

Fig. 7. Graph between Percentages of Molten Salts (NaNO3 and KNO3)

3. RESULTS AND DISCUSSION

Figure 8 shows graph of melting and boiling points for different ratios of molten salts. Melting point of molten salt is between 213C˚ and 242C˚ depending upon the percentage of $NaNO_3$ and KNO_3. Increasing the percentage of $NaNO_3$ in the mixture of salt, its melting point increases. In other words increase in percentage of KNO_3 causes decrease in melting point of mixture. Increase in melting point of mixture states that more heat will be given to battery in start to melt mixture.

Boiling point of molten salt is starting from 450C˚ and is goes up to 590C˚. Increasing the percentage of $NaNO_3$ in the mixture, its boiling point is increasing. Increasing boiling point is favorable for solar thermal battery. But with the increase in boiling point, there is an increase of melting point so more heat will be given to the battery in the start.

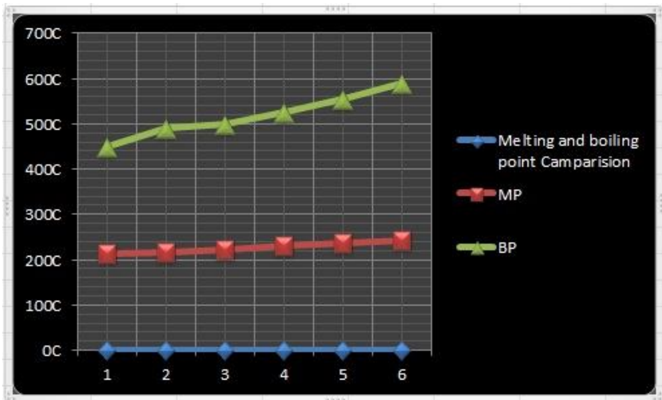

Fig. 8. Graph between Melting and Boiling Points of Molten Salt

A. Change in Temperature and Thermal Energy

Heat storage capacity of mixture increases with the increase in percentage of NaNO3.For 6.53kWh, optimal heat storage capacity is found at 65% NaNO3 and 35% KNO3. This heat storage capacity of mixture is suitable for solar thermal battery and is favorable in order to derive Sterling engine. Figure 9 shows relationship between change in temperature and thermal energy stored by solar thermal battery.

B. Charging and Discharging Time

For ideal batteries, charging duration should be lower as compared to the discharge time. Charging and discharging time depend on molten salt and seasonal conditions.

Charging of solar thermal battery is directly related to the heat supplied. Battery is designed on the principle of renewable and sustainable energy resources. Charging of solar thermal battery depends on charging source. On experimental stage battery was charged by artificial source. But basic source for heat application is solar thermal dish which has capability to grant high temperature within limited time. Charging and discharging time are elaborated in Fig. 10 and Fig. 11 respectively.

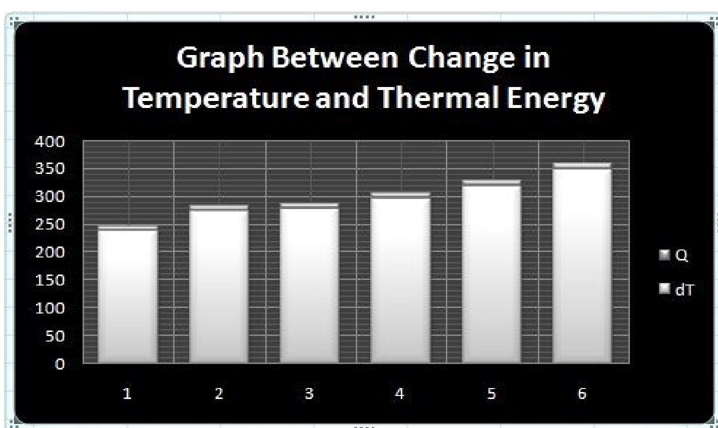

Fig. 9. Graph between Change in Temperature and Thermal Energy

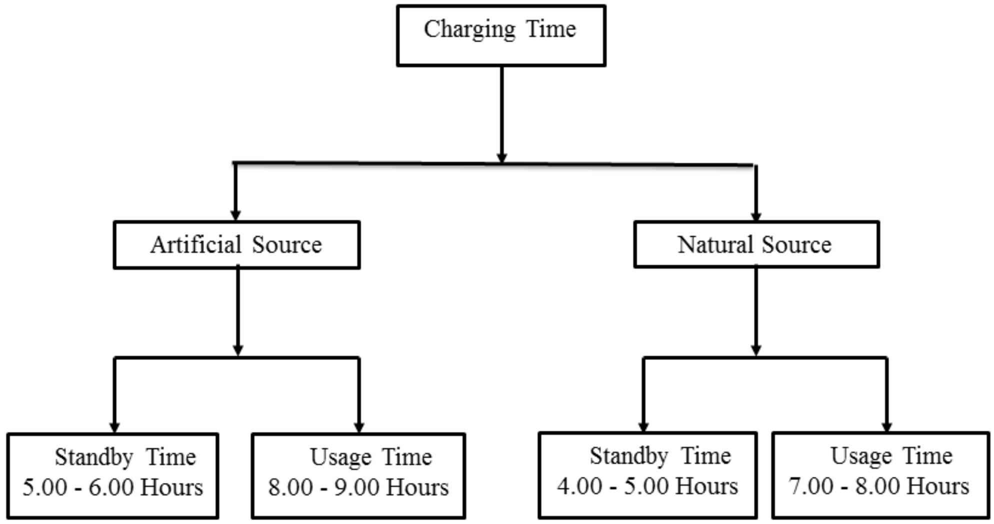

Fig. 10. Charging Time

Efficiency of a battery depends upon the backup time of a battery. Backup time of a battery is dependent on two major factors which are usage time and standby time. Usage Time of solar thermal battery, observed in working condition is nearly 4.00 to 5.00 hours. This time remains same when it is charged via artificial source or natural source. Standby Time is the time when the temperature of 590C˚ has been attained but battery is not in a working condition i.e. water pump is not switched on and no water is flowing through pipe for steam production. Standby time is also declared for sterling engine. This standby time is observed 4.00 to 5.00 days.

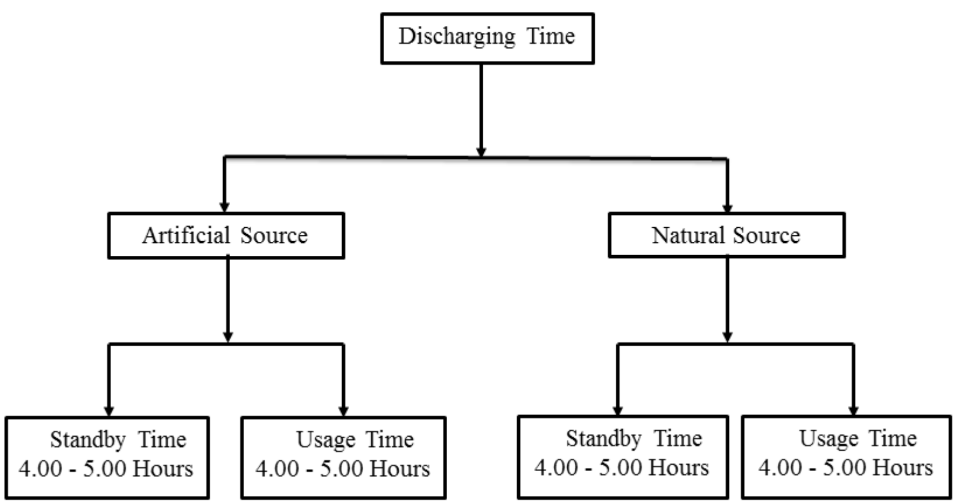

Fig. 11. Discharging Time

4. COST OVER BENEFIT ANALYSIS

$$Benefit\ cost\ ratio = \frac{Total\ benefits\ of\ project}{Total\ cost\ of\ project}$$

Battery life time = 25 years
Average daily load shedding in Pakistan = 5 hours
Sterling engine power = 1 KWh
Power consumption in a day =1x5= 5 KWh

Power consumption in 25 years = 5(365.25)25 = 45656.25 KWh
Current unit cost = 10 Rs
Total unit cost of 25 years = 10(45656.25) = 456562.5
Total cost of project Rs. = 200000/-

$$B.C\ ratio = \frac{456562.5}{200000}$$

$$B.C\ ratio = 2.28$$

If ratio is 1 or more than project cost is recovered in life time of project. If B.C. ratio is 2 cost of project is recovered in half of the life time of project and so on. In this case, cost will be recovered in 11years.

CONCLUSIONS

Solar thermal battery is a novel device for power generation. Device works by converting heat energy into power. This heat energy can also be stored in battery for later use in peak hours. In this paper different material, their combinations and their heat storage properties are studied in detail so to achieve maximum efficiency of Solar Thermal Battery. Best heat storage capacity is found in the mixture of two salts ($NaNO_3$ & KNO_3). It was also found that heat storage capacity of mixture increases with the increase in percentage of $NaNO_3$. For 6.53kWh, optimal heat storage capacity is found at 65% $NaNO_3$ and 35% KNO_3. This battery takes about 7-8 hour to charge while in use. Discharge time was found approximately about 5 hours. Benefit to Cost Ratio is about 2.28 which mean that its cost will be recovered within 11 years.

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