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CONCENTRATED SOLAR THERMAL POWER PLANT WITH MULTI-PCM RESERVOIRS FOR ELECTRICAL POWER GENERATION– AN IDEA

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ABSTRACT: Global warming is one of the most alarming threats to the whole world. A very large quantity of energy source which reaches the earth is solar energy. But the big challenge to scientists and the engineers is to store and convert this energy in the form of thermal or electrical energy. In solar power plants, the energy of the Sun is used to produce electricity. Such a plant can run only in the daytime, but if it is possible to store solar energy then it can also be used at night time. Time-dependence is the major problem of the solar thermal power plant. Thermal energy storage (TES) technology can store energy by using Phase change material (PCM) to overcome this difficulty. One viable option is the use of PCM materials that provide an efficient way of storing such energy. Initially, PCM remains in solid-state; it absorbs heat and melts into the liquid state. At night time, it releases heat and changes back to solid-state. In this work, concentrated solar power (CSP) technology, is used considering its higher efficiency. The use of PCM as latent heat storage is very effective. Three-phase change material reservoirs of different melting points have been used in series. Thermodynamic analysis has been done to find out the optimum mass flow rate of the heat transfer fluid from the low-temperature PCM reservoir. All the processes have been considered ideal.

Keywords: Thermal Energy Storage (TES), CSP plant, Phase change material (PCM), Thermodynamic analysis.

NOMENCLATURE

h= Enthalpy, kJ/kg
S= Entropy, kJ/ kgk
W_T= Turbine work, kJ/kg
$\dot{m}_1$= Mass flow rate of HTF at path 1, kg/s
$\dot{m}_2$= Mass flow rate of HTF at path 2, kg/s
V_3= Volume at 35^OC
$\dot{m}$= Total mass flow rate of HTF, kg/s
P= Pressure, bar
HTF= Heat transfer fluid
W_P= Pump work, kJ/kg
PCM_1= Phase change material 1
PCM_2 = Phase change material 2
PCM_3= Phase change material 3
LH_1= Latent heat of PCM1, kJ/kg
LH_2= Latent heat of PCM2, kJ/kg
Q_1= Heat transfer rate, kJ/kg
s= Specific heat of HTF, kJ/kgK

1. INTRODUCTION

Primarily energy is obtained in two forms that are renewable and non-renewable energy sources. Major environmental problems occur due to the use of traditional energy sources like natural gas, coal, petroleum, etc. Various type of advantage for using non-conventional energy sources like wind, solar and small hydro. From a historical point of view, solar energy is very old. Different researches are going on from 7th century BC till today.

Electricity generation by using solar energy is getting more attention from the last few decades. Solar power plant technology is an eco-friendly technology, so this technology is called by green technology. Solar power is used in two ways such as photovoltaic and solar thermal power plants. In this paper, the solar thermal power plant is used to generate electricity with the help of phase change material (PCM).

The Energy sector plays a very important role in an economic development country like India. This paper discusses the use of a multi-phase change material reservoir in series. All the processes have been considered ideal. A mathematical analysis has been done to find the optimum mass flow rate of the heat transfer fluid through the charging and discharging circuits.

Fig. 1 typically shows the classification system of different types of solar thermal power generation systems.

2. BASIC WORKING PRINCIPLE

- Sunlight is reflected by the mirror to the receiver.
- Receiver concentrates the solar energy and converts it into heat energy.
- After that, a generator is used to produce electricity from the heat energy.

The CSP can be classified as:

2.1 Parabolic Trough System (Fig. 2)
2.2 Power Tower System (Fig. 3)
2.3 Linear Fresnel System (Fig. 4)
2.4 Parabolic Dish System (Fig. 5)

2.1 Parabolic Trough System

The heat-collection element (HCE) that receives the sun radiation is mounted at the

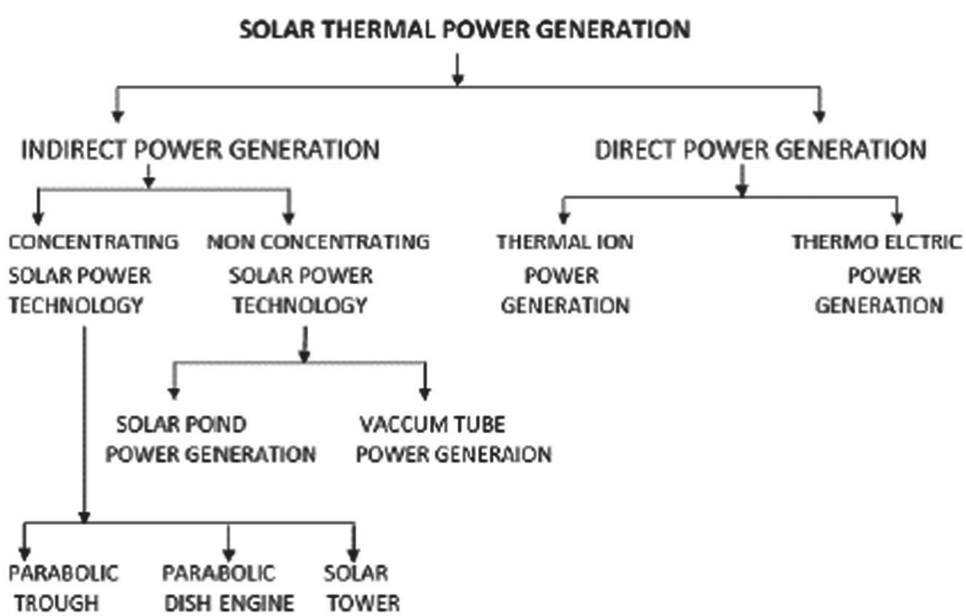

Fig. 1: Classification of Solar thermal power generation

top of the reflector as a focal line which receives the reflected radiation by long rows of parabolic reflectors. In this case, the sun is tracked around the north-south axis. The HCE involves an internal steel tube covered from outside by a solar surface and an external glass pipe, with a vacuum between them. Through the steel pipe and HTF are circulated. A heat exchanger is used for producing steam to be used to utilize it in the steam turbine by using the hot fluid from various rows of troughs [1, 2].

2.2 Power Tower System

Central Receiver Collectors, which have a point-focus receiver, produce higher temperatures compared to troughs and linear Fresnel reflectors. They achieve temperatures from 800 ºC to well over 1000 ºC by concentrating the sunlight 600-1000 times [1]. Solar tower technology uses a group of mirrors, where the sun is tracked by each mirror and the light is reflected on a static receiver on the top of a tower. Central receivers have been used to generate temperatures to power steam and gas turbines [1].

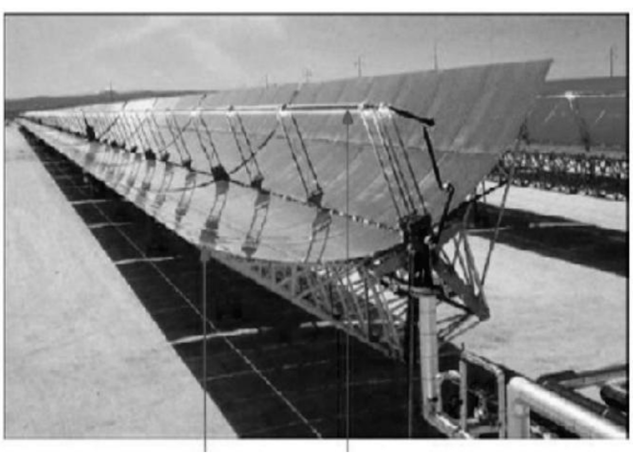

Fig. 2: Parabolic Trough System

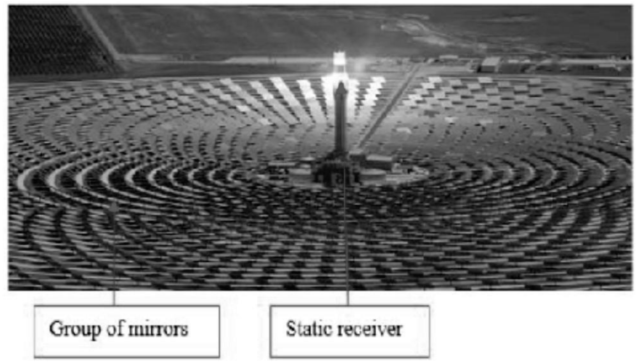

Fig. 3: Power Tower System

2.3 Linear Fresnel System

Linear Fresnel reflectors for CSP technology perform in a similar way to the parabolic trough collector system [5]. Long arrays of flat mirrors integrate linear Fresnel reflectors to concentrate the sun light onto a linear receiver. The receiver which is typically 10-15m tall is mounted on a tower. The mirrors can be suspended on one or two-axis tracking systems. Comparing to the parabolic trough collector, numerous Fresnel reflectors can be used with the benefit that the receiver is a separate component, and a tracking system is not necessary. Simpler, accurate and more efficient tracking can be made in this design. The HTF flows through the receiver, it then collects thermal energy and transfers it to the power block [5].

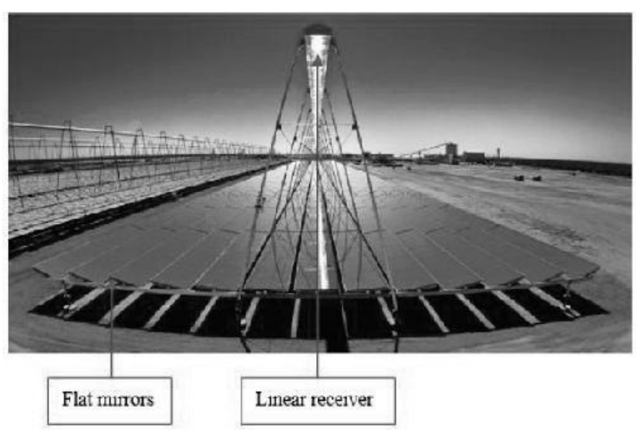

Fig. 4: Linear Fresnel System [4]

2.4 Parabolic Dish System

The dish system is suitable for applications requiring high temperatures because it is an ideal optical reflector. Dish systems are parabolic shaped and the receiver is fixed at the focal point, with the receiver moving with the dish. A dish system has the highest optical efficiency of all CSP types because the full aperture is directed towards the sun avoiding the cosine loss effect [4]. Table 1 shows the operating temperatures, tracking type, and typical power block size for available concentrating solar thermal power technologies.

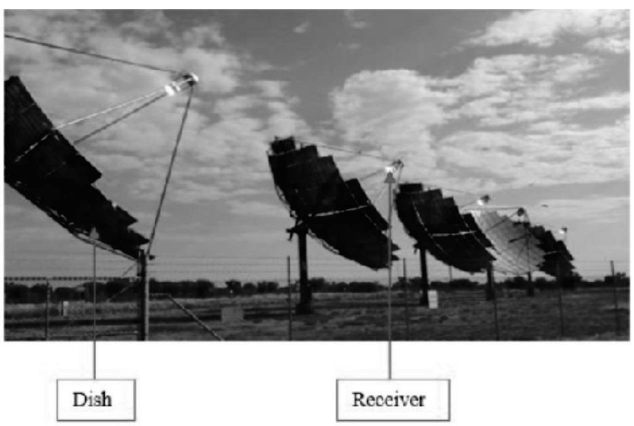

Fig. 5: Dish system

Table 1: Operating temperature, tracking, and average power block size for each type of concentrating solar thermal power technologies [4, 6]

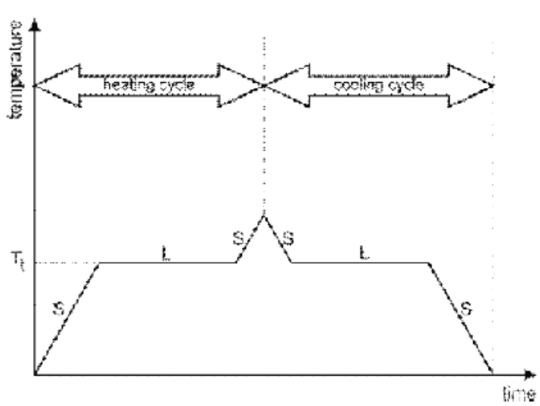

Fig. 6: Schematic heat curve for Phase change material; S-Sensible heat, L-latent heat

3. PHASE CHANGE MATERIAL

Phase change materials (PCM) provide an efficient way of storing energy. Initially, being in a solid-state, they absorb heat energy and melt into the liquid state. At night, PCM releases the heat during its freezing and transforms into solid-state again. According to the type of material, Fig. 6 depicts heat curve in temperature vs. time plane. PCM is used as heat storage material is a good solution. One of the most popular ways to store heat energy is latent heat system. PCM is used because it has two-fold advantages. One is high storage capacity and another is the low-temperature difference. Fig. 7 shows the different types of phase changes of PCMs according to their changes from one state to nowadays in engineering, thermal energy storage design using metallic PCMs is very challenging. It has high density and low specific heat which is unsuitable. Jankowski et al. reviewed and opined [7] that the use of high-temperature phase change material had been increasing.

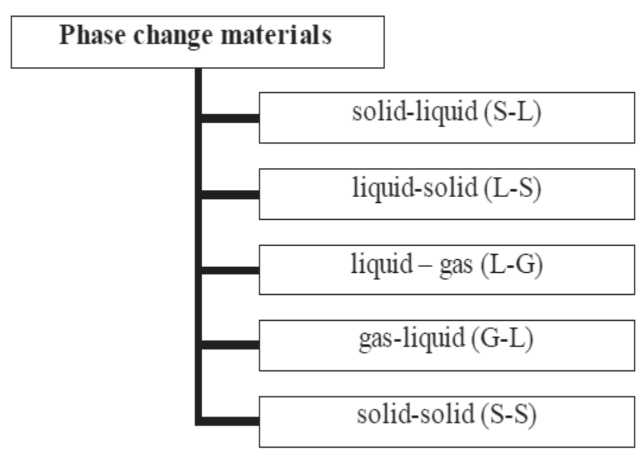

Fig. 7: Classification of PCMs – the type Transformation

Atkin and Farid [8] did research on graphite-based PCM used into heat a sink. It is observed that it can be effective for PV solar plants. By this application, the result shows that it is an improved technique for storing heat. On the other hand, Roman et al. worked [9] on compare of two different techniques. Two different roofs and PCMs were collected in the USA. Fig. 6 shows graphically of various PCMs at the different heat zone level. The Author gives some pointers on that technology for future generations. Fukahori et al. [10] described various encapsulated PCM with their higher corrosive resistance and very good performance enhanced material. Schematic diagram of a typical solar thermal power plant (STPP) layout is shown in Fig. 8.

Table 1: Operating temperature, tracking, and average power block size for each type of concentrating solar thermal power technologies

Technology	Operating temperatures solar concentrations (ºC)	Tracking	Average power block size
Parabolic Trough	150-400	Linear	143 (MW)
Central Receiver Tower	300-1200	Point	62 (MW)
Linear Fresnel	150-400	Linear	22 (MW)
Parabolic Dish	300-1500	Point	1 (MW)

Table 2: Specification of PCM used in this Paper

PCM	Melting Temperature, ºC	Latent heat of melting, kJ/kg	Specific Heat, kJ/kgK
Sodium Chloride (95.2%) + Nickel Chloride (4.8%)	573	558	1.80
Magnesium Chloride (37%) + Strontium Chloride (63%)	535	239	0.8
Magnesium (60%) + Copper (25%) + Zink (15%)	452	354	1.3

4. DESIGN & METHODOLOGY

This work is based on **1MW** electrical output. The height temperature of steam used in Rankine Cycle is 510^0C.

At that temperature, Enthalpy (h_1) = 3326.1 kJ/kg [The value of h1 is taken from Steam table]. And corresponding value of Entropy (S_1) = 6.3426 kJ/kgK.

$S_1 = S_2, S_2 = Sf_3 + X^*Sf_g$ (1)

$X = \frac{S_2 - Sf_3}{Sf_g} = \frac{6.3426-0.5049}{7.8494} = \frac{5.8377}{7.8494} = 74\%$

$h_2 = hf_3 + X^* hf_g$ (2)

$h_2 = 146.56 + 0.74 (2418.8) = 1936.47$ kJ/kg

Turbine work, $W_T = h_1 - h_2 = 3326.1 - 1936.47 = 1389.63$ kJ/kg

Again Pump work $W_p = V_3 * (P_4 - P_3)$ (V_3 at 35^0C is 0.001 m^3/kg) [Data taken from steam table]

= 0.001(16000000 – 56216)
= 15943.784 J/kg [Pressure at 35^0C is 0.056216 bar = 56216 Pa]
≈ 16 kJ/kg

h_3 = 146.56 kJ/kg, $h_4 = h_3 + W_P$ = 146.56 + 16 = 162.56 kJ/kg

For 1 MW electrical produced,
$\dot{m} = \frac{10^6}{W_T - W_P} = \frac{10^3 \text{kJ/s}}{1389.63-16} = 0.728$ kg/s is the water mass flow rate.

$Q_1 = h_1 - h_2 = 3326.1 - 162.56 = 3163.54$ kJ/kg

Total heat added in boiler = 0.728 * 3163.54 = 2303.06 kJ/s

$Q1 = \dot{m}_1 * (610 - 460) * S$ (3)

$2303.06 = \dot{m}_1 (610 - 460) * 1.89$
or, $\dot{m}_1$ = 8.70 kg/s, this is the mass flow rate of heat transfer fluid (HTF) in Path 1.

For 12 hrs, heat required to be added in the heat exchanger

$Q_1 * 12 * 3600$ kJ = 2303.06 * 12 * 3600 = 99492192 kJ (4)

Total mass of phase change material (PCM) to be melted

$PCM_1 * LH_1 + PCM_2 * LH_2 + PCM_3 * LH_3$ = 99492192 kJ (5)

After that 3 equations are got,

$12 * 3600 * \dot{m}_1 * S (610-580) = PCM_1 * LH_1$ (6)
$12 * 3600 * \dot{m}_2 * S (580-545) = PCM_2 * LH_2$ (7)
$12 * 3600 * \dot{m}_3 * S (545-460) = PCM_3 * LH_3$ (8)

Now, dividing equation (6) by equation (7),

one gets, $\frac{PCM1*LH1}{PCM2*LH2} = \frac{610-580}{580-545} = \frac{PCM_1*558}{PCM_2*239} = \frac{30}{35}$

$35PCM_1 * 19530 = 30PCM_2 * 7170$ or, $PCM_2 = 3.178PCM_1$ (9)

Again dividing equation (7) by equation (8),

one gets, $\frac{PCM2*LH2}{PCM3*LH3} = \frac{580-545}{545-460} = \frac{239\,PCM2}{354\,PCM3} = \frac{35}{85}$

$20315PCM_2 = 12390\ PCM_3$ or, $PCM_2 = 0.61PCM_3$ (10)

Putting the value of PCM_2 in equation (10), one may get, $PCM_3 = 5.2098PCM_1$ (11)

Putting the value of PCM_2 & PCM_3 in equation (5), one gets,

$(PCM_1 * 558) + (3.178PCM_1 * 239) + (5.2098PCM_1 * 354) = 99492192$

$3161.81\ PCM_1 = 99492192$ or, PCM_1 = 31466.84 kg

Again putting the value of PCM_1 and PCM_3 in equation (5), one may get,

$(31466.84 * 558) + 239PCM_2 + (5.2098PCM_1 * 354) = 99492192$

$239\ PCM_2 = 23900371.45$ or, PCM_2 = 100001.554 kg

Again putting the value of PCM_1 and PCM_2 in equation (5), one gets,

17558496.72 + (100001.554 * 239) + 354 PCM_3 = 99492192

354PCM_3 = 58033323.87 or, PCM_3 = 163935.943 kg

Now, calculated the rate of melting mass Of phase change materials, PCM_1, PCM_2 and PCM_3, as under expressed in kg/s.

$\dot{m}PCM_1 = \frac{31466.84}{12*3600}$ = 0.73 kg/s

$\dot{m}PCM_2 = \frac{100001.554}{12*3600}$ = 2.31 kg/s

$\dot{m}PCM_3 = \frac{163935.9431}{12*3600}$ = 3.80 kg/s

Now, found out mass flow rate ($\dot{m}_2$) in path 2 as under.

$$\dot{m}_2 * S * (610 - 460) = \dot{m}PCM_1 * LH_1 + \dot{m}PCM_2 * LH_2 + \dot{m}PCM_3 * LH_3 \quad (12)$$

$\dot{m}_2$ * 1.89 * 150 = (0.73 * 558) + (2.31 * 239) + (3.80 * 354)
$\dot{m}_2$ = 8.13 kg/s

Total mass flow rate, $\dot{m} = \dot{m}_1 + \dot{m}_2$ = 8.70 + 8.13 = 16.83 kg/s

So, Plant Efficiency (□) = $\frac{(h_1 - h_4) - (h_2 - h_3)}{(h_1 - h_4)}$ = $\frac{(3226.1 - 162.56) - (1936.47 - 146.56)}{(3226.1 - 162.56)}$ = 42%

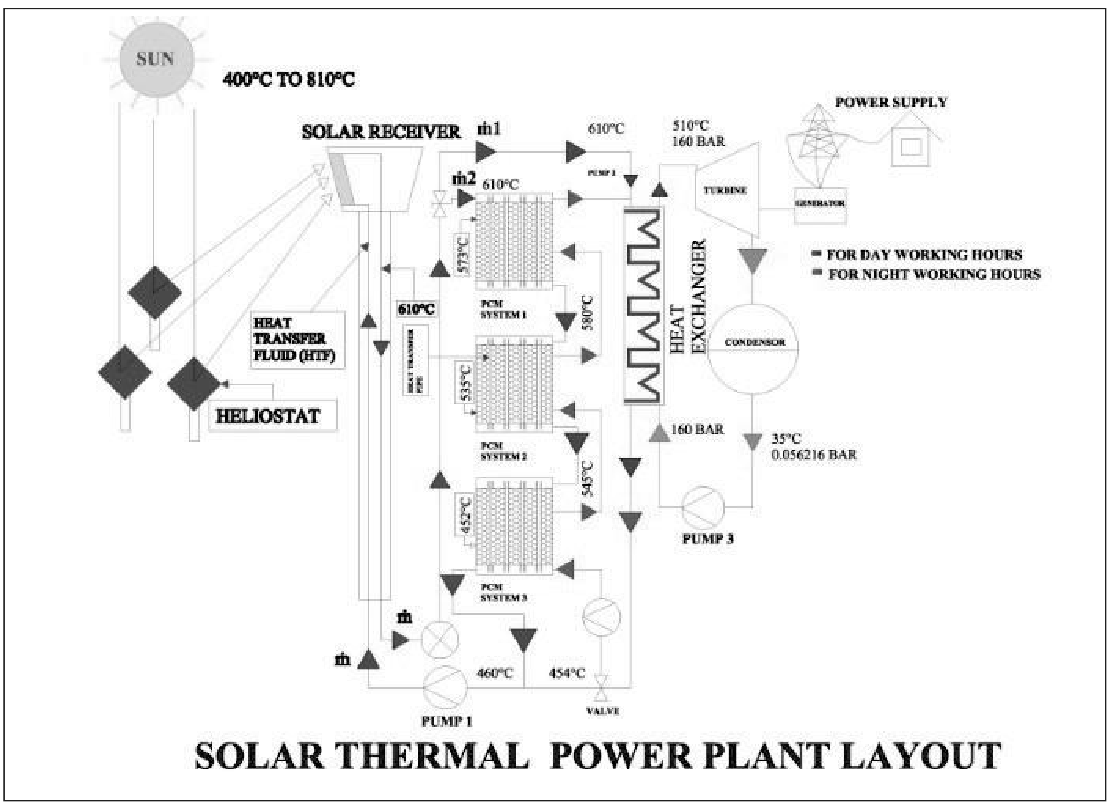

Fig. 8: Schematic diagram of STPP

5. RESULTS AND DISCUSSION

Power output is strongly dependent upon the outlet temperature of heat transfer fluid. Plot of heat input with temperature is shown in Fig. 9. Net power output from a solar power plant with three Phase change material (PCM) reservoirs shows a downward trend when outlet temperature of Heat transfer fluid (HTF) increases. This graph shows that five different outlet temperatures have their different power output. It also shows the optimum outlet temperature of heat transfer fluid. Again, power output variation with the corresponding heat input can be seen from Fig. 10. Naturally, with the increase in heat input, power out also increases.

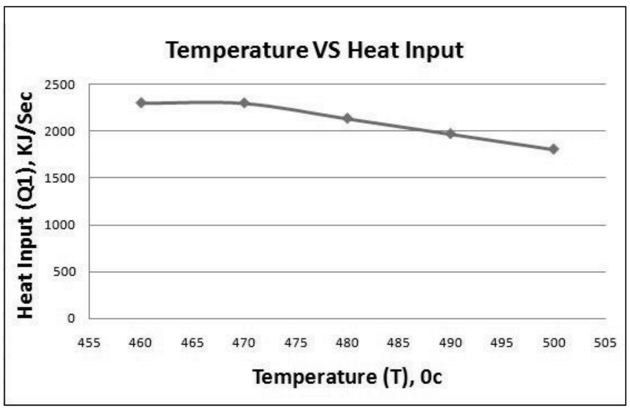

Fig. 9: Plot of heat input with temperature

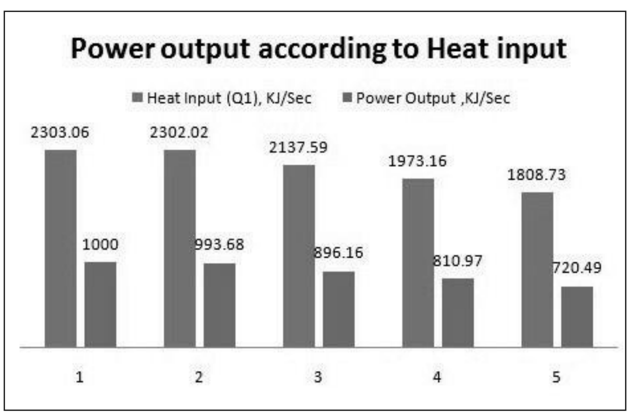

Fig. 10: Power output variation with Heat input

6. CONCLUSION

The main challenge in solar thermal power plant is its availability of solar energy, which is time dependence. In this work three reservoir of difference phase change materials have been used, so that the power production becomes uninterrupted. The three-Phase change materials are selected in such a way that they are arranged in order according to their melting point. It clearly increases the availability of the system by reducing irreversibility due to a large temperature difference between the working fluid and Phase change material. Thermodynamic analysis has been done to find out optimum operating condition and dependence of power production on the temperature of working fluid.

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