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Solar Thermal power Plant with Double PCM reservoirs for Uninterrupted Power Production

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Abstract: Concentrated Solar Power (CSP) is mostly used as heat reservoir in case of solar thermal power plants. Day by day use of solar power is becoming more and more popular as a green energy source. Nevertheless, it has a great disadvantage of time dependence. Various options have been tried over the past few decades, to overcome this difficulty. The researchers have tried two types of heat storage. These are sensible heat storage and latent heat storage. This work is based on latent heat storage by phase change material (PCM). Two types of PCM reservoirs have been used in series in this work. Irreversibility of the system is reduced due to these two PCM reservoirs at two different temperatures. All processes have been considered as ideal. Various process parameters have been calculated for the total plant with fixed designed value of power plant capacity.

Keywords - Phase Change Material (PCM), Solar thermal Storage, Heat transfer Fluid (HTF), Concentrating Solar plant (CSP), Latent heat storage (LHS), Sensible heat Storage (SHS).

Nomenclature:

h = Enthalpy KJ /Kg	P = Pressure	PCM_1 = Phase Change Material $_1$
S = Entropy KJ / Kg	$\dot{m}$ = Mass flow rate of heat transfer fluid KJ / Sec	PCM_2 = Phase Change Material $_2$
W_T = Turbine work	$\dot{m}_1$ = Mass flow rate of HTF at path 1	LH_1 = Latent heat of Phase Change Material $_1$
W_P = Pump Work	$\dot{m}_2$ = Mass flow rate of HTF at path 2	LH_2 = Latent Heat of Phase Change Material 2
V_3 = Volume at $40^o{}_C$	Q_1 = Heat transfer rate KJ / Kg	S = Specific heat of Heat transfer fluid

I. INTRODUCTION

For last few years, energy demand has been exponentially increasing. However, because of emissions of greenhouse gases and pollutants, use of fossil fuel is restricted and discouraged throughout the world. As a result, use of renewable sources is being encouraged by scientific community as well as by government. The inter government panel on climate change (IPCC) report shows that human plays a significant role on climate change, due to CO_2 emissions from energy consumption[1]. Reduction of CO_2 emission is necessary within next few years. More use of renewable energy sources and energy efficient systems are main target to reduce CO_2 emission. A detailed description of these gaseous and particulate pollutants and their impacts on the environment and human life is presented by Dincer [2,3]. Solar Thermal energy source is the most promising green energy source in tropical country like India. Nevertheless, it has major disadvantage of time dependence. Today, one of the main factors that must be considered is energy and one of the most important issues is the requirement for a supply of energy that is fully sustainable [4, 5]. Storing of Solar thermal energy for use in the night time is a major challenge to the researchers. Phase change Material (PCM) is considered one of the viable alternatives to solve this problem. There are various types of PCM with different characteristics such as- melting point, amount of latent heat, phase in room temperature, specific gravity, heat conductivity, etc. In this work, we have designed one solar thermal Power Plant of capacity 1 MW in ideal condition, which can run 24 hours in a day. Two PCM have been used in series, to store the solar thermal energy to be used for the night. Furthermore, governmental policies concerning energy and developments in the world energy markets will certainly play a key role in the future level and pattern of energy production and consumption [6]. Renewable energy systems can have a beneficial impact on the environmental, economic, and political issues of the world. At the end of 2001, the total installed capacity of renewable energy systems was

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equivalent to 9% of the total electricity generation [7]. By applying a renewable energy intensive scenario the global consumption of renewable sources by 2050 would reach 318 exajoules [8].

II. THERMAL STORAGE

A solar thermal power plant has four elements: solar field heat transfer fluid (HTF), thermal storage System and at last power generation system (fig. 1).

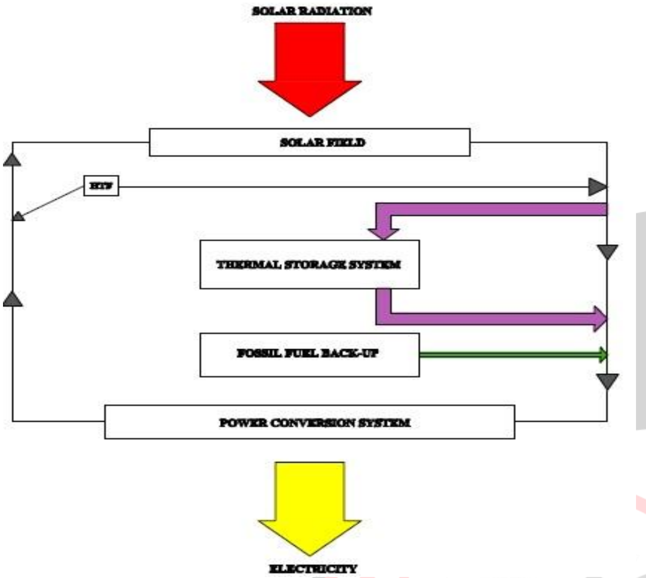

Fig 1. Elements of solar thermal power plant

In some plants, back up arrangement of supplementary fuel is also used for meeting the demand of primary energy source when required. The thermal storage system is used to store energy for night and/or cloudy days to enhance plant performance. Solar energy is available only during the day that is why thermal storage application is very important. Generally, thermal storage system is of two types. One is active storage system and other one is passive storage system. In active storage System heat transfer occurs between the system and the heat source. Therefore, this system is characterised by forced convection heat transfer. In passive storage system heat transfer occurs between the system and heat source by natural convection without assistance of any external devices [9]. Active storage systems can be divided into direct and indirect systems. In the direct systems, the heat transfer fluid (HTF) is used also as storage medium, while in the indirect systems, a second medium is used for storing the heat [10].Thermal energy can basically be classified according to the way heat is stored: such as sensible heat, latent heat or chemical energy.

Sensible heat is related to changes in temperature of a medium with no change in phase. Moreover, latent heat is related to change in phase between liquid, gas and solid.

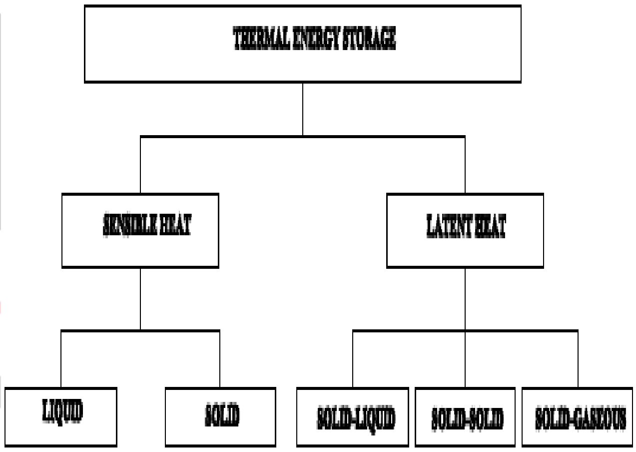

Fig. 2 Methods of thermal energy storage

III. PHASE CHANGE MATERIALS

Phase change material is a material that changes its phase at constant temperature while storing or releasing heat. This is very useful property in case of power generation.

The PCM acts as constant temperature heat source and hence an improved efficiency can be obtained from a power plant, using this type of heat source. PCM has gained more attention in recent few years because of its high-density energy storage at a constant temperature. The PCM to be used in the design of thermal-storage systems requires desirable thermo-physical, kinetics, chemical and economical properties [11] [12] [13]. Thus, generally, a material is not able to achieve all these requirements.

Figure 3.shows common classes of PCM related with the melting enthalpy and the melting temperature [12].

One option to decrease the storage cost is to optimize the temperature difference between the charging / discharging water and the PCM. These points should be further investigated in future simulations studies [14]. An important possibility is the implementation of PCMs. However, these materials possess a low thermal conductivity, so it is needed a strong research in the development of techniques and systems which could increase the capacity of PCMs to storage solar energy [15].

Phase change materials are used for storing energy in latent heat storage system due to their good thermo physical properties and reduced storage volumes compare to sensible heat storage systems [16, 17].

Researchers have been conducting and testing with many PCMs in different ways into a TES system. Gil et al. have chosen hydroquinone as PCM for medium.

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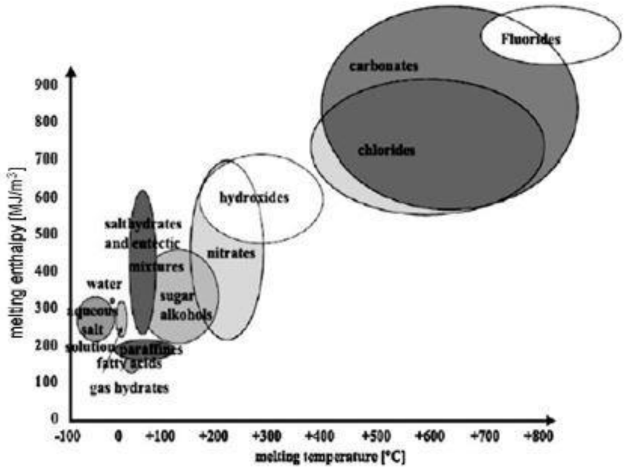
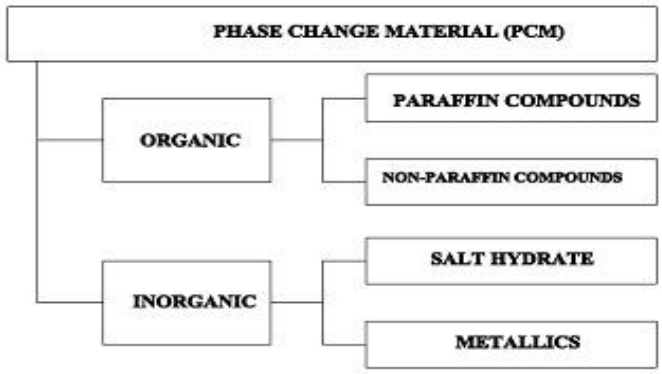


Fig.3 Classes of PCM related with melting enthalpy and melting temperature [12]

Temperature range for storing the energy in a Shell and Tube heat exchanger and tested with and without fins [18]. Schreiber et al., have investigated on adsorption thermal energy storage systems for the energy storage density and obtained higher efficiencies during charging and discharging for higher temperature ranges [19].



Esapour et al., have conducted tests on a multi-tube heat exchanger with water as HTF and RT35 as the PCM [20].

Faegh et al., have done experimental investigation on solar energy storage using PCM. In this test, there is no direct contact between the HTF and the PCM. The energy is transferring to PCM through condenser. The results showed that the yield increased by 86% as compared to the system without PCM and an increased efficiency of 50% [21].

Medrano et al., have done investigation experimentally the heat transfer process during melting (charge) and solidification (discharge) of five small heat exchangers working as latent heat thermal storage systems. Commercial paraffin RT35 is used as PCM. Results show that the double pipe heat exchanger with the PCM embedded in a graphite matrix is the one with higher values and the compact heat exchanger is the one with the highest average thermal power [22].

Regin et al., have conducted a numerical analysis of thermal storage system where Paraffin as a Phase change material. They concluded that the solidification time is too long due to low heat transfer coefficient, phase transition temperatures reduces the melting time and charging and discharging are higher for small radius capsules than larger capsules [23]. Jesumathy et al., designed an energy storage system to study the heat transfer characteristics of paraffin wax during melting and solidification processes in a vertical annulus energy storage system. The experimental results proved that the PCM melts and solidifies congruently, and the melting front moved from the top to the bottom of the PCM container whereas the solidification front moved from bottom to the top along the axial distances in the PCM container [24]. Many researchers have concentrated on paraffin wax and Palmitic acid, tested in different heat exchangers. Paraffin and Palmitic acid eutectic mixture have been chosen and tested in Spherical storage unit [25].

Phase Change Material (PCM) is mainly classified in two groups: Organic and inorganic compound. Organic compound PCM has more advantage over inorganic compound PCM. It has relatively low melting point which is not compatible to a power plant using steam as working fluid. But their non-corrosive behaviour makes them suitable for use in containers of different materials. On the other hand inorganic PCM compounds show a volumetric latent thermal energy storage capacity relatively larger than that of organic compounds. PCM materials can be divided in two groups as in figure 4.

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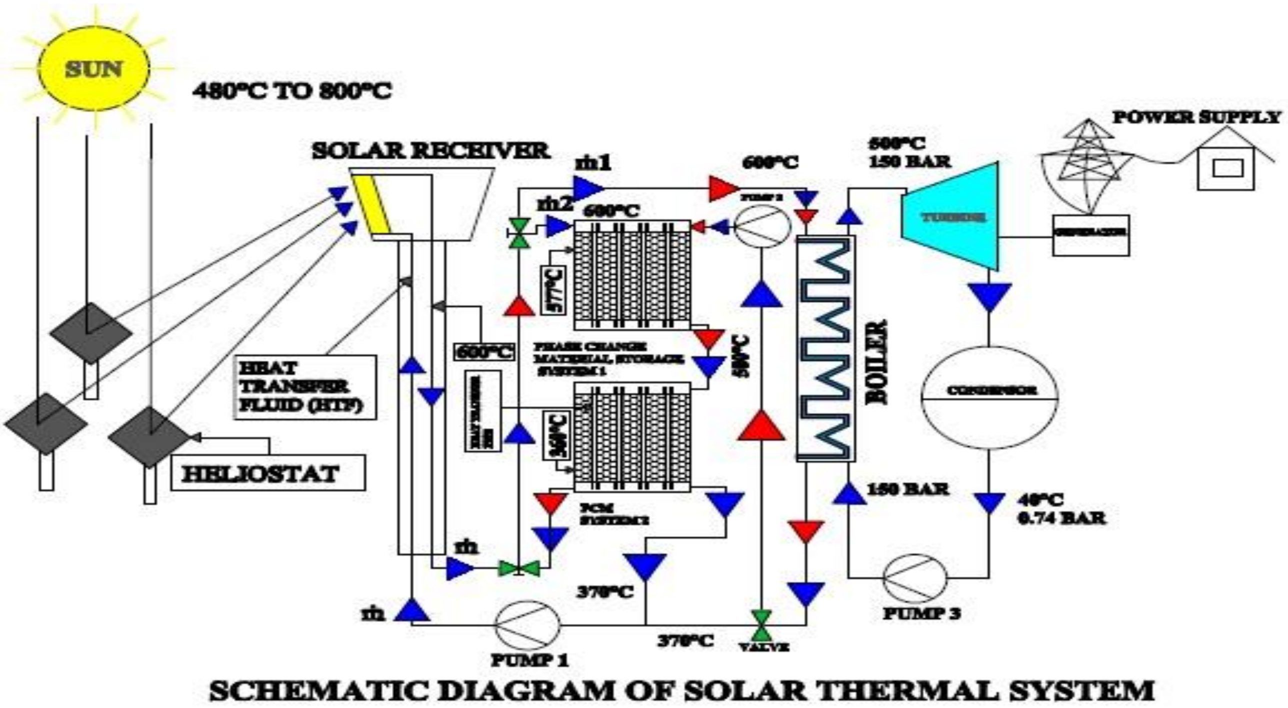

Fig 4. Classification of PCM

A PCM needs to have these following characteristics to be good storage medium:

- High specific heat
- High thermal conductivity
- Melting point desired to operating range
- Change in volume is small during operation
- Chemical stability
- Available in large quantity at low cost

In this paper we use metallic phase change material Aluminium-Silicon alloy, AlSi12 and potassium hydroxide because of the fact that Metallic PCMs offer the potential for high density, high temperature thermal energy storage. They also have high thermal diffusivity, which eliminates the need for large heat exchange surfaces.

Table 1 Properties of Phase Change Material [PCM] [26, 27]

PCM	Melting Temp. 0_C	Latent Heat KJ/Kg	Sp. Heat KJ/Kg
Aluminium Silicon alloy,AlSi12	577	560	1.038
Potassium hydroxide	360	150	1.47

IV. HEAT TRANSFER FLUID

Heat transfer fluid (HTF) plays an important role in concentrated solar power (CSP) production. It delivers heat to the water when it encounters water inside the heat exchanger and steam is generated. The generated steam is sent to the turbine for power production. Mean temperature of heat addition primarily depends on the temperature of HTF entering in the heat exchanger.

Selection criteria of HTF

- High operating range
- Non- corrosive temperature
- Low viscosity
- Safe to use
- Low freezing point
- Low cost

The heat transfer fluids used in concentrated solar power (CSP) technology are molten salt, synthetic oils, air, water, glycerol based, etc. Now-a-days air and water are not being used. Heating on air increases the volume and so large heat exchanger should be installed. As a result, investment cost also increases. In this paper we use molten nitrate salt that contains Sodium nitrate $(Nano_3)$, 60% w and Potassium Nitrate $(Kno_{3)}$, 40% w. Advantage of use of molten nitrate salt is its high thermal conductivity, that is why its heat storage capacity is also good.

Table 2 Properties of Heat Transfer Fluid (HTF) [28]

HTF	Melting Temp. o_C	Heat of Fusion KJ/Kg	Sp. Heat KJ/Kg
Sodium Nitrate $Nano_3$ 60% w + Potassium Nitrate Kno_3 40% w	370	161	1.6

V. METHODOLOGY

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For 1MW Thermal Power plant, we have calculated the result.

The highest temperature of steam used in Rankine Cycle is 500^oC.

We have found out the value of

Enthalpy (h_1) = 3310.6 KJ/Kg, [Take the value of h_1 from steam table]. And Corresponding value of

Entropy(s_1) = 6.3487 KJ/Kg, [Take the value of s_1 from steam table]

We know $\quad s_1 = s_2$

$\therefore s_2 = Sf_3 + X * Sf_g \quad$ [x is dryness factor]

$$X = \frac{S_2 - Sf_3}{Sf_g} = \frac{6.3487-0.5721}{7.6862}$$

$$X = 0.75$$

Entropy$(h_2) = hf_3 - x * hf_g$

= 167.45 + 0.75(2406.9)

= 1972.62 KJ/Kg.

We know, Turbine Work = $W_T = h_1 - h_2$

= 3310.6 – 1972.62

= 1337.98 KJ/Kg

Now, we have calculate pump work

Pressure at 40^oC is 0.073750 bar = 7375 Pa

[Data is being taken from steam table]

V_3 at 40^oC is ~ 0.001 m^3/Kg

We know,

$$W_p = V_3 (P_4 - P_3)$$

$$= 0.001 * (15000000 - 7375)$$

$$\sim 15 \text{ KJ/ Kg}$$

Now enthalpy (h_3) = 167.45 KJ/Kg

[Value of h_3 is taken from steam table corresponding temperature 40^oC]

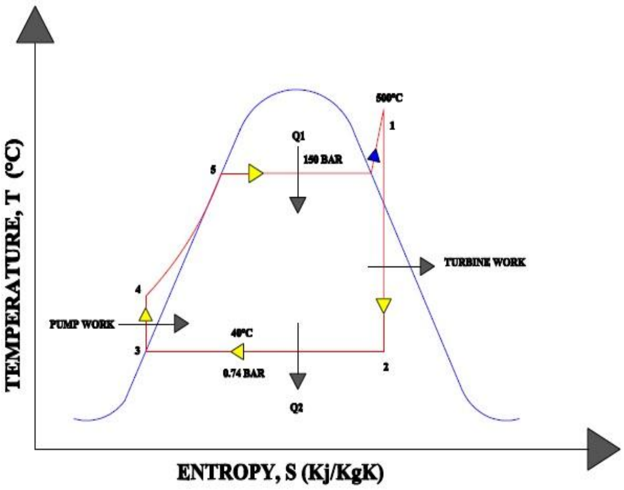


Fig. 6 Rankine Cycle Diagram use in this work

We Know Pump work $(w_p) = h_3 - h_4$

$\therefore$ Enthalpy $(h_4) = h_3 + w_p$ = 167.45 + 15

= 182.45 KJ/Kg

Water mass flow rate for 1MW electricity produce is

$$\dot{m} = \frac{10^3 \text{ KJ/Sec}}{W_T - W_P} = \frac{10^3}{1337.98-15} = 0.756 \text{ KJ/Sec}$$

Heat transfer rate $(Q_1) = h_1 - h_4$ = 3310.6 – 182.45

= 3128.15 KJ/Kg

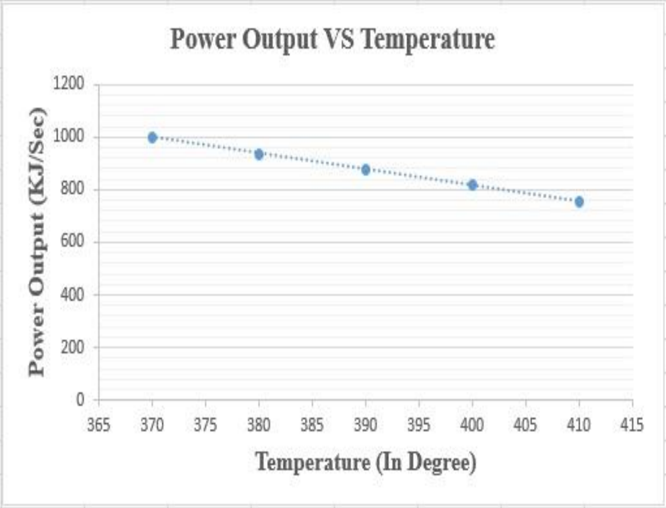
Total heat added to the boiler

= 0.756 * 3128.15 = 2364.88 KJ/Sec

Now we find out mass flow rate of Heat transfer fluid (HTF) in path 1 is $\dot{m}_1$

$Q_1 = \dot{m}_1$ * (600-370)*s

[S is sp. Heat of heat transfer fluid]



2364.88 = $\dot{m}_1$ * (600-370)*1.6

$\dot{m}_1$ = 6.43 Kg/Sec

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

= $Q_1 * 12 * 3600$ KJ

= 2364.88 * 12 * 3600

= 102162816 KJ

Total mass of PCM to be melted, is

$PCM_1 * \text{Latent heat}_1 + PCM_2 * \text{Latent heat}_2$ = 102162816 kg (1)

Now we get two equations

12*3600*$\dot{m}_2$*s*(600-580) = $PCM_1 * \text{Latent heat}_1$ (2)

Another equations is

12*3600*$\dot{m}_2$*s*(580-370) = $PCM_2 * \text{Latent heat}_2$ (3)

Now,

$$\frac{PCM_1 * \text{Latent heat}_1}{PCM_2 * \text{Latent heat}_2} = \frac{12 * 3600 * \dot{m}_2 * s * (600-580)}{12 * 3600 * m_2 * s * (580-370)}$$

$$= \frac{PCM_1 * 560}{PCM_2 * 150} = \frac{20}{210}$$

$= 11760\, PCM_1 = 300 * PCM_2$

$= PCM_2 = 39.2 PCM_1$ (4)

Now put the value of PCM_2 in equation (1) we get,

$PCM_1 * \text{Latent heat}_1 + PCM_2 * \text{Latent heat}_2$ = 102162816

PCM_1 = 15863.80 Kg

Again put the value of PCM_1 in the equation (1), we get

$PCM_1 * \text{Latent heat}_1 + PCM_2 * \text{Latent heat}_2$ = 102162816

PCM_2 = 680979.70 Kg

Now we calculate PCM_1 & PCM_2 are melt Kg/Sec

$$\dot{m}PCM_1 = \frac{15863.80}{12*3600} = 0.37 \text{ Kg/Sec}$$

$$\dot{m}PCM_2 = \frac{680979.70}{12*3600} = 15.77 \text{ Kg/Sec}$$

From here, we have to find out mass flow rate of heat transfer fluid (HTF) in path 2 is

$\dot{m}_2 * s * (600-370) = \dot{m}PCM_1 * \text{Latent heat}_1 + \dot{m}PCM_2 * \text{Latent heat}_2$

Then, $\dot{m}_2 * 1.6 * 230 = (0.37 * 560) + (15.77 * 150)$

$$\dot{m}_2 = \frac{207.2+2365.5}{368} = 7.0 \text{ Kg/Sec}$$

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Now we calculate total mass flow rate of heat transfer fluid (HTF)

$\dot{m} = \dot{m}_1 + \dot{m}_2 = 6.43 + 7.0 = 13.43$ Kg/Sec

VI. RESULT AND DISSCUSSION

The power output from the Rankine Cycle strongly depends upon the outlet temperature of the heat transfer fluid (HTF). When outlet temperature is 380°C, the power output is calculated by following method.

$Q_1 = \dot{m}_1 * (600-380) * 1.6 = 6.43 * 220 * 1.6 = 2263.36$ KJ /sec

Now, $Q_1 = (h_1 - h_4) * \dot{m}$

$2263.36 = (h_1 - 182.45) * 0.756$

$h_1 = 3176.30$ KJ / Kg

We know, $s_1 = s_2$

$$\frac{\Delta S_1}{\Delta S} = \frac{\Delta h_1}{\Delta H} \quad \ldots\ldots (5) \; [\Delta h = (3191.5 - 3159.7)]$$

$= 31.8$

$[\Delta S = (6.1904 - 6.1468)] \qquad = 0.0436$

[Taking the value of Δh and ΔS from superheated steam table corresponding value of $h_1 = 3176.30$]

Put the value in equation (5), we get $\frac{S_1 - 6.1468}{0.0436} = \frac{h_1 - 3159.7}{31.8}$

or $\frac{S_1 - 6.1468}{0.0436} = \frac{3176.30 - 3159.7}{31.8}$

$S_1 = 6.17$

Now we find our dryness factor (X) $= \frac{S_2 - Sf_3}{Sf_g} = \frac{6.17 - 0.5721}{7.6862}$

$X = 0.73$

$h_2 = hf_3 + X * hf_g$

$= 167.45 + 0.73\,(2406.9)$

$= 1924.49$ KJ /Kg

Turbine work $(W_T) = h_1 - h_2$

$= 3176.30 - 1924.49$

$= 1251.81$ KJ

Network output,

$(W_T - W_P) * \dot{m} = (1251.81 - 15) * 0.756$

$= 935.03$ KJ /Sec

Similarly, we can find out power output corresponding to rest of different outlet temperature.

VII. CONCLUSION

Net power output from a solar power plant with two Phase change material (PCM) reservoirs shows a downward trend when outlet temperature of Heat transfer fluid (HTF) increases. Two different PCMs have been used to reduce the outlet temperature up to 300 °c. With one PCM this much reduction of temperature is not possible and consequently net power output also drops largely.

Charging and discharging duration of PCM for continuous power production depends on geographical location of the site. In present work 12 hours charging and 12 hours discharging have been considered.

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