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Design and Analysis of Natural Circulation based Integral Receiver System for 2 MW Electric Beam down Solar Thermal Plant

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Abstract—*The National Action Plan on Climate Change (NAPCC), outlined by the Government of India, primarily aims at identifying potential opportunities and delineating the path forward for implementation of technologies that address India's twin needs: sustainable development, adaption and mitigation of commercial emissions in an accelerated manner.*

In view of the above, India is targeting 100GW$_e$ solar energy by 2022. Huge amount of energy is being used in industries for process heating, chemical, metallurgical purpose and for transportation which can be very efficiently achieved by solar thermal plants. In addition, thermal storage is also efficient and cost effective in solar thermal technology. Considering these aspects a 2MW$_e$ (electric) solar thermal power plant based on beam down technology has been designed. In this plant a 2MW$_e$ (9MW$_{th}$ thermal) natural circulation based receiver system has been designed which uses primary coolant as molten nitrate salt (40% KNO_3 and 60% $NaNO_3$) and secondary coolant as steam/water, in this primary coolant and secondary coolant works on natural circulation principle. Receiver also provides 1 hour thermal storage for sudden clouding and continuous rolling of turbine.

Integral Receiver System has been designed and optimized. Salt side thermal hydraulic calculations have been performed using LBENC (Lead Bismuth Eutectic Natural Circulation). LBENC code consists of mass momentum and energy equation of fluid and conduction equation of wall. Salt temperature and mass flow rate have been analyzed using LBENC. The molten salt temperature and heat transfer coefficient with time was evaluated and used as boundary condition to analyzed steam/water system performance using RELAP-5(Reactor Excursion and Leak Analysis Program). Steam flow rate, water flow rate and temperature in steam generating system analyzed using RELAP-5. The overall paper presents the optimized design of 9MW$_{th}$ integral receiver system and their analysis and results.

1. INTRODUCTION

In day-to-day life demand on fossil fuel goes on increasing. The Problem of emissions and global warming due to the fossilized fuels has been considered. One way to solve these issues is to reduce the use of fuels and focus on the cleaner sources such as nuclear, solar, wind, hydro etc. A Country like India on account of its geographic conditions receives the tremendous amount of solar energy which can be trapped. Among the eight national missions under the NAPCC, outlined by the Government of India, the National Solar Mission is one of the key missions in its strategy to achieve climate change mitigation related objectives [1].

The popular term Concentrated Solar Power (CSP) like parabolic trough, linear Fresnel reflector, Dish Sterling, Solar Power Towers etc. CSP systems use lenses, mirrors, and tracking systems to focus a large area of sunlight into a small area, where a fluid is heated to produce steam to the turbine for power generation [2]. In this study, the focus limited to solar power towers. The Solar Power Towers are based on either beam-up or beam-down technology. In beam up, the receiver is placed at the top of the tower and in beam down, the receiver is placed at the bottom of the tower. In beam down, the heliostats reflect the sunlight onto a hyperboloid mirror placed at the top of the tower. The hyperboloid mirror reflects the incident light downwards onto the receiver placed at the bottom. It has a number of advantages over the beam-up technology.

In beam down plants, the receiver is at the surface level and the tower needs to be designed to support only the mirror. Installation and maintenance of such plants are also easy. This technology opens the window for natural circulation operation. This eliminates the need for pumping also the

Integral receiver design is possible which combine the receiver, storage and Steam generating system (SGS).

The Solar power generation capacity potential of each of the states of India and northwestern part of India [3, 4] has been studied and they considered factors like availability of wastelands, direct normal irradiance. The estimated potential for solar thermal power generation in India is 756GW and India is targeting 100GW$_e$ solar energy in 4 to 5 years. The various HTFs have been proposed for solar thermal applications like liquid metals and molten salt. The liquid metals like sodium and Lead-bismuth eutectic (LBE) offer very high H.T.C. and also thermally stable at a high temperature up to 800°C resulting higher plant efficiency [5]. The applicability of Liquid Metals as HTF (LBE) [6] has been discussed. By using LBE as HTF the corrosion of structural material takes place. Comparison of the liquid sodium metal and molten salt such for solar applications [7] has also been studied. The molten salt has high specific heat capacity compared to liquid metals. They found out molten salt requires less storage volume and it is cheaper compared to liquid metals.

The different storage systems like reference system (three tanks) and modification on reference system like two-tank storage system and their performance have been analyzed [8]. In two-tank storage, less volume required resulting in low cost of storage possible. Comparison of the thermocline storage (steam generating system inside the storage) and two tank configurations have been studied [9]. They find out the capital investment of thermocline storage 33% lower than two tank storage. The theoretical formulation and solution procedure used in LBENC code and the validation of the code using experimental data obtained for the Liquid Metal Loop [10] have been discussed. Thermal hydraulic analyses of absorber tubes for Fresnel plants using RELAP [11] have been studied.

From the above literature in the present study, the design of integral receiver system for 9MW$_{th}$ (8MW for SGS and 1MW for storage)has been carried out by using molten salt in primary side and steam/water in secondary side and both loops works on natural circulation. Also, this paper presents the molten salt loop and SGS analysis carried out.

2. DESIGN OF INTEGRAL RECEIVER SYSTEM:-

The design of integral receiver system is based on following design basis:

1. The Receiver is designed for 9MW$_{th}$ power generation. 8MW$_{th}$ would be used for power generation via SGS system and remaining 1MW would be storage.
2. An 8MW$_{th}$ constant power extraction through SGS system and steam at 350°C and 40 bar pressure is generated with 25% evaporator exit quality.
3. 1-hour thermal storage is designed. The salt temperature varies from 450°C to 550°C in 9-hour operation.
4. Maximum Receiver Surface temperature limited to 650° from the point of molten salt degradation.

Receiver system collects the concentrated solar energy. It contains a receiver, storage and three SGS. All the details of integral receiver system shown in Fig.1. In this design storage and SGS is an integral part and connected with a riser and downcomer part. The individual risers placed on the periphery of hemispherical cavity type receiver. The molten salt heated in this receiver and supplied to storage through the riser. The molten salt transfers heat to SGS and moves in the individual downcomer which is connected to the receiver. The size of the receiver is 9m diameter and annular space of 8mm found by optical calculations [12].

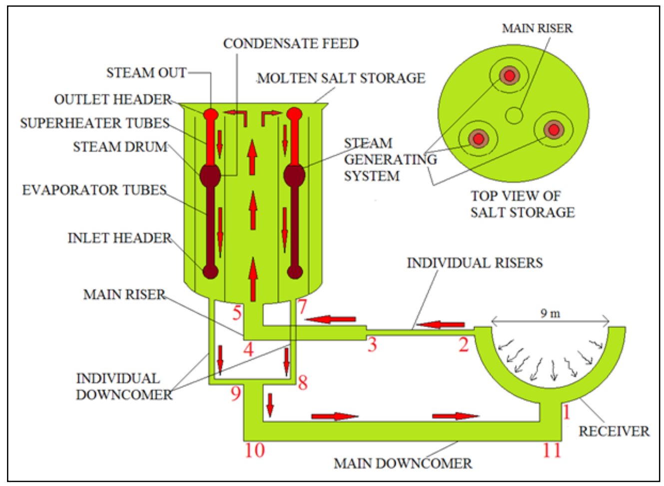

Fig. 1: Integral Receiver System

The SGS includes an inlet header (IH) followed by an evaporator. There is a steam drum (SD) to separate the vapor-liquid mixture and send the vapors to a superheater which is finally drawn out of an outlet header (OH). The IH, OH and SD are vertical type components. An overall heat and mass balance for the entire SGS and the individual components was carried out to estimate the heat loads, individual component flows and temperature conditions. Table 1 shows all major process parameters.

For the design calculations, the thermo-physical properties as a function of temperature for the molten salt were used [13]. The stored energy required for 1-hour operation is 8MWhr. The molten salt storage for required to limit the temperature change between 450 to 550°C is about 187 ton. The storage volume works out to be 105.98 m^3.

Table 1: Major process parameters of SGS

Parameters	Evaporator	Superheater
Heat Rating (MW)	6.98	1.017
Salt inlet temperature (°C)	439.62	450
Salt outlet temperature (°C)	359.9	439.62
Salt Flow (kg/s)	58.68	58.68

Steam/Water inlet temperature (°C)	235	250
Steam/Water outlet temperature (°C)	250	350
Steam drum pressure (bar)	40	
Exit quality	0.25	-
Water flow (kg/s)	13.92	-
Steam flow (kg/s)	-	3.48

The heat transfer calculations have been carried out for SGS and pressure drop found out for molten salt loop. The material used for evaporator and superheater tubes is SS 321. The correlation proposed by Yu-Ting Wu et al. [14] was used for finding salt side H.T.C. The evaporator section divided into subcooled and boiling region, the water side H.T.C. in boiling region is calculated using Chen's correlation [15]. Fig. 2 shows the detailed design parameters of single SGS.

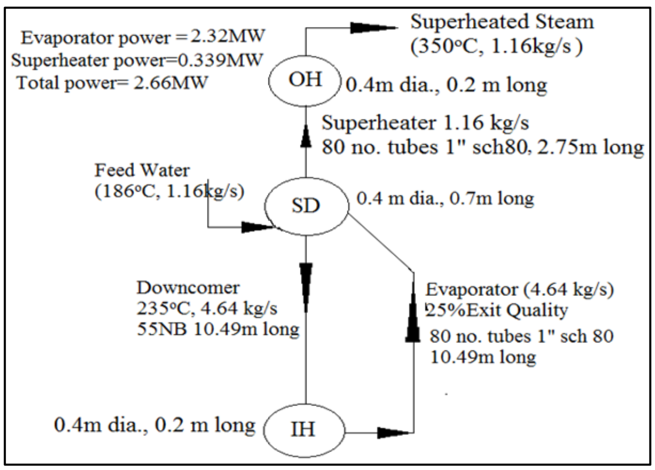

Fig. 2: Design parameters of Single SGS

The molten salt loop sizes have been designed in such a way that the buoyancy head available for this height is sufficient to drive the natural circulation system and equal to total pressure drop in the molten salt loop. The worst case scenario during the operation of this natural circulation loop is that in the early morning hours when there is no solar flux available and the salt temperature is also at its minimum 450°C. In this case, there would be maximum salt flow required. So if this system is designed to operate in this worst case scenario, we can ensure that the natural circulation system will perform under all other operating conditions.

The details of the geometry of the molten salt loop are shown in Table 2.

Table 2: Molten Salt loop line sizes and fittings details

Component Name	Line Size	Length (m)	No. of 90° Bends
Main Downcomer	250NB sch40	13.2	2
Main Riser	200NB sch40	3.4	1
Individual Downcomers (3 no.)	150NB sch40	3.2	3
Individual Risers (4 no.)	100NB sch40	5.5	4
Storage Vessel	3.06m	14.34	-
Salt channel	500 mm	14.34	-
Receiver	9 m Dia. hemispherical	4.5	-

The above molten salt loop is designed at 450°C. The salt inlet temperature varies from 450 to 550°C in storage during the 8-hour operation. The heat carrying capacity of molten salt goes on increasing. Thus the salt flow required to extract constant power to SGS needs to be controlled. As the salt temperature increases, the available Log Mean Temperature Difference (LMTD) increases so the mass flow rate of salt required should reduce in order to reduce the overall heat transfer coefficient. Remaining 1 hour stored energy is used with temperature variation from 550°C to 450°C. The results coming out from the 9-hour operation reported in next section.

3. ANALYSIS OF INTEGRAL RECEIVER SYSTEM

The analysis carried out in two parts first is molten salt loop and second is the steam generating system.

3.1 Analysis of molten salt loop by using LBENC code

LBENC is used to study the transient performance of single-phase natural circulation based molten salt loop. This code solves the following governing equations: Energy Equation for the Fluid.

$$\left(\frac{\partial T}{\partial t}\right) - \alpha\left(\frac{\partial^2 T}{\partial s^2}\right) + \frac{W}{A_{in}\,\rho_o}\left(\frac{\partial T}{\partial s}\right) = \frac{-4h_{in}(T - T_w)}{\rho_o D_{in} C_p}$$

Momentum Equation for the Fluid

$$\frac{\Delta s_i}{A_{in}}\left(\frac{\partial W}{\partial t}\right) = \rho_o g\big(1 - \beta(T_i - T_o)\big)\Delta z_i - \frac{f_i \Delta s_i}{D_{in,i}}\left(\frac{W}{2\rho_o {A_{in,i}}^2}\right) - \Delta p_i - \Delta p_{acc,i}$$

Energy Equation for the Wall

$$\left(\frac{\partial T_w}{\partial t}\right) - \alpha\left(\frac{\partial^2 T_w}{\partial s^2}\right) = \frac{-4h_{in}(T_w - T)}{\rho_w C_{p_w}}\left(\frac{D_{in}}{{D_o}^2 - {D_{in}}^2}\right) - \frac{-4h_o(T_w - T_x)}{\rho_w C_{p_w}} + \frac{-4q}{\rho_w C_{p_w}}\left(\frac{D_o}{{D_o}^2 - {D_{in}}^2}\right)$$

Fig. 3 shows the schematic of the molten salt loop used for LBENC. The geometry of molten salt loop as shown in Table 3 was given as input to the LBENC. Also this analysis requires loss coefficient as a function of temperature to control the salt flow through the system so as to extract constant power in SGS. An approximate value of this loss coefficient was obtained by trial and error method and given as input to LBENC. This value was input to the LBENC code for analysis. A constant power of 9MW was given as input to the heater (receiver surface) during the first 8-hour duration. In the remaining 1-hour, the power in the recevier is zero and the SGS is operated by using its stored energy. The transient analysis was carried out for 9-hour period.

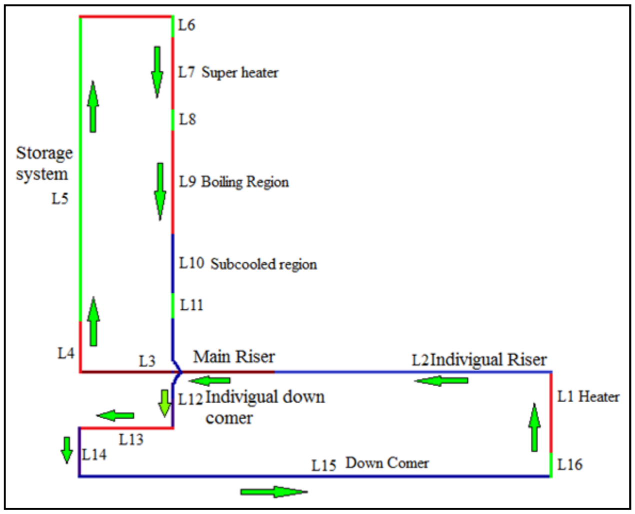

Fig. 3. The salt loop schematic used for LBENC analysis

Table 3. Geometry of salt loop for LBENC analysis

Component Name	Compone nt ID	Lengt h (m)	Diamete r (m)	Wall Thicknes s (mm)	Loss Coeffici ent
Heater	L1	4.5	9	8	10
Riser horizontal	L2	5.5	0.1023	6	1
Riser horizontal	L3	3.2	0.2027	8.2	1
Riser vertical	L4	0.2	0.2027	8.2	1
Storage	L5	14.34	3.06	8.2	1
Outlet Header	L6	0.2	0.4	14.27	1
Superheatin g	L7	2.75	0.024	1.245	1
Steam Drum	L8	0.7	0.4	14.27	1
Boiling	L9	8.11	0.024	1.245	1
Subcooling	L10	2.38	0.024	1.245	1
Inlet Header	L11	0.2	0.4	14.27	1
Downcomer	L12	2	0.1544	8.2	1
Downcomer	L13	1.2	0.1544	8.2	1
Downcomer	L14	3	0.3033	10.3	1
Downcomer	L15	9.9	0.3033	10.3	1
Downcomer	L16	0.3	0.3033	10.3	1

3.2 Performance of the Steam Generating System using RELAP-5

RELAP-5 is a highly generic code used for calculating the behavior of a reactor coolant system during a transient, can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and non-nuclear systems involving mixtures of vapour, liquid, non-condensable gases, and non-volatile solute.

It solves six differential equations for mass, momentum and energy conservation for the two phases, i.e. water and vapor are solved for each fluid cell.

A transient analysis of the secondary system was carried out using RELAP-5. The single SGS has been taken for analysis.

The input and nodalization scheme used for analysis is given in Fig. 4. A Time Dependent Volume (TDV) at 40 bars and 350˚C is connected to the OH to release the steam produced in the system. A TDV at 40 bars and 186˚C is connected to the downcomer.

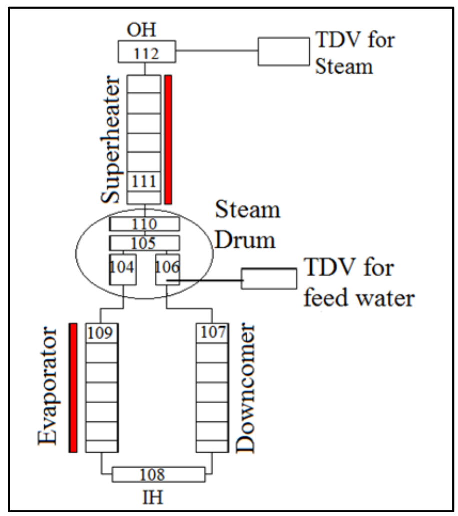

Fig. 4: Nodalization scheme used for RELAP analysis

The system was subjected to the transient salt side boundary conditions of temperature and H.T.C. (found out by design calculations) as shown in Fig. 5, 6 and 7 for superheater, boiling and subcooled region respectively. The analysis was carried out for 9 hours.

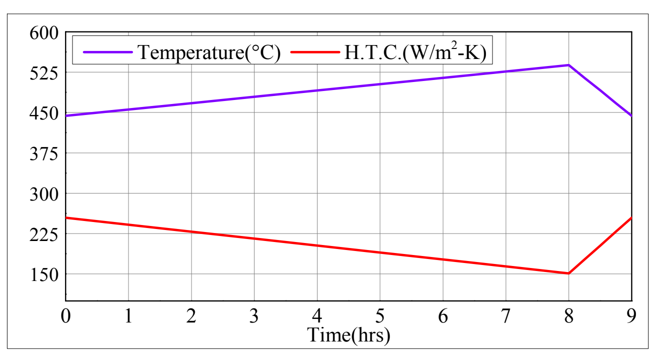

Fig. 5: Temperature and H.T.C. with time in super heater

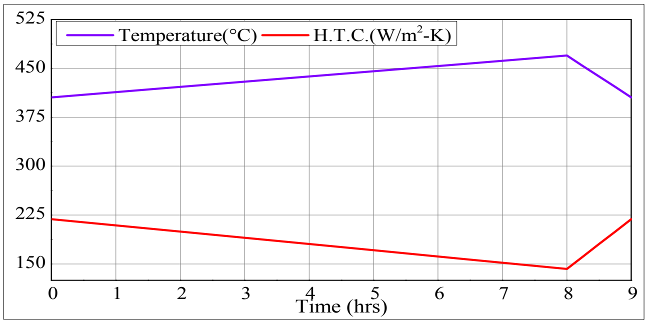

Fig. 6: Temperature and H.T.C. with time in boiling region

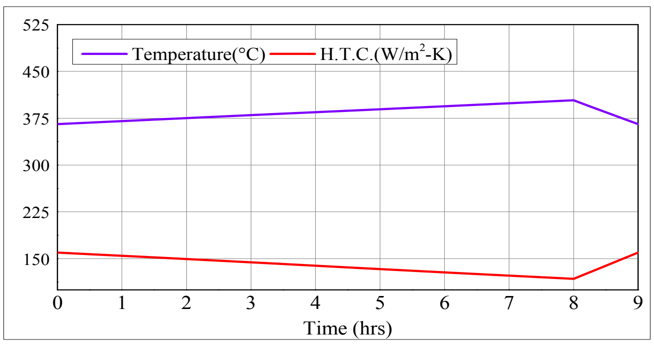

Fig. 7: Temperature and H.T.C. with time in sub cooled region

4. RESULTS AND DISCUSSION

Fig.8 shows the variation in temperature and mass flow rate of salt from design calculations. The temperature increases from 450°C to 550°C in first 8 hours and decreases from 550°C to 450°C in 1 hour that completes 9 hours operation.

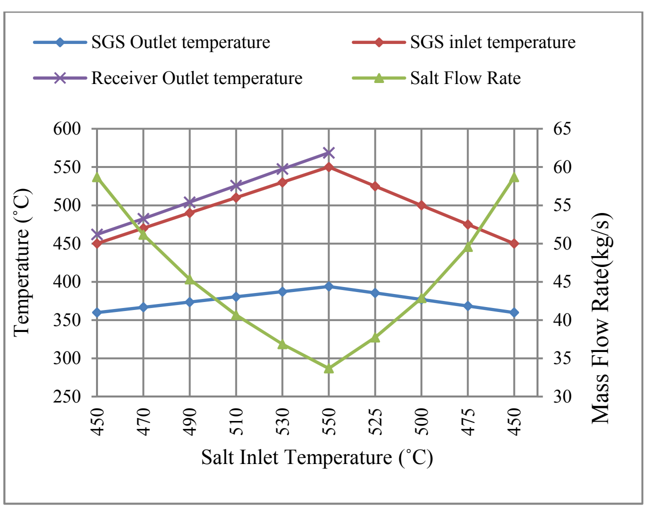

Fig. 8: Salt temperatute and mass flow rate variation from design calculations

The mass flow rate in varies from 58.68 kg/s to 33.62 kg/s for constant power to SGS. The outlet temperature from SGS varies from 360°C to 393°C. Also the outlet temperature from a receiver in first 8 hours varies from 461.9°C to 568.7°C. In remaining 1 hour the power in receiver system is zero and outlet temperature of the receiver is same as the outlet temperature of SGS.

It can be noted that the temperature differential at inlet and outlet of SGS is smaller at the start of the day. At this point the salt flow is higher, resulting in lower temperature drop for constant power being extracted. When the salt is at the maximum temperature towards the solar energy rich operation, the required salt flow is less. So by the above logic, the temperature differential is higher.

Fig. 9 shows the results of LBENC and compared with design results as shown in Fig.8. The small variation in temperature and mass flow rate is observed. The variation is observed because of loss coefficient considered in LBENC. The prediction by the code is found to be acceptable.

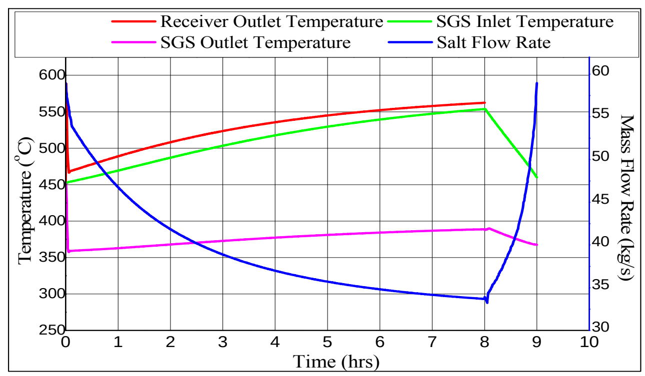

Fig. 9: Parameter variation from LBENC

Fig. 10 and 11 shows the various parameters of single SGS with time found out by using RELAP-5 and compared with design parameters indicated in Fig.2. The results show that the secondary system parameters are not altered by the changes in the salt side conditions and we are able to get constant process parameters. The prediction by RELAP-5 is acceptable.

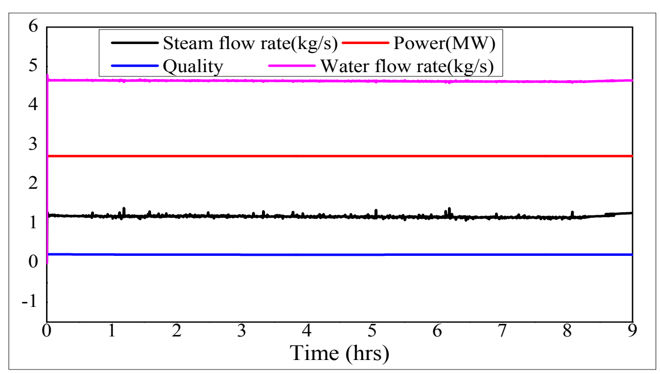

Fig. 10. Variation of water and steam flow rate, quality and power in single SGS with time

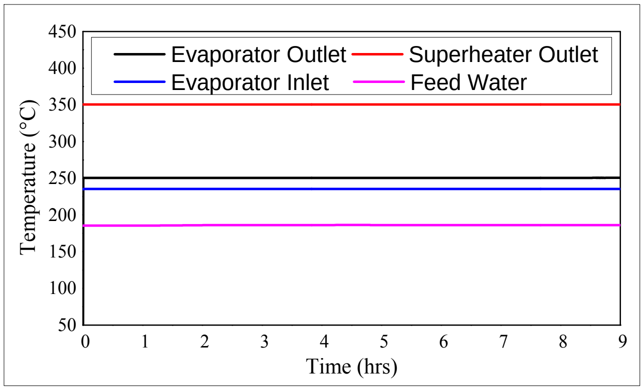

Fig. 11. Variation in temperature with time

5. CONCLUSION

- The optimum design of SGS is found out of to be 80 number of tubes in evaporator and superheater section. The designed molten salt loop which is operated by natural circulation.
- In design of the $9MW_{th}$ natural circulation system with solar energy, variation of the mass flow rate of salt is in the range of 58.68 kg/s to 33.62 kg/s.
- The transient behavior of the molten salt loop is analyzed using LBENC. It gives good agreement of design results with temperature variation.
- The performance of steam generating system is analyzed using RELAP-5. The system parameters are in good agreement with calculated design parameters with error of ±2%.

Nomenclature:-

CSP Concentrated Solar Power

SGS Steam generating system

HTF Heat Transfer Fluid

H.T.C. Heat Transfer Coefficient [W/m^2-K]

LBENC Lead Bismuth Eutectic Natural Circulation

RELAP Reactor Excursion and Leak Analysis Program

A_{in} Flow area [m^2]

C_p Specific heat capacity of fluid [J/kg-K]

C_{pw} Specific heat capacity of SG tube [J/kg-K]

D_o External diameter [m]

D_{in} Internal diameter [m]

f_i Friction factor

g Acceleration due to gravity [m/s^2]

h_{in} Internal heat transfer coefficient [W/m^2-K]

h_o External heat transfer coefficient [W/m^2-K]

q Heat flux [W/m^2]

s Spatial coordinate [m]

T Temperature of fluid [K]

T_w Temperature of SG tubes [K]

T_x Temperature of external fluid [K]

W Mass flow rate of fluid [kg/s]

α Thermal diffusivity [m^2/s]

α_w Thermal diffusivity of SG tube [m^2/s]

β Volumetric temperature expansion coefficient of fluid [1/K]

Δp_i Change in static pressure [Pa]

$\Delta p_{acc,i}$ Acceleration pressure drop [Pa]

$\boldsymbol{\rho}$ Density of fluid [kg/m^3]

$\boldsymbol{\rho}_w$ Density of SG tube wall [kg/m^3]

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