# Numerical and Experimental Analysis of Scheffler Concentrator Receiver for Steam Generation Using Phase Change Material

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**Abstract-** This paper proposes a design of receiver of a scheffler dish solar concentrator which uses the phase change material to store the thermal energy. For this, water is used for direct steam generation from the receiver. The proposed model consists of a phase change material (PCM) present in between the inner and outer cylinder of the copper receiver. A binary mixture commonly known as solar salt (60% $NaNO_3$-40% $KNO_3$) is used as PCM for analysis. It helps to get rid of fluctuations due to sudden weather changes. Scheffler solar concentrator of 16 $m^2$ area with a fixed focus is used to concentrate the solar radiations to the receiver. The purpose of this study is to see the effect of solar salt on steam generation and compare it with the results obtained without the use of solar salt in the receiver experimentally as well as numerically using Finite Element Method. Numerical analysis was performed using Transient thermal analysis in Ansys-16 and experimental investigations were performed. Results showed that the use of PCM in the receiver not only increases the mass flow rate of the steam but also the duration of steam generation by storing the thermal energy.

**Keywords** Solar Power; direct steam generation; phase change material; Finite Element Method.

## 1. Introduction

The world is slowly and steadily aligning towards the use clean energy in order to reduce its dependence on conventional energy resources which is a major source of pollution worldwide. This is the motivation for new innovations as there is dearth of better technologies with higher efficiencies. Solar energy can serve a broad range of our energy need and can be easily implemented for different applications [1-3]. Thermal energy storage systems has an essential feature to make an efficient use of solar energy due to the inherent intermittence of this energy source. These systems allow making use of thermal energy accumulated in hours of high solar radiation, reducing the mismatch between supply and demand of energy [4-5].

Scheffler concentrator or collector is used to concentrate solar rays to the receiver positioned at focus. Receiver contains the fluid as well as phase change material which is heated due to incident concentrated solar flux. Reflector of solar concentrator has efficiency in range of 85%-90% while overall efficiency in range of 30 - 45%. The coefficient of absorption of receiver decides the amount of heat absorbed. The losses due to radiation and conduction start to rise with temperature of receiver, however the convective losses are dependent on many variables including wind flow of surface of receiver. Many efforts are being made to study losses in order to improve efficiency of receiver and thereby total system [6-10].

For the purpose of thermal storage, nitrate salts are selected because of their favorable properties as compared with other options, some of which are listed in Table 1. These nitrate salts have low corrosion rates with common piping materials and are thermally stable in the upper temperature range as required by steam rankine cycle. They have low vapour pressure and are widely available as well as relatively inexpensive.

**Table 1**: Characteristics of the nitrate salts and Therminol VP-1 [11]

| Property | Solar Salt | Hitec | Hitec XL (Calcium Nitrate Salt) | LiNO3 mixture | Therminol VP-1 |
|---|---|---|---|---|---|
| Composition, % | | | | | biphenyl/ diphenyl oxide |
| $NaNO_3$ | 60 | 7 | 7 | | |
| $KNO_3$ | 40 | 53 | 45 | | |
| $NaNO_2$ | | 40 | | | |
| $Ca(NO_3)_2$ | | | 48 | | |
| Freezing point, C | 220 | 142 | 120 | 120 | 13 |
| Upper temperature, C | 600 | 535 | 500 | 550 | 400 |
| Density @ 300C, kg/m3 | 1899 | 1640 | 1992 | | 815 |
| Viscosity @ 300C, cp | 3.26 | 3.16 | 6.37 | | 0.2 |
| Heat capacity @ 300C, J/kg-K | 1495 | 1560 | 1447 | | 2319 |

Solar salt was selected for the experiment purpose as the upper operating temperature of it is high ($600^0$C) and as compared to other nitrate salt it is one of the lowest cost nitrate salt. The only disadvantage is the high freezing point of $220^0$C. Hitec Salt offers a lower freezing point of about $140^0$C but at a higher cost hence it is not commercially acceptable [12-14].
A step towards such effort is to experimentally analyze the performance of receivers under various conditions. Mathematical model was build first and then validated through experimental data. Once such model is made it becomes a predictive tool to forecast any new condition or change. Steam generation capacity of any receiver depends on solar heat flux and distribution on its surface. Transient thermal analysis simulation tool is used to study this temperature distribution and heat flow from external surface of receiver to inner fluid. Experimental work co-related with numerical studies on different condition i.e. with and without PCM is creating some credible and validated basis to build reliable model. Experimental and numerical study of temperature distribution occurring from faces of cylindrical receiver was carried out. Experiment was conducted for fluid inlet temperature 30˚C and for receiver with and without PCM.

## 2. Experimental Setup and Investigation

### *2.1. Construction Details*

The reflector is a small lateral section of a much larger paraboloid. The inclined cut produces the typical elliptical shape of the Scheffler-Reflector. The sunlight that falls onto this section of the paraboloid is reflected sideways to the focus located at some distance of the reflector. The axis of daily rotation is located exactly in north-south direction, parallel to earth axis and runs through the centre of gravity of the reflector. Scheffler solar concentrators are a special type of parabolic solar concentrator based off of the lateral section of a paraboloid as shown in Fig. 1. Due to its construction, a Sheffler concentrator only requires one axis tracking as disscussed, and the fixed focus is away from the incident beam radiation and away from the dish itself.

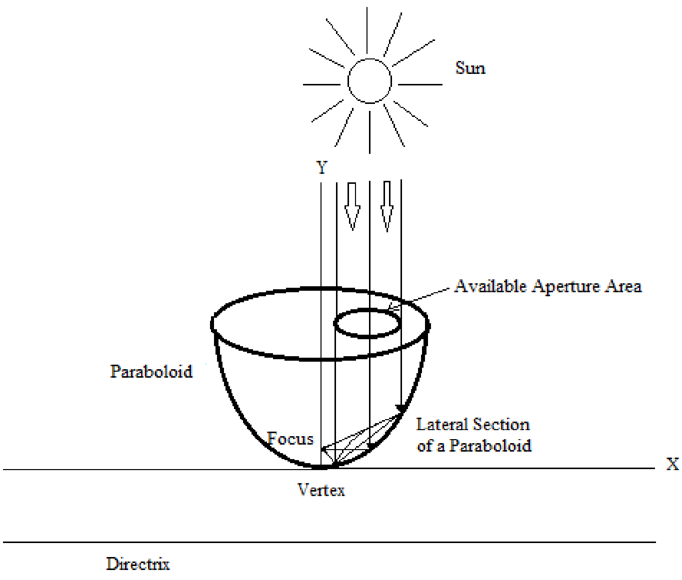


**Fig. 1.** Section of Scheffler reflector in a paraboloid

While designing a parabola curve for the Scheffler reflector, all calculations are made with respect to equinox with zero solar declination. To calculate the equation of the parabola curve, the calculations are made by considering the side view of the paraboloid. As a result, paraboloid and reflector frame are drawn in the form of a parabola curve and straight line respectively. This can be clearly undersdtood through the basic parabola equations with its axis passing through the y-axis can be written in the form as given in equation (1).

$$P(x) = m_p x^2 + C_p \quad (1)$$

Where $m_p$ is the slope of parabola and $C_p$ is the y-intercept of the parabola [15].
In Table 2. the specification of 16 $m^2$ Scheffler Dish is listed which was used for the experimental investigation of the research work and Fig. 2 shows the scheffler dish at the experimental site.

**Table 2**: Specification of 16 $m^2$ Scheffler Dish

| Module Description | Rating |
|---|---|
| Surface area of collector | 16 $m^2$ |
| Aperture area of collector | 11.65 $m^2$ |
| Dimension and Shape | Parabolic |
| Reflectivity | 92% |
| Thermal Output capacity | 5.5 K.w. |
| Thermal Efficiency | 42%(approximate) |
| Foot print ground area for the Setup | 35 $m^2$ |

**Fig. 2.** Scheffler dish solar concentrator

*2.2. Receiver Configuration*

The Subject study about the cylindrical type receiver with two conditions namely, with and without PCM.Table 2. shows the properties of the the materials that are used for the fabrication of receiver as well as the phase change material used.

**Table 2**: Properties of receiver and PCM

| Properties | Receiver | PCM |
|---|---|---|
| Material | Copper | $NaNo_3$:$KNo_3$(60: 40 by weight) |
| Melting Point | 1084.62 °C | 220°C |
| Specific Heat | 0.385 kJ/kg-K | 1.6 kJ/kg-K |
| Thermal conductivity | 401 W/(m·K) @20˚c | 0.51 W/(m·K) @20˚c |
| Mass, Kg | 4.42 | 5 |

Fig. 3. Shows Computer Aided Design (CAD) model for cylindrical receiver used in experiment. Receiver has outer diameter of 0.33 m and axial length of 0.2 m. Receiver material was chosen as copper for it has great thermal conductivity.

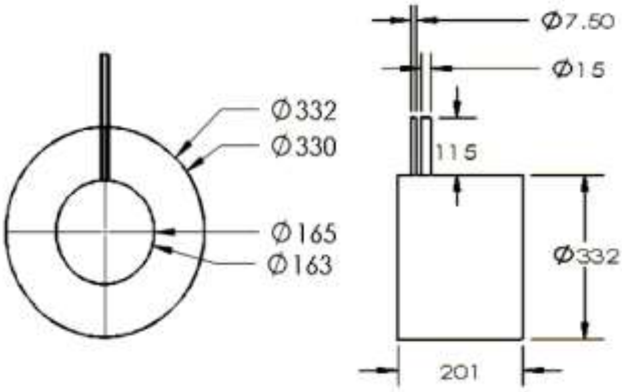


**Fig. 3.** Cylindrical receiver dimensions

Fig. 4(a). shows the receiver containing the solar salt which was used to conduct the experiment. As it is clear from the figure, solar salt is present in the outer cylinder but outside the inner cylinder whereas water is present in the inner cylinder.The cylindrical receiver that only contains the water in the inner cylinder without solar salt is shown in Fig. 4(b). The capacity of the inner cylinder is 4000 ml and can also serve for continuous water circulation as there are two pipes connected to the inner cylinder containing water. The pipe with 15 mm diameter is used as water inlet and the pipe with 7.5 mm diameter is used for steam evaporation. The receiver was painted black to increase the absorptivity.

**(a)** with Solar salt **(b)** without Solar salt

**Fig. 4.** Experimental model of Cylindrical receiver

Experimental study was done for receiver:-
1. Normal position, with PCM and water inlet temperature 30 ˚C.
2. Normal position, without PCM and water inlet temperature 30 ˚C.

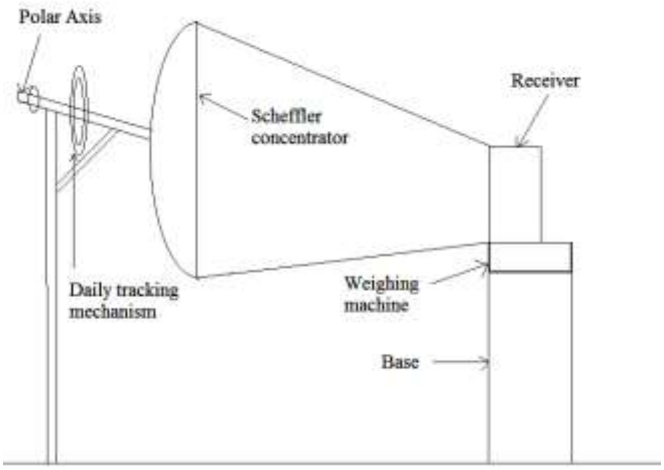


**Fig. 5.** Schematic diagram of the experimental setup

Fig. 5. shows the Schematic diagram of the whole setup consisting of scheffler concentrator as well as receiver along with the tracking mechanism of the concentrator

## 3. Numerical Investigation Using Transient Thermal Analysis

In this case 3D numerical analysis was performed using Transient thermal analysis module. The aim was to study the temperature distribution on receiver surface and mass of evaporated vapour quantity of water giving a mass flow rate of steam. Hence numerically better receiver was identified.

### *3.1. Pre processing: Mathematical Model and Domain*

The initial step of a numerical analysis was to create a geometrical model. The modeling and meshing of the receiver was done in the FEA software itself. The graphical representation of the mesh model of the two cylindrical receivers is represented in fig. 6(a) and fig. 6(b).

**(a)**. With PCM **(b)**. Without PCM

**Fig. 6.** Meshing model for Cylindrical Receiver

The meshing properties of the two receivers geometry used in the Finite element analysis can be seen in the table 3. These data gives a clear idea about the quality of meshing done for the finite element analysis.

**Table 3** : Meshing Properties

| Receiver Type | Meshing Properties | |
|---|---|---|
| | Number of Meshing Elements | Number of Meshing Nodes |
| Receiver with PCM | 32338 | 170210 |
| Receiver without PCM | 110635 | 772755 |

### *3.2. Solver:*

Analysis involving phase change which can be approached using ANSYS Mechanical products are:
(a) The freezing (or solidification) of a liquid.
(b) The melting of a solid.
A phase change analysis must be solved as a thermal transient analysis. Phase change analysis was done considering following points:-
– A small initial and minimum time step size was used.
– The "Line Search" solution option was used in the phase change analysis.
– The material property of Solar salt was not available in Workbench Mechanical Engineering Data. The property was added to the Engineering Data sources and the enthalpy of the solar salt was defined.

### *3.3. Post Processing*

In post processing, the output of simulations from solver were converted to graphics form. In both cases of simulation namely receiver with PCM and receiver without PCM, results were in the form of graphics for normal condition. The temperature distribution on the surface of receiver, solar salt as well as water in the inner cylinder was studied. The volume fraction of water was used to determine the value of mass flow rate, calculated by mass of water evaporated divided by time taken by it.

## 4. Result and Discussions

### *4.1. Results of Experimental Investigation*

A simulation was carried out with the described model and the input data of a sunny day of March. Fig. 7(a). shows the measured Direct Normal Irradiance (DNI), Fig. 7(b). shows the Ambient Temperature and Fig. 7(c) shows the Wind Speed at the test site on March 19, 2018. Data starts at 11 AM and the concentrator is defocused at 3 PM. After the simulation the receiver water was decanted to collect remaining water volume to compute steam generation rate. The results were tabulated along with the numerical results in the section 4.3.

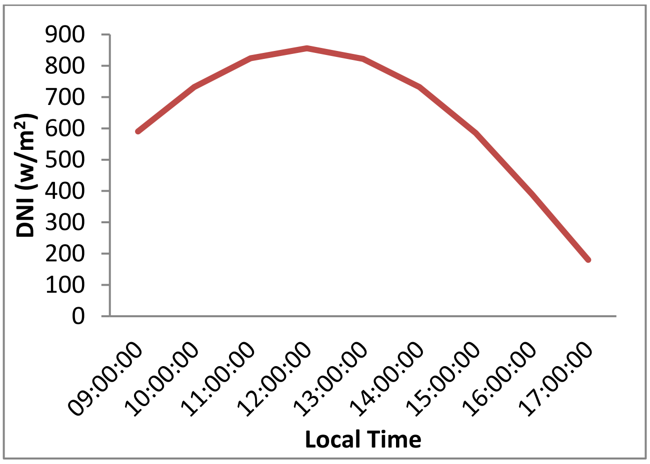


**Fig. 7**(a). DNI as on March 19, 2018

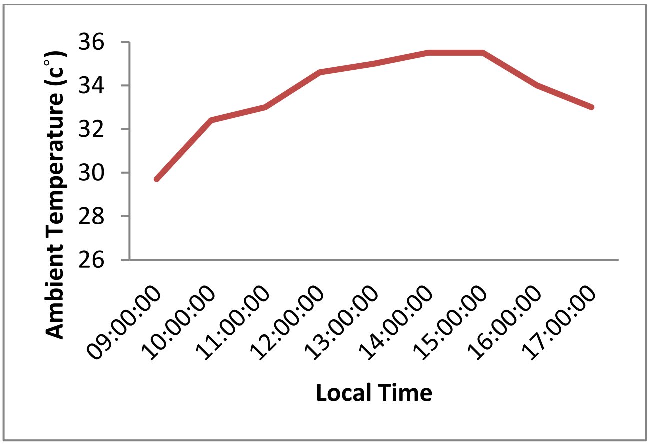


**Fig. 7**(b). Ambient Temperature as on March 19, 2018

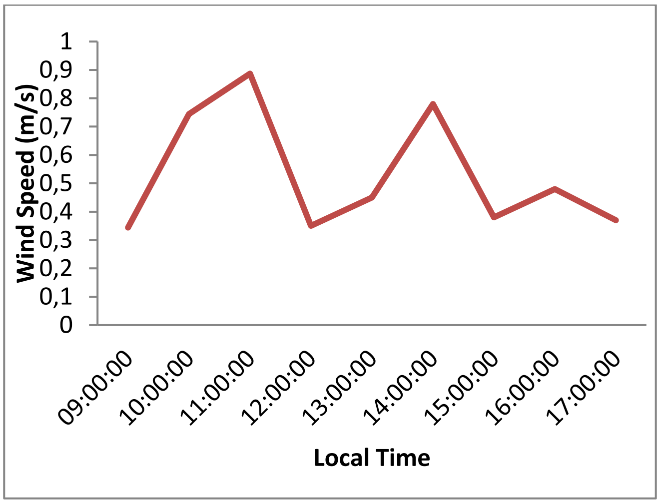


**Fig. 7**(c). Wind speed as on March 19,2018

The rate of evaporation is tabulated with the numerical result in the section 4.3. to show the variation.

### *4.2. Results of Numerical Investigation*

The initial quantity of water was 4000ml which was approximately about the volume of the inner cylinder of the receiver. Fig. 8(a). and Fig. 8(b). shows the distribution of temperature on the outer surface of cylindrical receiver without and with PCM.

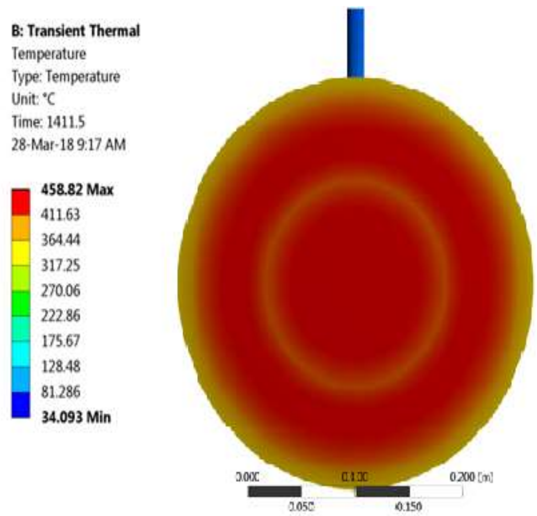


**Fig 8(a)**. Temperature distribution on receiver without PCM while the dish is focused.

From Fig. 8(a). it can be seen that the maximum temperature reached in the cylindrical receiver not containing the solar salt in 45 minutes of focused solar concentrator is 458 ˚C. In the next case simulations was carried out for the cylindrical receiver containing the solar salt in 45 minutes of focused solar concentrator as shown in Fig. 8(b). It was observed that the maximum temperature reached in this case was higher and was about 604 ˚C.

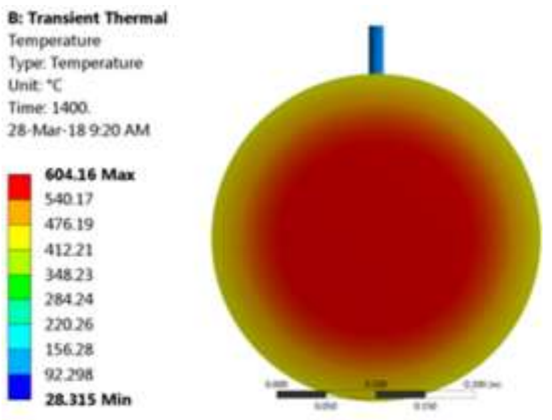


**Fig. 8(b)**. Temperature distribution on receiver with PCM while the dish is focused.

The receiver was kept on the focus of the concentrator for 45 minutes and then the the concentrator was defocused. Both the rise and decline of the maximum temperatures were observed and graphs were plotted as shown in Fig. 9(a). and Fig. 9(b).

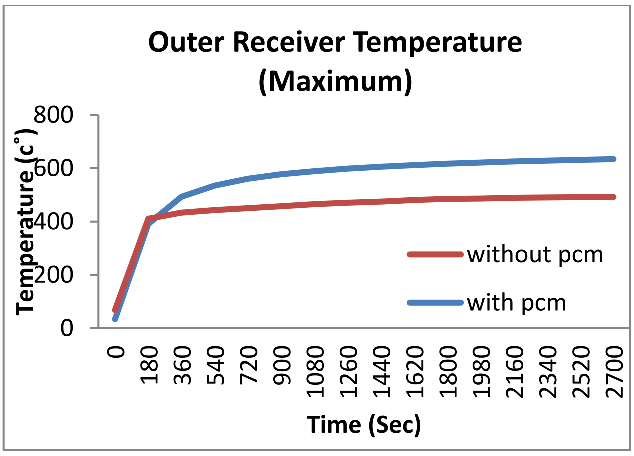


**Fig 9(a)**. Maximum outer receiver Temperatures of the two receivers while the dish is focused

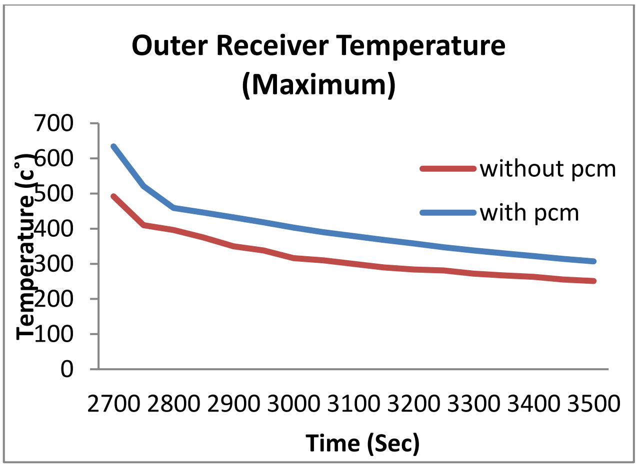


**Fig 9(b)**. Maximum outer receiver Temperatures of the two receivers while the dish is defocused

Fig. 9(a). shows a clear difference in temperature that occurs on the surface of receiver when the solar salt was used and without the solar salt keeping the concentrator focused on the receiver. The receiver with solar salt achieves a higher temperature than that of receiver without the Solar salt. Also, Fig. 9(b). shows the difference in temperature that occurs on the surface of the two receivers when the concentrator is defocused on the receiver. This shows the difference in cooling rate of receiver in both condition of the receiver.

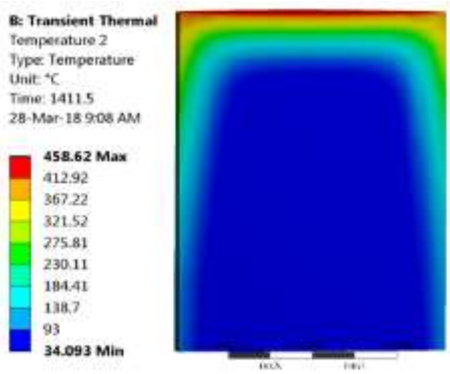


**Fig. 10**(a). Temperature distribution of water without PCM

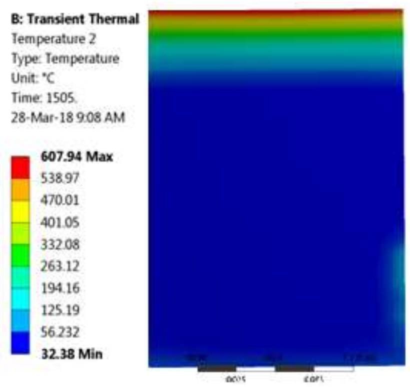


**Fig. 10**(b). Temperature distribution of water with PCM

Fig. 10(a). and 10(b). shows the Temperature distribution in the water of the two receivers graphically. The red part shows the maximum temperature achieved. It can also analyzed that the steam generation in receiver with solar salt is more than without containing it. Also the temperature distribution is more even in the receiver containing the solar salt.

*4.3. Validation of Numerical Investigation*

**Table 4.** : Comparison of Numerical and Experimental Mass Flow rate Without and With PCM

| **Parameters** | **Mass Flow Rate of Steam ( Kg/hr )** | | **Percentage difference (%)** |
|---|---|---|---|
| | **Numerical** | **Experimental** | |
| Without PCM | 0.72 | 0.65 | 9.72 |
| With PCM | 0.87 | 0.8 | 8.04 |

The numerical results show a good agreement with the experimental values. The percentage difference between the numerical and the experimental result was also below 10%. Higher quantity of steam was converted when the phase change material was used in the receiver with an inlet temperature of water of 30 ˚C.

## 3. Conclusion

Numerical and Experimental analysis was carried out for two receivers under same ambient condition with inlet water temperature 30˚C. The emphasis was on investigation of temperature distribution and mass flow rate of steam as it is an essential parameter to design any application of solar concentrator and use solar power. As solar salt stores the thermal energy, it acts as a thermal battery reducing the fluctuations in heat and rising the overall temperature of the receiver. The analysis showed that the cylindrical receiver containing the solar salt gives better steam generation rate than the same receiver without the solar salt.

The experimental results collaborate with Numerical investigation within 10% of each other and thus validating the numerical analysis using Transient Thermal Analysis. The graphical representation of temperature distribution helps to understand the change in steam generation and also shows uneven heating in receiver not containing the solar salt. It can now be expected that the receiver model developed can be used for further study to optimize its performance for better.

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