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Thermodynamic Analysis of Phase Change Material Based Thermal Energy Storage System for A Solar Power Plant

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Abstract: **In recent times emissions of harmful gases like CO_2 can cause hazardous effect on the environment. There are several ways to reduce these emissions. Application of Renewable energy sources is a common and effective method to overcome these problems. Here, in this paper the analysis on Hybrid type Thermal Energy Storage (TES) technology in a Solar Power Plant with suitable Phase Changing Material (PCM) and Heat Transfer Material (HTF). TES stores the thermal energy by heating the PCM with the help of HTF. Later this energy can be used in heating and vaporizing the water into steam and utilize in the power plant. The suitable PCM and HTF to generate a certain amount of power is analyzed in this paper.**

Keywords — Concentrated Solar Plants, Thermal energy storage, Phase change materials, Heat Transfer Fluid, Sensible Heat, Latent Heat.

I. INTRODUCTION

Currently, energy, environment and sustainable development are the major concerns to the countries all over the world. The long-term usage of fossil fuels (e.g., coal, oil and natural gas) has caused environment pollutions and greenhouse effects. The resulting global climate change and resource exhaustion can seriously threaten human survival and development. Renewable energy sources, including solar, wind, hydro, geothermal, etc. [1], have been increasingly attractive to many countries for their natural advantages on sustainability and cleanliness. Solar energy is considered as one of the most promising renewable energy sources, because of its abundance and easy-access to the most parts of the world. However, due to the intermittency in availability and constant variation of solar radiation, the output of a solar energy system is highly fluctuating if no or small inertia (thermal or electrical) is included. This poses strong needs for energy storage in solar energy systems to store energy at high solar irradiances for later uses whenever there is a demand while solar irradiance is not enough. With the energy storage systems associated to reduce the discrepancy between the demand and supply, solar energy systems can be more reliable and efficient in operation.

In order to develop efficient and economical energy storage systems, various energy storage technologies have been proposed [2], such as compressed air energy storage, pumped storage hydro-power, flywheel energy storage, thermal energy storage, electrochemical energy storage, hydrogen storage and so on. They are employed in different application fields depending on their specific characteristics on energy storage. Among all the storage methods, thermal energy storage (TES) is one of the most economical systems in practical applications, and it allows the storage of thermal energy by heating or cooling a storage medium to be used at a later time [3]. TES has been applied in a broad range of fields: district heating, domestic hot water, thermal comfort, concentrated solar plants (CSP), chemical industry, food industry, etc. [4, 5, 6, 7]. It has also been proven that the usage of TES can improve the performance of whole system operation, save the fuel consumption, lower the investment and operation costs, increase the energy supply security and mitigate the pollution to the environment if it is appropriately designed. To obtain the above benefits for an energy system, it is critical to choose a suitable thermal energy storage approach. The selection of thermal energy storage depends on the type of energy source, required storage duration, operating condition, economic viability, etc. The most mature and widely used approach is sensible heat storage. Latent heat storage and thermochemical energy storage have also attracted extensive research and development efforts in the last two

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decades, as they can offer higher heat storage capacities and lower heat losses during the energy storage processes.

II. SOLAR POWER PLANT WITH TES

Solar thermal storage (STS) refers to the accumulation of energy collected by a given solar field for its later use. In the context of this chapter, STS technologies are installed to provide the solar plant with partial or full dispatchability, so that the plant output does not depend strictly in time on the input, i.e., the solar irradiation. STSs are TES systems where the source of heat is provided by the solar field, capturing the excess of energy not directly converted into power or other useful utility. As such, most TES technologies known can be adapted and have been adopted in solar applications, in particular for power production. A detailed review on this topic can be found in the literature.

The selection of an STS is determined by a set of physical, chemical, environmental, and economic properties.

- Energy density of the storage material
- Heat transfer and mechanical properties
- Chemical compatibility and stability
- Thermodynamic reversibility
- Environmental impact
- Thermal losses
- Cost

To these properties one may add automation and control and health and safety requirements as factors that influence the performance of STS when integrated in a given solar plant. Efforts made toward enhancement of a particular property often results in trade-off situations. For instance, effort in heat transfer improvements brings about normally a cost increase. Thus, designing and operating STS is not always an off-the-shelf pick-up process.[8]

Basic thermodynamics of energy storage

There are three types of TES systems: sensible heat storage, latent heat storage, and thermochemical storage. Table 1.3 shows characteristics for the three types of TES plus the electrical storage, for comparison purposes.

Sensible heat storage

When the energy is stored increasing or decreasing the temperature of a storage material, sensible heat storage is occurring. The storage material can be water, air, oil, rock beds, brick, concrete, etc. Each material has its own advantages and disadvantages, but usually the material is selected according to its heat capacity and the available space for storage.

The amount of energy stored is calculated following the Eq. (1.1):

$$Q = m\, C_P\, \Delta T \qquad (1.1)$$

Here,

Q is the amount of heat stored in the material (J),

m is the mass of storage material (kg),

C_P is the specific heat of the storage material (J/kg-K), and

ΔT is the temperature change (K).

Latent heat storage

Latent heat storage uses the phase transition of a material. Usually, solid-liquid phase change is used, by melting and solidification of a material. Upon melting heat is transferred to the material, storing large amounts of heat at constant temperature; the heat is released when the material solidifies. Materials used for latent heat storage are called PCMs.

The amount of heat stored is calculated following the Eq. (1.2):

$$Q = m\, \Delta h \qquad (1.2)$$

Here

Q is the amount of heat stored in the material (J),

m is the mas of storage material (kg), and

Δh is the phase change enthalpy (J/kg).

The advantages Latent Heat Storage (LHS) are

- It has a high storage density. Small temperature changes can result in storing large amounts of heat.
- As the change of phase at a constant temperature is a time-consuming process, it becomes possible to smooth temperature variations.

Thermochemical energy storage

Thermochemical energy storage is produced when a chemical reaction with high energy involved in the reaction is used to store energy. The products of reaction should be able to be stored and the heat stored separately during the reaction should be able to be retrieved when the reverse reaction takes place (Mehling and Cabeza, 2008). Therefore, only reversible reaction can be used for this storage process.

The advantages of thermochemical energy storage include the following

- There is no requirement of insulation as the components can be stored separately.
- Since there is less heat loss, energy can be stored for a very long term.

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- The energy density is high compared to PCMs. Hence it provides more compact energy storage [9].
- Consumption of less space.

TES systems can store heat or cold to be used later, at different conditions such as temperature, place, or power. Implementing storage in an energy system provides benefits like better economics, reduction of pollution and CO_2 emissions, better performance and efficiency, and better reliability.

When designing TES systems several requirements should be considered: high energy density in the storage material, good heat transfer between the HTF and the storage material, mechanical stability, chemical stability, storage material and container compatibility, reversibility, low thermal losses, and easy control.

III. PHASE CHANGE MATERIAL

Phase Change Materials for TES provides an elegant and realistic solution to increase the efficiency of the storage and use of energy in many domestic and industrial sectors [10–16]. The application of PCMs for energy storage reduces the mismatch between supply and demand, improves the performance and reliability of energy distribution networks and plays an important general role in conserving energy [11,17–20]. PCMs exhibit a high enthalpy of fusion with the ability, in a relatively small volume, to store or release large amounts of energy as latent heat during melting and solidification. Additionally, practical PCMs require their upper and lower phase transition temperatures to be within the operational temperature range for a given application and possess high thermal conductivity for efficient heat transfer with congruent phase-change behavior to avoid irreversible separation of their constituents [21,22].

Classification of PCMs

Over the last 40 years different classes of materials, including hydrated salts, paraffin waxes, fatty acids, the eutectics of organic and non-organic compounds and polymers have been considered as potential PCMs.

PCMs can be divided into three main groups – based on the temperature ranges over which the TES phase transition occurs:

(i) Low temperature PCMs -

With phase transition temperatures below 15˚C, usually used in air conditioning applications and the food industry;

(ii) Mid temperature PCMs -

The most popular – with phase transition temperatures in the range 15–90˚C with solar, medical, textile, electronic and energy-saving applications in building design;

(iii) High temperature PCMs -

With a phase transition above 90˚C developed mainly for industrial and aerospace applications [15,23].

PCMs can also be classified by their mode of phase transition: gas–liquid, solid–gas, solid–liquid and solid–solid systems.

Among the various PCMs, the Inorganic PCMs are considered in this paper for the Solar Power System due to the high heat of fusion and high melting point temperature. Different inorganic PCMs with their above-mentioned properties are mentioned in the below table;

Compound	Melting temperature (˚C)	Heat of fusion (KJ/Kg)
$AlCl_3$	192	280
$LiNO_3$	250	370
$NaNO_3$	307	172
KNO_3	333	266
Na_2O_2	360	314
KOH	380	150
$KClO_4$	527	1253
LiH	699	2678
$MgCl_2$	714	452
NaCl	800	492
Na_2CO_3	854	276
KF	857	452
LiF	868	932
K_2CO_3	897	235
NaF	993	750
MgF_2	1271	936

IV. HEAT TRANSFER FLUID

Heat Transfer Fluid (HTF) is one of the most important components for overall performance and efficiency of CSP systems. Since a large amount of HTF is required to operate a CSP plant, it is necessary to minimize the cost of HTF while maximizing its performance. Besides transferring heat from the receiver to steam generator, hot HTF can also be stored in an insulated tank for power generation when sunlight is not available.

The heat transfer fluids are classified into the following categories,

i. Air,
ii. Water/Steam,
iii. Thermal Oil,
iv. Organics,
v. Molten Salts,
vi. Liquid Metals.

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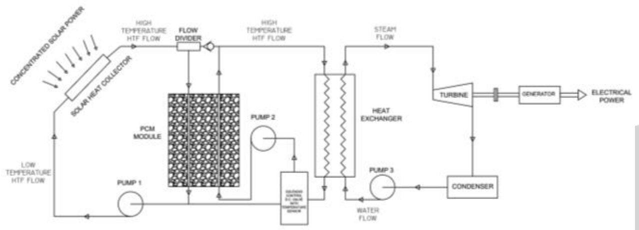
Among the above said fluids molten salts are considered for this system due to its high range of working temperature and better thermal conductivity.

Molten salts: Solar molten salts are salt mixtures, mainly nitrates, which can be used for thermal storage applications as well as heat transfer fluids thanks to their chemical characteristics. Molten salts exhibit many desirable heat transfer qualities at high temperature: high density, high specific heat capacity, high thermal stability and very low vapor pressure. Moreover, molten salts are cheaper and have less environmental impact than synthetic oil: they are non-polluting, nonflammable, more abundant and offer cost savings because of reduced thermal tanks and piping. The major challenge of molten salts is their high freezing point which leads to operations and maintaining costs for freeze protection.



V. SCHEMATIC DIAGRAM OF THE CSP

The following are the main components of the Conceptual Solar Power Plant,

a. Solar Concentrator,
b. Receiver,
c. Pump,
d. PCM Module,
e. Flow Divider,
f. Direction Control (D.C.) Valve,
g. Heat Exchanger,
h. Turbine,
i. Generator, and
j. Condenser.

The following are the assumptions taken for the design and calculations of the solar power plant,

a. Power Plant capacity is 0.5 MW.
b. Efficiency of the cycle is 30%.
c. Loss of heat during the process is negligible and thus ignored.
d. Duration of sunlight is 12 hours.
e. The flow divider split the input flow equally i.e., output flow ratio is 1:1.
f. The range of temperature of HTF assumed to be within the stability limit.
g. The specific heat of HTFs is considered to be constant for the working range.

VI. CALCULATIONS

Considering a 0.5 MW Solar Power Plant, the amount of PCM material and HTF material are required to be determined. Among the various PCM and HTF materials (discussed in Chapter-4 and Chapter-5), some suitable materials are considered and calculations are made accordingly.

We know the efficiency of the cycle,

$$\eta = \frac{W_{NET}}{Q_1}$$

Here,

$W_{NET} = net\ work\ done.$

$Q_1 = heat\ supplied.$

Let us consider the Efficiency (η) is 30%.

Now, for 0.5 MW Solar Power Plant we get,

$$0.3 = \frac{0.5}{Q_1}$$

Or, $Q_1 = \frac{0.5}{0.3}$

$\therefore Q_1 = 1.67$ MW

Again, we can write

The amount heat supplied by the Heat Transfer Fluid $(Q') = (m'_{HTF} \times C_P \times \nabla T)$

Now, $(m'_{HTF} \times C_P \times \nabla T) = 1.67 \times 10^3$

Or, $\{m'_{HTF} \times C_P \times (T_1 - T_2)\} = 1.67 \times 10^3$

From this equation, considering the suitable HTF material, the mass flow rate of HTF can be determined.

In the night time or the time when the sunlight is insufficient, the heat will be transferred from the Phase Changing Material.

Considering 12 hours of night time or insufficient sunlight we can write,

The total amount of heat required $= 1.67 \times 10^3 \times 12 \times 3600$

The amount of heat absorbed from the PCM by the HTF to operate the plant during night time or the time when the sunlight is insufficient $(Q_2) = m_{PCM} \times L_{PCM}$

Therefore,

$m_{PCM} \times L_{PCM} = 1.67 \times 10^3 \times 12 \times 3600$

From this equation, considering the suitable PCM material, the mass of the PCM can be determined.

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The calculation is further programmed in MATLAB for ease in calculation.

```
clc
close all
n= input("Enter the value of n:");
Wnet= input("Enter the value of Wnet:");
Q1=(Wnet/n);
Cp= input("Enter Cp:");
T1= input("Enter T1:");
T2= input("enter T2:");
MHTF=((Q1*10^3)/(Cp*(T1-T2)));
t= input("Enter the time when sunlight is insufficient");
Htotal=Q1*10^3*t*3600;
LPCM= input("Enter the value of LPCM:");
mPCM= Htotal/LPCM;
fprintf('the mPCM is %d\n', mPCM)
```

MATLAB Program:

Analysis-1

MATLAB Workspace 2:58:37 PM
June 10, 2023

Name	Value	Size	Class
Cp	0.913	1×1	double
Htotal	72000000	1×1	double
LPCM	2678	1×1	double
MHTF	3.0425	1×1	double
mPCM	26886	1×1	double
n	0.3	1×1	double
Q1	1.6667	1×1	double
t	12	1×1	double
T1	850	1×1	double
T2	250	1×1	double
Wnet	0.5	1×1	double

Considering, Na-K-Zn Chloride as the HTF and LiH as the PCM in analysis-1

Analysis-2

MATLAB Workspace 1:22:16 PM
June 13, 2023

Name	Value	Size	Class
Cp	1.44	1×1	double
Htotal	72000000	1×1	double
LPCM	2678	1×1	double
MHTF	2.7233	1×1	double
mPCM	26886	1×1	double
n	0.3	1×1	double
Q1	1.6667	1×1	double
t	12	1×1	double
T1	500	1×1	double
T2	75	1×1	double
Wnet	0.5	1×1	double

Considering, Halotechnics SS-500 as the HTF and LiH as the PCM in analysis-2

Analysis-3

MATLAB Workspace 4:13:38 PM
June 13, 2023

Name	Value	Size	Class
ans	0.3	1×1	double
Cp	1.091	1×1	double
Htotal	72000000	1×1	double
LPCM	2678	1×1	double
MHTF	3.2503	1×1	double
mPCM	26886	1×1	double
n	0.3	1×1	double
Q1	1.6667	1×1	double
t	12	1×1	double
T1	600	1×1	double
T2	130	1×1	double
Wnet	0.5	1×1	double

Considering, Na-K-Li Nitrates as the HTF and LiH as the PCM in analysis-3

Analysis-4

MATLAB Workspace 5:07:31 PM
June 13, 2023

Name	Value	Size	Class
Cp	1.1	1×1	double
Htotal	72000000	1×1	double
LPCM	2678	1×1	double
MHTF	3.9872	1×1	double
mPCM	26886	1×1	double
n	0.3	1×1	double
Q1	1.6667	1×1	double
t	12	1×1	double
T1	600	1×1	double
T2	220	1×1	double
Wnet	0.5	1×1	double

Considering, Solar Salt as the HTF and LiH as the PCM in analysis-4

Analysis-5

MATLAB Workspace 5:50:03 PM
June 13, 2023

Name	Value	Size	Class
Cp	0.79	1×1	double
Htotal	72000000	1×1	double
LPCM	2678	1×1	double
MHTF	4.9063	1×1	double
mPCM	26886	1×1	double
n	0.3	1×1	double
Q1	1.6667	1×1	double
t	12	1×1	double
T1	700	1×1	double
T2	270	1×1	double
Wnet	0.5	1×1	double

Considering, Halotechnics SS-700 as the HTF and LiH as the PCM in analysis-5

Analysis-6

MATLAB Workspace 5:13:42 PM
June 13, 2023

Name	Value	Size	Class
Cp	0.81	1×1	double
Htotal	72000000	1×1	double
LPCM	1253	1×1	double
MHTF	3.2661	1×1	double
mPCM	57462	1×1	double
n	0.3	1×1	double
Q1	1.6667	1×1	double
t	12	1×1	double
T1	850	1×1	double
T2	220	1×1	double
Wnet	0.5	1×1	double

Considering, Na-K-Zn Chloride as the HTF and $KClO_4$ as the PCM in analysis-6

Analysis-7

Considering, Halotechnics SS-500 as the HTF and $KClO_4$ as the PCM in analysis-7

MATLAB Workspace 5:25:16 PM
June 13, 2023

Name	Value	Size	Class
Cp	1.22	1×1	double
Htotal	72000000	1×1	double
LPCM	1253	1×1	double
MHTF	3.2144	1×1	double
mPCM	57462	1×1	double
n	0.3	1×1	double
Q1	1.6667	1×1	double
t	12	1×1	double
T1	500	1×1	double
T2	75	1×1	double
Wnet	0.5	1×1	double

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Analysis-8

Considering, Na-K-Li Nitrates as the HTF and $KClO_4$ as the PCM in analysis-8

MATLAB Workspace 5:20:07 PM
June 13, 2023

Name	Value	Size	Class
Cp	1.091	1×1	double
Htotal	72000000	1×1	double
LPCM	1253	1×1	double
MHTF	3.3948	1×1	double
mPCM	57462	1×1	double
n	0.3	1×1	double
Q1	1.6667	1×1	double
t	12	1×1	double
T1	600	1×1	double
T2	150	1×1	double
Wnet	0.5	1×1	double

Analysis-9

MATLAB Workspace 5:28:14 PM
June 13, 2023

Name	Value	Size	Class
Cp	1.1	1×1	double
Htotal	72000000	1×1	double
LPCM	1253	1×1	double
MHTF	3.9872	1×1	double
mPCM	57462	1×1	double
n	0.3	1×1	double
Q1	1.6667	1×1	double
t	12	1×1	double
T1	600	1×1	double
T2	220	1×1	double
Wnet	0.5	1×1	double

Considering, Solar Salt as the HTF and $KClO_4$ as the PCM in analysis-9

Analysis-10

Considering, Halotechnics SS-700 as the HTF and $KClO_4$ as the PCM in analysis-10

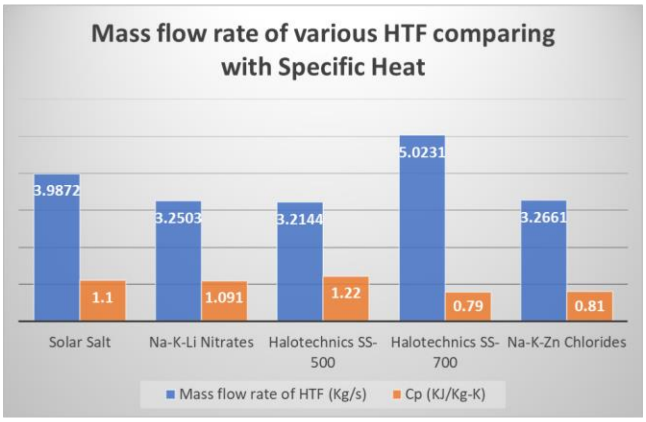
MATLAB Workspace 5:46:41 PM
June 13, 2023

Name	Value	Size	Class
Cp	0.79	1×1	double
Htotal	72000000	1×1	double
LPCM	1253	1×1	double
MHTF	5.0231	1×1	double
mPCM	57462	1×1	double
n	0.3	1×1	double
Q1	1.6667	1×1	double
t	12	1×1	double
T1	700	1×1	double
T2	280	1×1	double
Wnet	0.5	1×1	double

VII. CONCLUSION

The PCM based Thermal Energy Storage for A Solar Power Plant can be implemented in different areas and has the potential to meet the global energy demand. This method also put an end to the obstacle of intermittency. In this paper different combinations of Phase Changing Material and Heat Transfer Material are analyzed and results are obtained accordingly. The results help to select a suitable Phase Changing Material and Heat Transfer Material depending on various thermal properties.

The following bar chart shows the mass flow rate of the HTF along with the specific heat of respective HTF.



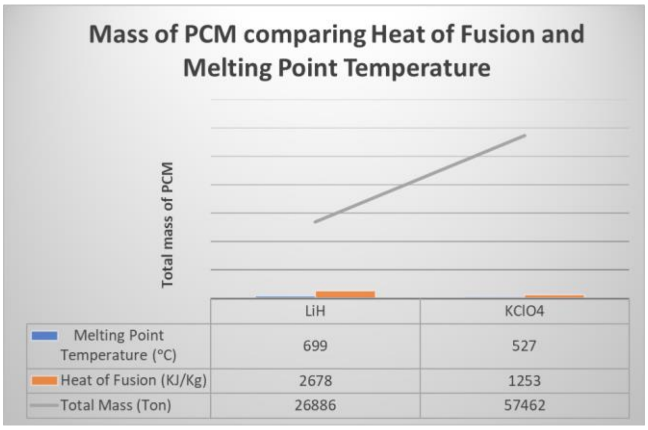
7.1. Mass flow rate of various HTF comparing with Specific Heat

From the bar chart, it is obtained that Na-K-Zn Chlorides, Na-K-Li Nitrates and Halotechnics SS-500 are the most suitable HTF used in the system. The properties of those HTFs are compared and described in the table 7.1.

7.1. Thermal properties of the suitable HTFs [24,25,26,27,28]

HTF	Na-K-Zn Chlorides	Na-K-Li Nitrates	Halotechnics SS-500
Composition	NaCl (7.5)–KCl (23.9)–$ZnCl_2$ (68.6)	$NaNO_3$ (28)–KNO_3 (52)–$LiNO_3$ (20)	$NaNO_3$ (6)–KNO_3 (23)–$LiNO_3$ (8)–$CsNO_3$ (44)–$Ca(NO_3)_2$ (19)
Melting point (°C)	204	130	65
Stability limit (°C)	850	600	500
Viscosity (Pa s)	0.004 (at 600– 800 °C)	0.03 (at 300 °C)	N/A
Thermal conductivity (W m-1 K-1)	0.325 (at 300 °C)	N/A	N/A
Heat capacity (kJ kg-1 K-1)	0.81 (at 300– 600 °C)	1.091	1.22 (at 150 °C)

The mass of specific PCMs depending on the heat of fusion and the melting point temperature are showing in the following chart.



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7.2. Mass of PCM comparing Heat of Fusion and Melting Point Temperature

From the chart, it is obtained that mass of LiH utilized compare to $KClO_4$ is much less. The essential properties of LiH and $KClO_4$ are described in the table 7.2.

7.2. Properties of the suitable PCMs

Material	$KClO_4$	LiH
Physical properties	Clear colorless to slightly yellow, Odorless.	Off-white, Grey, or translucent;
Molar Mass (g/mol)	138.55	7.95
Density (g/cm^3)	2.52	0.76-0.8
Melting Point	400°C	680 °C
Boling Point	400°C	900-1000 °C
Specific Gravity	2.52	0.82
Risk Codes	Explosive when mixed with combustible material, Harmful if swallowed.	LiH forms dust clouds that may explode when they come in contact with heat, flame, or oxidizing materials.

The study on Phase Changing Material (Chapter-4) and Heat Transfer Material (Chapter-5) allow to choose the suitable material required for a the PCM based Thermal Energy Storage for a Solar Power Plant having specific capacity. The analysis is also performed in MATLAB which creates an easy and effective way for future work.

In this paper some of the conditions are considered as identical. Conditions like heat loss during the process must be reduced to zero which cannot be completely achievable but with suitable insulating method the amount of heat loss can be negligible. The efficiency of the power generation cycle can also be improved with some upgradations and modifications.

Currently, implementation of renewable energy sources to generate power is extensively required. This paper based on such a concept can be effective from environmental perspective.

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