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# Simulation of thermocline thermal energy storage system using C

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**ABSTRACT:** Solar thermal power generation is a modern technology, which has already shown feasible results in the production of electricity. Thermal energy storage (TES) is a crucial element in solar energy applications, which includes the increase of building thermal capacity, solar water heating systems for domestic use, and Concentrated Solar Thermal power plants for electricity generation. Economic, efficient and reliable thermal energy storage systems are a key need of solar thermal power plants, in order to smooth out the insolation changes during intermittent cloudy weather condition or during night period, to allow the operation. To address this goal, based on the parabolic trough power plants, sensible heat storage system with operation temperature between 300°C – 390°C can be used. The goal of this research is to design TES which can produce 1MWe. In this work simulation is performed to analyze the Liquid medium STES using C. In this case different liquid medium TESs is investigated and out of all mixed-media single-tank thermocline TES is selected and designed based on the Schumann equation. In particular, this equation is numerically solved, in order to determine energy storage, at different locations and time inside the storage tank. Finally, due to their feasibility, low cost of manufacturing and maintenance are designed and sized to the minimum possible volume.

**KEYWORDS:** Sensible thermal Energy storage, single tank, thermocline, modeling, minimum volume.

## 1 INTRODUCTION

Thermal energy storage (TES) is a critical element in solar energy applications, including in the increase of building thermal capacity, solar water heating systems for domestic use, and Solar Thermal power plants for electricity generation. In order to meet the changes in solar radiation and peak demands a fully functional storage system may be required in a solar thermal power plant. The usage of relatively cheap storage system is the major advantage of solar thermal power plant compared with other power plants. For continuous operation of the plant the thermal energy storage system is used which store energy and can smooth out the plant operation during intermittent cloudy weather conditions also. Therefore, thermal storage plays an important role with the key technologies on economics of energy for the future success of solar thermal technology.

Molten-salt thermocline TES for solar thermal power plants can: (1) offer power plants the potential to continuously deliver electricity without fossil-fuel backup; (2) meet peak demand independent of weather conditions; (3) increase the storage temperature above 450$^{o}$C to raise the Rankine cycle efficiency above 40% ; and (4) save 35% of cost compared to a two-tank storage system. In a molten-salt thermocline, a molten salt (e.g., Hitec or Hitec XL) is used as the heat transfer fluid (HTF) that transports the thermal energy between the storage unit and the other sections of the power system such as the collector field and the steam generator. Separation between the hot and cold zones of the molten salt is naturally ensured by buoyancy forces; stable thermal stratification is thus maintained in the fluid in a single tank.

### 1.1 SINGLE-TANK THERMOCLINE SYSTEM

In a single-tank or thermocline system, hot and cold fluids are stored in the same tank. This system provides one possibility for reducing the cost of storage tanks. Here the hot and cold fluids are separated because of the stratification, and the zone between the hot and cold fluids is called the thermocline as shown in Fig. 1.

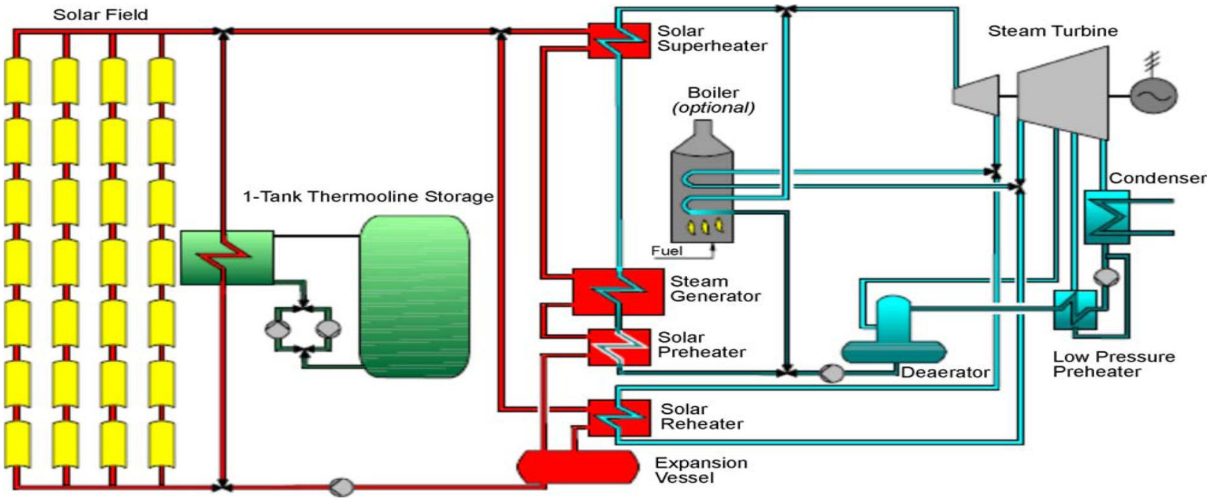


*Fig. 1. Single-tank indirect thermocline thermal energy storage [1]*

#### 1.1.1 CONVENTIONAL SINGLE-TANK THERMOCLINE SYSTEM

The final reduction in storage tank volume is achieved when the storage tank volume equals the storage fluid volume. As shown in Fig. 2, the storage tank is filled with cold fluid at the beginning of the operation. The thermal energy is made available in the form of hot collector fluid and then from the bottom of the storage tank the cold fluid is withdrawn and heated. Then the storage tank is filled with the hot storage fluid again. By doing it properly, the less dense hot storage fluid will “float” on top of the cold storage fluid, creating what is termed a *thermocline*. However, about 10% of height in the storage tank contains mixture of the cold and hot medium. This phenomenon actually occurs quite commonly in many fluid systems ranging from the ocean to residential hot-water heaters.

Conventional single tank systems, due to their thermal stratifications are less desirable and maintaining stratification is much simpler in solid media. But this thermal stratification behaviour can be decreased by designing a new concept of mixed-media single tank thermocline system.

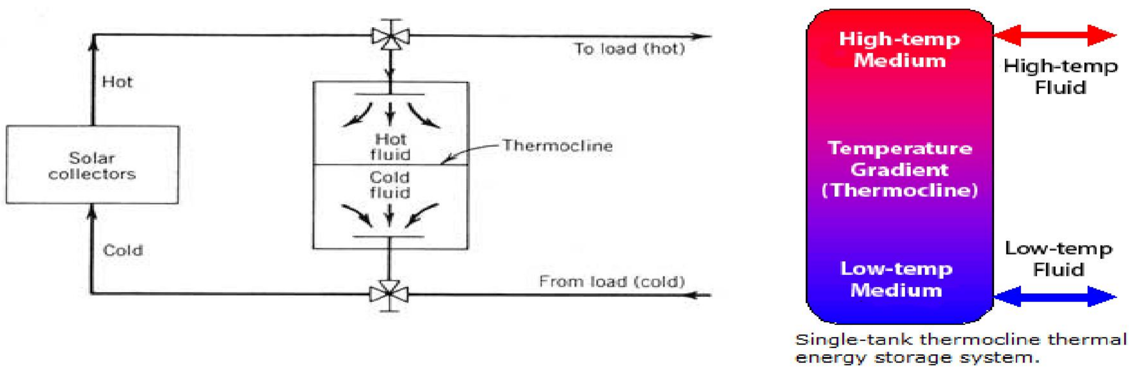


*Fig. 2. Thermocline thermal energy storage*

### 1.1.2 MIXED-MEDIA SINGLE TANK THERMOCLINE SYSTEM

Once the tank volume has been reduced to a minimum through the use of single tank thermocline system, the next step in reducing the capital cost of the storage system is to reduce the cost of the storage fluid as shown in Fig. 3. Organic heat-transfer oils are typically used in high-temperature solar energy systems to avoid the cost of high-pressure plumbing systems. Unfortunately, most organic heat-transfer oils are expensive. Mixed-media thermocline storage systems seek to displace expensive heat-transfer oil inventory in storage with less expensive materials such as rock and sand.

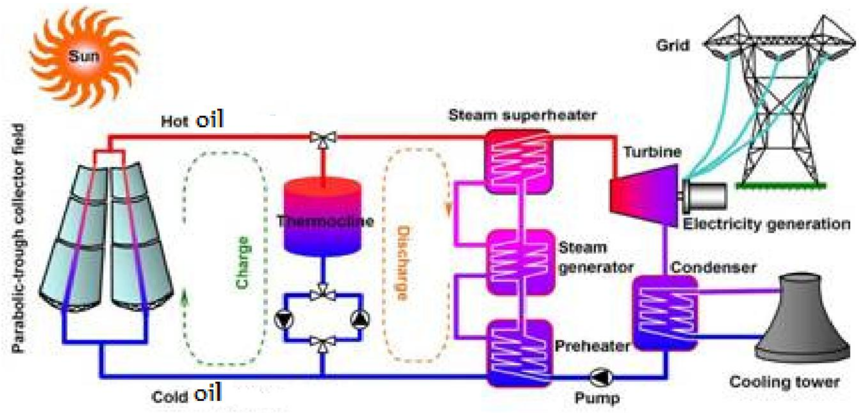


*Fig. 3. Mixed-media single tank thermocline system*

Advantages of the single tank thermocline system are: [1]

- Decrease of storage tanks cost.
- Low cost of the filler materials (rocks and sand).
- Thermocline system is about 35% cheaper than the two-tank storage system.

The disadvantages are:

- It is more difficult to separate the hot and cold HTF.
- Maintaining the thermal stratification requires a controlled charging and discharging procedure, and appropriate methods or devices to avoid mixing.
- Design of storage system inlet and outlet is complex.

## 2 TES ANALYSIS USING MIXED-MEDIA SINGLE TANK THERMOCLINE SYSTEM

The solid medium chosen for this project work is nominally 2.54 cm (1 in.) diameter gravel plus sand. Two sizes are used in the storage tank to obtain the void fraction of about 0.25-0.30. Thus, this concept reduces the quantity of oil used in the conventional thermocline storage by about 75%. Top and bottom manifolds are employed to distribute the heat transfer oil across the cross section of the tank.

The assumptions generally made for methemaical analysis, as shown of heat transfer in a thermocline storage system are the following:

- One dimensional heat flow.
- The fluid flow is one dimensional.
- The bed is assume uniformly packed having the same apparent density and the same uniform apparent thermal capacity throughout.
- The temperature gradient in the radial direction are assumed neglegible.
- No mass transfer.
- Thermal gradients within solid particles are neglected.
- Heat loss to the enviroment neglected.
- Internal heat generation is absent.

The main objective of this design is to obtain a solution for temperature of the rocks (solid) and the fluid as a function of time and distance along the bed. The design procedure is to make a transient heat balance for rocks as well as the fluid.

In order to describe the thermal and geometric properties of the storage as shown in the above Fig. 4 a number of parameters are involved; typically these are particle size, void fraction, storage cross sectional area and storage length, superficial fluid velosity and the Reynolds number.

The porosity or void fraction, $\varepsilon$, is given as:

$$\varepsilon = \frac{void\ volume}{Total\ volume} \tag{1}$$

Volumetric heat transfer coeffiecient:

$$h_v = a * h \tag{2}$$

where *a* is surface area of rocks per unit volume, *h* is the heat transfer coefficient per unit surface area rock.

Superficial mass velocity (mass flux) is:

$$G = \frac{4\dot{m}}{\pi D^2} \tag{3}$$

The energy balance for the fluid element can be written as:

$$\rho\varepsilon A * dx * C_p \frac{\partial T}{\partial t} dt + GA * C_p \frac{\partial T}{\partial x} dx.dt + h_v A * dx\left(T_f - T_s\right)dt + U_L \pi D * dx\left(T_f - T_0\right)dt = 0 \tag{4}$$

where, the first term represents the change in the energy stored in the fluid, the second term the energy carried away (convected away) by the fluid, the third term the energy supplied by fluid to the solid, and the last term the heat loss from the walls to the surroundings.

Then dividing by *Adx* and neglecting heat loss to the surrounding

$$\rho\varepsilon * c_p \frac{\partial T_f}{\partial t} dt + GC_p \frac{\partial T_f}{\partial x} dt + h_v\left(T_f - T_s\right)dt = 0 \tag{5}$$

And again dividing by $\rho\varepsilon C_p$

$$\frac{\partial T_f}{\partial t} + \frac{G}{\rho\varepsilon}\frac{\partial T_f}{\partial x} + \frac{h_v}{\rho\varepsilon C_p}\left(T_f - T_s\right) = 0 \tag{6}$$

Similar heat balance for the solid particles yields

$$\rho_s(1-\varepsilon)c_{ps}\frac{\partial T_s}{\partial t} = h_v(T_f - T_s) \tag{7}$$

Here, the term on the left side accounts for heat capacity of solid (sensible heat storage), and the right hand side accounts heat gain from fluid.

$$\frac{\partial T_s}{\partial t} = \frac{h_v}{\rho_s(1-\varepsilon)c_{ps}}(T_f - T_s) \tag{8}$$

By introducing non-dimensional variables to replaces *x* and *t*:

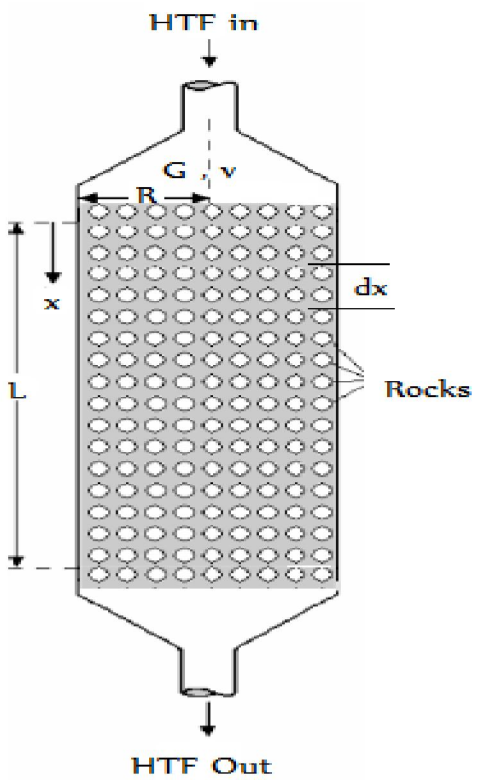


*Fig. 4. Model of mixed media thermocline thermal energy storage*

$$\tau = \frac{h_v t}{\rho_s C_{ps}(1-\varepsilon)} \qquad And \qquad X = \frac{\pi D^2 h_v x}{4\dot{m}C_{pf}} \tag{9}$$

Equations 6 & 7 are solved by Schumann [4] to obtain a non-dimensional temperature distribution. The solution, as a function of non-dimensional X (axial distance) and $\tau$ (time), are given by:

$$\frac{T_s}{T_{fi}} = 1 - e^{-(X+\tau)} \sum_{n=0}^{\infty} X^n \sum_{k=0}^{\infty} \frac{(X\tau)^k}{k!(k+n)!} \tag{10}$$

And $$\frac{T_f}{T_{fi}} = 1 - e^{-(X+\tau)} \sum_{n=1}^{\infty} X^n \sum_{k=0}^{\infty} \frac{(X\tau)^k}{k!(k+n)!} \tag{11}$$

The result of the terms on right hand side of equation 10 & 11 are listed on the Appendix chart result.

The energy stored in the storage material at any instant of time is given by [3]:

$$= \int_0^L [(1-\varepsilon)\rho_s C_{ps}(T_s - T_i) + (\varepsilon\rho_f C_{pf}(T_f - T_i)] \frac{\pi}{4} D^2 dx \tag{12}$$

To determine the temperature distribution within the storage Equations 10 and 11, are solved using. For the results, refer Appendix Chart results.

### 2.1 CALCULATING VOLUME OF THE STORAGE A NUMERICAL SIMULATION PROCEDURE

For this purpose it is assumed that:

- Initially the storage is filled with HTF and sold(Rock) at ambinte temperature of $27^0$C.
- Inlet temperature of the HTF is $300^0$C.
- Mass flow rate is 0.5kg/s.
- Void fraction is 0.28.

Property of the HTF

In the case of the mixed-media thermocline system installed at Barstow, CA, extensive testing of fluid stability in the presence of the hot rocks was performed. The storage fluid chosen was a commercial organic heat-transfer fluid, Caloria HT-43®. This fluid was found to be stable over long periods when in contact with rock of temperatures up to 300$^{o}$C.

Caloria HT 43, is liquid under atmospheric pressure below temperature of 315$^{0}$C. Its operation temperature was between 218$^{0}$ – 302$^{0}$C. It is marketed by, ExxonMobil Lubricants & Specialties.

To produce a saturated steam at T=250$^{0}$C for continues 1 hour at a mass flow rate of the steam at 2.88 kg/s , the energy required is 27.75GJ.

$$Q_s = \rho V C_p \Delta T \tag{13}$$

$$= (\rho V C_p \Delta T)_s + (\rho V C_p \Delta T)_f$$

$$27.75 * 10^9 J = (2245(V)800 * 273)_s + (800(V)2100 * 273)_f$$

$$227.5 = 4.903 V_s + 4.586 V_f$$

***Table 1. Property of Caloria oil and solid rock***

| Property | Caloria HT43 @ 300$^{0}$C [7] | Quartzite and silica sand [4] |
|---|---|---|
| Density | 800 kg/m$^3$ | 2245 kg/m$^3$ |
| Specific heat capacity | 2100 J/(kg.k) | 800 J/(kg.k) |
| Viscosity | 5.0*10$^{-6}$ m$^2$/s | |
| Thermal conductivity | 0.13 w/(m.k) | 0.13 w/(m.k) |

Since the economics of thermocline system are a stronger function of the void fraction, design was done to determine the highest packing density of quartzite and silica sand, based on the experiment done on reference [2], void fraction of 0.28 is taken.

$$\varepsilon = \frac{V_f}{V_f + V_s} \tag{14}$$

$$0.28 V_s = 0.72 V_f$$

Therefore: $V_f = 16.14 m^3$

$$V_s = 41.5 m^3$$

Total volume of the storage is: $V_T = 57.64 m^3$

Number of pieces of rocks, based on reference, average diameter of rock is 2.45cm.

$$V_{rock} = \frac{4}{3}\pi * r^3 \tag{15}$$

$$= 8.58 * 10^{-6} m^3$$

$$N0. of\ pieces\ of\ rocks\ are = 4{,}836{,}690$$

Therefore, if the total volume is divided into six equal parts, size of a single storage is

L = 3.06 m and R = 1 m

### 2.2 Pressure Loss

The pressure loss across a mixed single-tank thermocline storage unit is also is important since large volumes of fluid are being handled. Chandra and Willits [6] have suggested the correlation:

$$\Delta P = \frac{LG^2}{\rho_f d}\varepsilon^{-2.6}\left[1.7 + \frac{185}{R_e}\right] \tag{16}$$

Assuming mass flow rate of 0.5 kg/s

Then $$G = \frac{4\dot{m}}{\pi D^2}$$

= 0.159 kg/(s.m$^2$)

And $$R_e = \frac{Gd}{\mu_f} \tag{17}$$

= 807.72 laminar flow

Therefore the pressure drop is 201 N/m$^2$ on single thermocline storage.

## 3 Results of the Temperature Distribution on a Single Thermocline Thermal Energy Storage

These results are collected based on the value on Appendix Chart result, which are obtained from the compiler after computing Eq. 6 & 7 using C programming. Moreover, all assumptions assumed previously considered here.

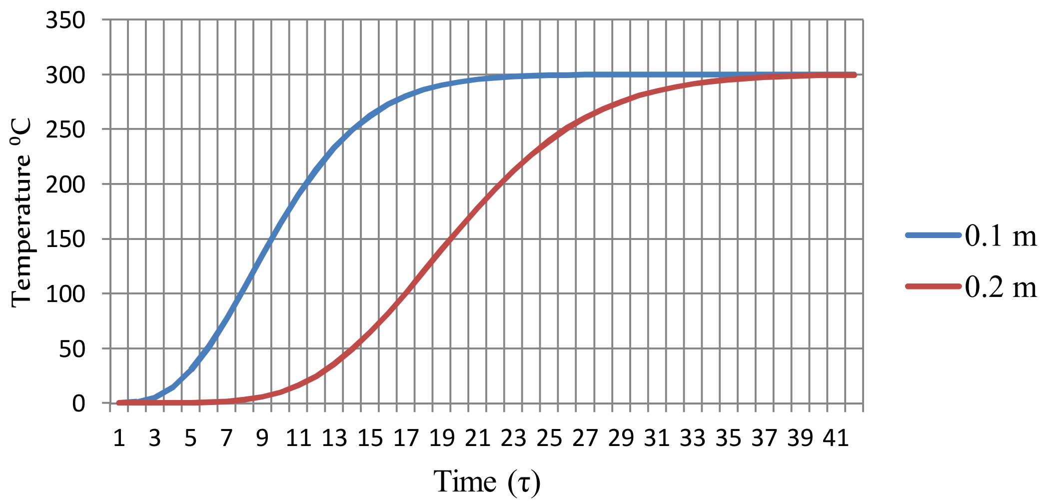


*Fig. 5. Temperature distributions on the HTF (oil) at different positions*

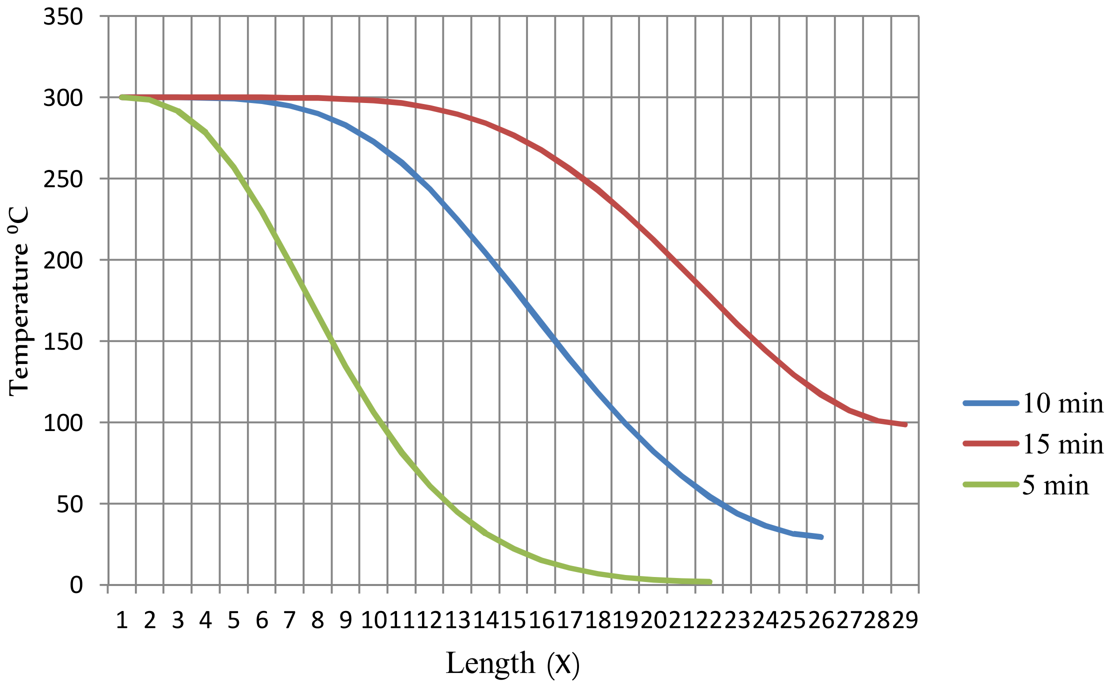


*Fig. 6. Temperature distributions on the HTF (oil) in different times*

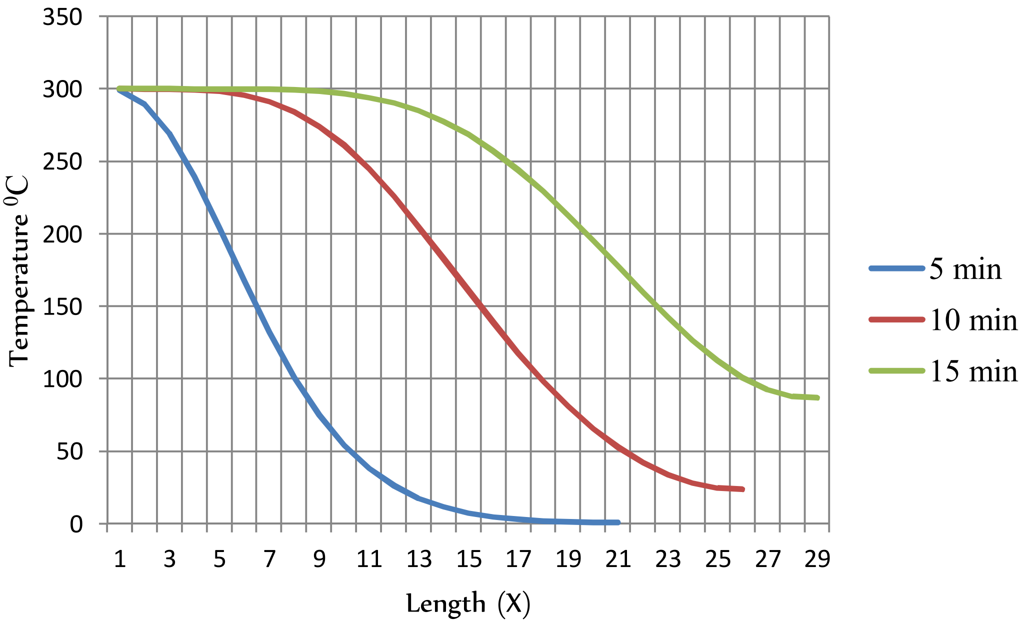


*Fig. 7. Temperature distributions on the solid rocks at different times*

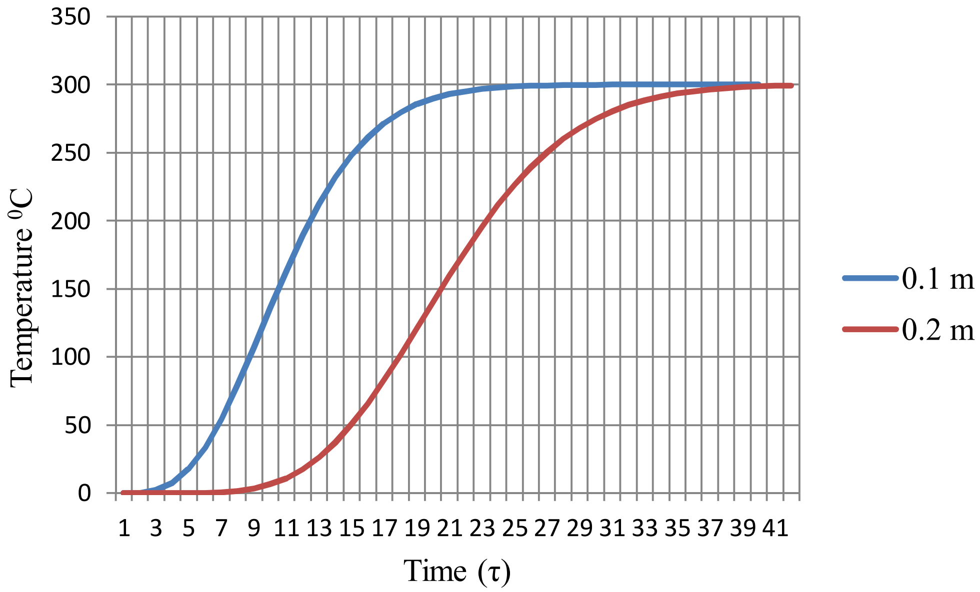


***Fig. 8. Temperature distributions on the solid rocks at different positions***

This temperature vs. time or distance distribution graph Fig. 5, 6, 7 and 8 show temperature decreasing in the direction of flow. Since the hot fluid is supplied from the top, the top part of the storage is higher in temperature than the bottom until temperature equilibrium occurs in the storage.

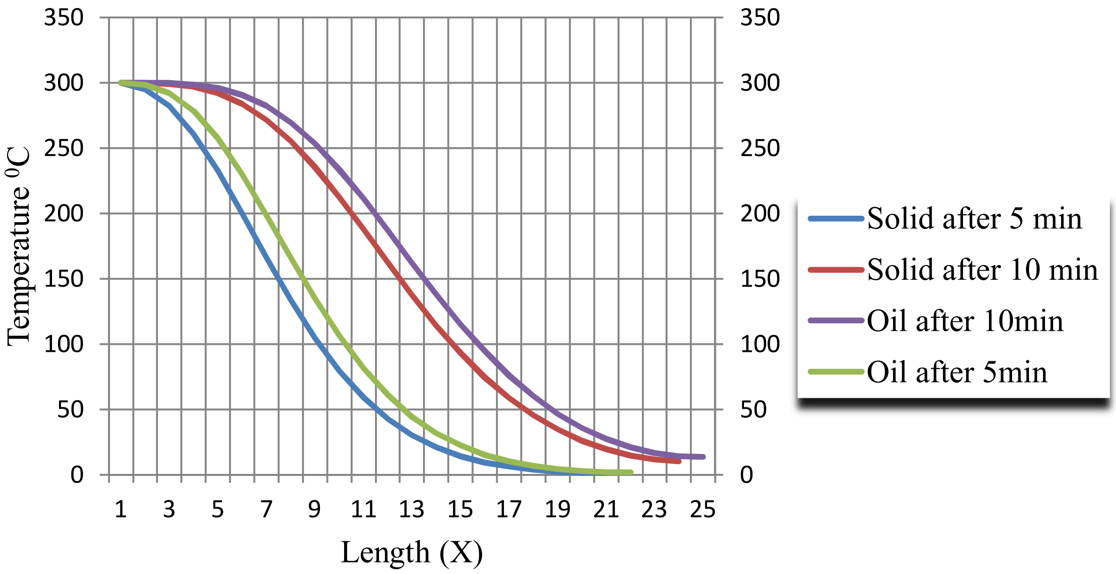


***Fig. 9. Temperature distributions on the storage in different times***

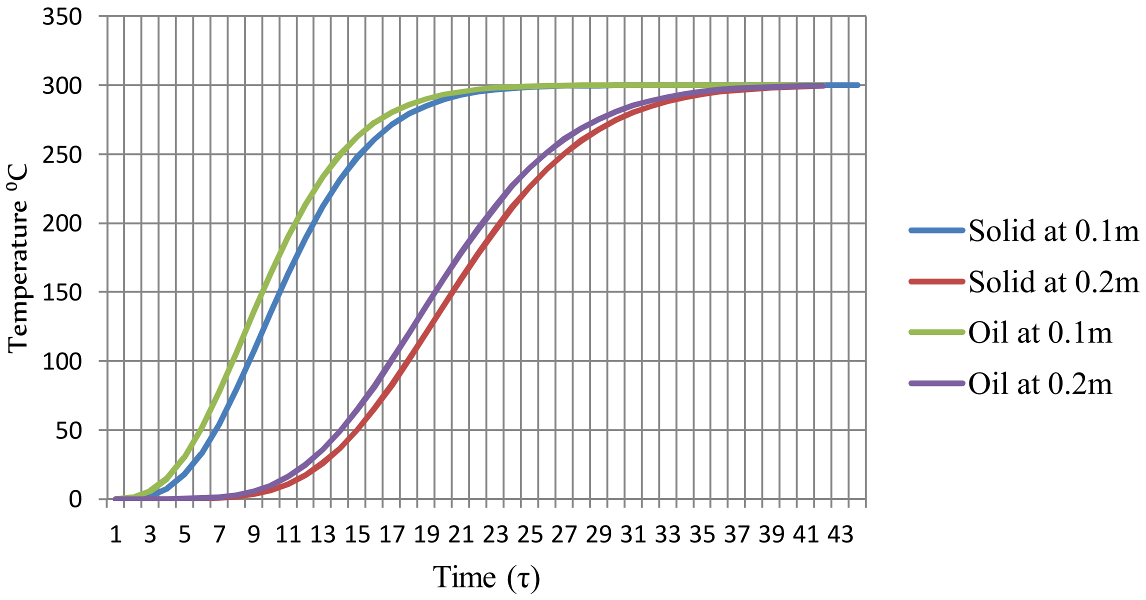


***Fig. 10. Temperature distributions on the storage at different positions***

Figures 9 & 10 show that, temperature of the HTF is greater than the solid rock at any position inside the storage except at the top and bottom that is temperature assumed to be equal.

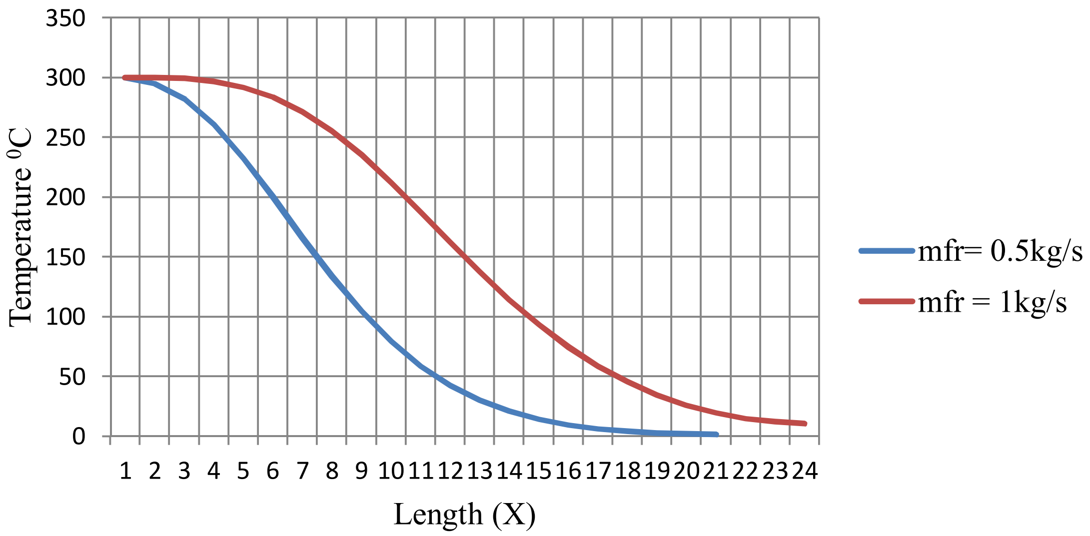


***Fig. 11. Temperature distributions on the solid rocks as the mass flow rate changes***

Figure 11 shows temperature distribution on the storage for which the mass flow rate is increased from 0.5kg/s to 1kg/s. The temperature of the storage also increases or in other words it will be charged faster.

## 4 CONCLUSION

Simulation of thermocline thermal energy storage system is performed using “C” and with careful design of the tank inlet and outlet diffusers, mixing of the hot and cold fluids can be minimized, leading to a rather small transition region between the hot and cold fluid regions. Understanding of particular property of the hot storage fluid and its stability in the presence of hot solid rock in any potential for the catalytic degradation of the fluid. Careful consideration must be paid to the tank design to prevent tank rupture due to stresses. As the tank heats up, its internal volume increases and the solid media settles. When the tank cools, stress builds up at the bottom of the tank as the solid media is compressed.

Based on the literature surveys on different liquid media TESs to select the most optimum, feasible-design TES and by comparing in all these manufacturing cost, design and HTF cost Mixed- media single-tank thermocline system seems cheapest. Total volume of the storage is $V_T = 57.64m^3$. Number of pieces of rocks based on reference [5], average diameter of rock is 2.45cm. $N0. of\ pieces\ of\ rocks\ are = 4{,}836{,}690$. Therefore, if the total volume is divided into six equal parts, size of a single storage is L = 3.06m and R = 1m

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