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Design Optimization & Numerical Evaluation of Parametric Variation on Thermal Energy Storage (tes) Systems in Domestic Hot Water Application

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ABSTRACT

In spite of known advantages ofrenewable energy sources e.g.-solar energy, its use is still limited because of lack of its efficient storage methods and cost effectiveness. This paper includes study of solar domestic water heater application. Present system under investigation consists only water storage tank. It does not include other components of the system such as-flat plate collector etc. Storage temperature of water is modelled as a function of inlet mass flow rate, inlet fluid temperature, outlet mass flow rate, heat loss to ambient throughinsulation placed at outer periphery of the tank. Unsteady heat transport via *conduction through tank, insulationandcombined convection and radiationheat loss to the ambient* are modelled. To accommodate parameter variation, numerical method is preferred over analytical method. Parameters of problem are mass flow rates (In and out), inlet temperature, insulation thickness, type of insulation etc. Optimized resultsare obtained by using numerical method implemented with Microsoft Excel worksheet. These optimized results are recommended for manufacture of water storage tank of domestic solar water heater.

***Keywords*–Thermal Energy Storage (TES), solar energy, Solar Domestic Water Heater(SWH)**

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I. INTRODUCTION

Today, energy is a crucial topic because its usage has increased significantly in the lastdecades(Table.I)[1]as a result of increased industrial production. Oil, coal and natural gas, which are named as “fossil fuels”, have been Theprimary source of energy since the nineteenth century. However, disadvantages of the primary energy sources overcome its advantages in terms of environmental issues and depletion of fuel reserves. Due to decrease in present fuel reserves and cost of searching new ones, the cost of retrieving fuel increases and this form of energy production gets more expensive. It has been widely accepted that the portion of fossil fuels has to bedecreasedwith increasing utilization of renewable energy.Solar energy is the potential candidate to meet global energy requirements in a sustainable way for heating. However, it can be affected by various factors such as cloud cover or seasonal variation in solarradiation. Thermal Energy Storage systems can reduce the effect of these factors by providing energy to the systems during decrease in solar intensity.Therefore,there is an increasing interest related to design of Thermal Energy Storage (TES) units to enhance efficiency of solar systems. Thus, Thermal energy storage (TES) is considered one of the most important advanced energy technologies and recently, increasing attention has been paid to the utilization of this essential technique for thermal applications ranging from heating to cooling, particularly in buildings.SWH is approved and readily available technology which uses renewable energy for water heating. Different types of SWH are available and can be used as per the application. There are two types of water heating systems based on the typeof the circulation: Naturalcirculation(Thermosyphon solar system) and Forced circulation. Natural circulation solar water heaters are simple in design and low in cost. Forced circulation water heaters are used in freezing climates and for commercial and industrial applications.

TABLE1:
FUTURE ENERGY DEMAND

1000 Moet	**1990**	**2020**	**% Rise**
Industrialized countries	4.1	4.6	12
Central and eastern Europe	1.7	1.8	05
Developing Countries	2.9	6.9	137
World	8.7	13.3	52

Note-Moet-Million oil equivalent ton energy unit.

A.Need for SWH-

Most of the hot water demand in various applications is met by heating water through conventional energy, that is, electric geysers running on largely fossil power or natural gas based heating systems. Apart from being highly polluting, conventional electric heaters consume only a percentage of the actual electricity that is dispatched from the power plants across long transmission distances, which have large transmission losses. A good reason to use SWHS instead of conventional energy based systems, is that it offsets those greenhouse gases that would have been generated had the water been heated by electric power or natural gas. Most of the times, water heating (especially in the domestic sector) coincides with the peak load timings of the grid. This results in higher peak loads if most of the hot water demand is being met from conventional electric heaters. From the point of view of demand side management, it becomes indispensable to adopt non-conventional energy-based and energy efficient technologies, which can generate hot water with minimal requirements and dependence on fossil fuels, thereby contributing to shaving off the peak load. On the industrialfront, a major portion of thermal energy requirements in the sector lies in the temperature range of 50 °C–250 °C, which corresponds to the low/medium temperature range of solar thermal systems. These include dairy, food processing, textiles, hotels, edible oil, chemical, marine chemicals, bulk drug, breweries, and distilleries. Many of these industries also use hot water in the range of 70 ◦C–90◦C .Theserequirements are presently met primarily by combustion of fossil fuels like coal, lignite, and fuel oil.

Solar energy, being abundant and widespread in its availability, makes it one of the most attractive sources of energies. Tapping this energy will not only help in bridging the gap between demand and supply of electricity but shall also save money in the long run. According to the Ministry of New and Renewable Energy (MNRE), Government of India, a 100 litre capacitySWHS can replace an electric geyser for residential use and may save approximately 1500 units of electricity, annually, under Indian conditions. Thus, a typical family can save 70%–80% on electricity or fuel bills by replacing its conventional water heater with a solar waterheating system. It has also been estimated that a 100 litres per day (lpd) system (2 m2 of collector area) installed in an industry can save close to 140 litres of diesel in a year. So also, usage of solar water heater to supply pre-heated boiler feed water can help saving 70%–80% of fuel bills. Reduction of pollution and preservation of environmental health are some of the co-benefits of this technology. This is probably why the use of solar energy for water heating has become one of the largest applications of solar thermal systems today. Based on the above mentioned equivalence (100 lpd system saves 1500 units of electricity), it is estimated that in generating the same amount of electricity from a coal-based power plant, 1.5 tonnes of CO2 is released into atmosphere annually. One million SWHSs installed in homes will, therefore, result in reduction of 1.5 million tonnes of CO2 emission into the atmosphere.

Clearly, SWHS is one of the most cost effective, viable, and sustainable options available for hot water generation today.It is a fact that most of the houses build today choose electric water heaters. The main reason is because they are easy to install and inexpensive. However, research has shown that in an average household with electric water heater spends about 25% of its home energy costs on heating water. According to the Florida Solar Energy Centre, it was found that U.S.A homes using solar water heaters can save as much as 50-85% annually on the utility bills over the cost of an electric water heater. Depending of the fuel sources the solar water heater can be more economically over the lifetime of the system than heating water with electricity, fuel oil, propane or natural gas .Solar water heaters do not pollute because they avoid carbon dioxide, nitrogen oxides, sulphur dioxide and the other air pollution and wastes. When a solar water heater replaces an electric water heater, the electricity displaced over 20 years represents more than 50 tons of avoided carbon dioxide emissions.

B.Status and Trends: Global and Indian Experiences-

The demand of SWHSs has been increasing significantly in the few past decades and studies have shown that SWHS installations are increasing throughout the world. As a resultthe global solar market achieved a growth rate of 15% in 2007.Fig.1 and 2 clearly indicates the scope of work in thearea of SWHS[2].

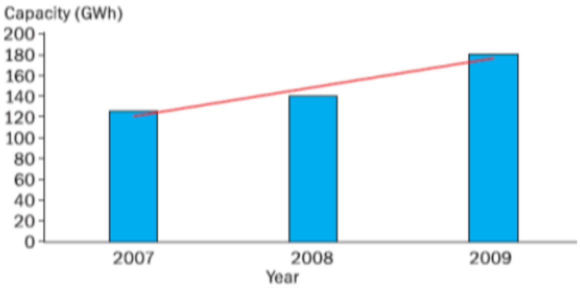

Fig.1-Trend in capacity addition of SWHS

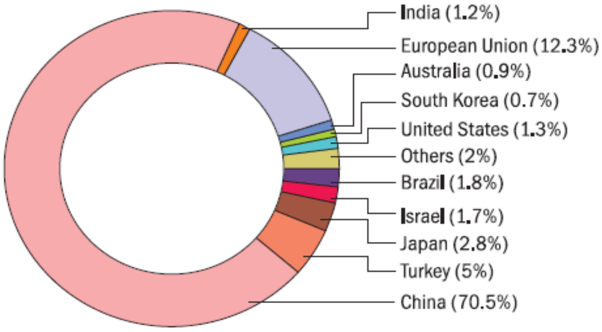

Fig.2-Global Picture of SWHS in 2008

II.LITERATURE REVIEW

It is reported in the literature that-

1)Soteris A. Kalogirou [3] performed an analysis of the environmental problems related to the use of conventional sources of energy and the benefits offered by renewable energy systems. The varioustypes of collectors including flat-plate, compound parabolic, evacuated tube, parabolic trough, Fresnel lens, parabolic dish and heliostat field collectors were followed by an optical, thermal and thermodynamic analysis of the collectors and a description of the methods used to evaluate their performance. The thermal performance of the solar collector was determinedby obtaining values of instantaneous efficiencyfor different combinations of incident radiation, ambient temperature, and inlet fluid

2) Bukola O. Bolaji [4] performed design and experimental analysis of flow inside thecollector of a natural circulation solar water heater. The result shown was that the system performance depends very much on both the flow rate through the collector and the incident solar radiation and the system exhibited optimum flow rate of 0.1 kg/s-m2.

3) Fanney and Klein [5] performed side by side experimental investigations to evaluate the influence of the thermal performance of solar domestic hot water systems. The system was a direct solar hot water system utilizing a natural circulation return tube to the storage tank. Result of the system show improvements in the overall system performance as a result of lowering thecollector fluid flow rate.

4)Volker Weitbrecht et al., [6] performed the results of an experimental study conducted in a water solar flat plate collector with laminar flow conditions to analyse the flow distribution through the collector. LDAmeasurements were carried out to determine the discharge in each riser, as well as pressure measurements to investigate the relation between junction losses and the local Reynolds number. Analytical calculations based on the measured relations are used in a sensitivity analysis to explain the various possible flow distributions in solar collectors.

5)Duffie, J.A and W.A. Beckman [7] performed annual simulation to monitor the thermal performance of a direct solar domestic hot water system operated under several controlled strategies. According to [6], higher flow rate leads to higher collector efficiency factor. However, it also leads to higher mixing in tank and therefore, a reduction in the overall solar water heating system efficiency.

6)The system of Wang X.A., Wu. L.G. [8] performed several collectors with parallel connection and which can be interpreted as a single collector where the number of risers must be multiplied by the number of collectors and were analysed. Various studies reviewed above have shown theimportance of performance improvement of the collector in solar water heating. In this study fluid flow system of a density gradient solar water heater is designed and constructed with the aim to reduce the cost and to bring out better efficiency.

III.METHODS OF THERMAL ENERGY STORAGE

A.Sensible HeatThermal Energy Storage (SHS)-

Storage of solar thermal energy by heating liquid or a solid without changing the phase is called as Sensible Heat Thermal Energy Storage. In this method, energy is stored by changing the temperature of the storage medium (e.g.– water,oil,bricks,sand, rock beds).This system is consist of a storage medium, a container and input output devices, the amount of energy stored by TES device is proportional to difference between the storage input and output temperatures, the mass of the storage medium, and the mediums heat capacity. It is available for the both short andlong term storage (e.g. – rock and earth beds , water tank for short time (daily).Large water or oil tanks, solar ponds and aquifers for long term storage (Monthly or Annual).The basic equation for the amount of heat stored in a mass of material is given by -

$Q = m\ Cp\ \Delta T$ OR $Q = \text{density} \times Cp \times V \times \Delta T$

Where,

m -Mass of the material in the tank

Cp – Specific Heat of the material

ΔT - Temperature Rise

V- Total Volume of the material in the tank

Q – Amount of the heat stored

Some commonly used TES materials and their properties are summarized in Table II [9].

TABLE II:
PROPERTIES OF SOME COMMONLYUSED TES MATERIALS IN SENSIBLE HEAT TES METHOD

Material	**Density (Kg / m3)**	**Specific Heat (J/ kgK)**	**Volumetric Thermal Capacity (10^6 J/m3K)**
Clay	1458	879	1.28
Brick	1800	837	1.51
Wood	700	2390	1.67
Concrete	2000	880	1.76
Aluminium	2710	896	2.43
Iron	7900	452	3.57
Steel	7840	465	3.68
Water	988	4182	4.17

B.Latent HeatThermal Energy Storage (LHS)-

Storage of solar thermal energy in which the heating (i.e.-Storage) material undergoes Phase change (PCM) and a small temperature rise is sufficient to store heat or cold is called as Latent Heat Thermal Energy Storage.

PCMs are materials with high latent heat of phase change. The latent heat of melting is absorbed during phase change from the surrounding and released during freezing with decrease in ambient temperature without significant change in material temperature. The phase change temperature and enthalpy are two basic properties of PCM. (Ref. Table No.3)[10]. Myristic acid , palmitic acid and stearic acid with melting temperature between 50 and 70 deg.C are the most promising PCMs for water heating. Compared to inorganic PCMs (e.g. salt hydrates),the organic PCMs such as paraffin are more stable and show no corrosive behaviour to the surrounding container.

The high chain fatty acid esters are the new material class of the organic PCMs.The basic equation for the amount of heat stored in a mass of material is given by,

Q = Mass x Heat of Fusion

The storage operates isothermally at the melting point of the material.

TABLE III:

PHASE CHANGE TEMPERATURES AND ENTHALPIES OF THE NOVEL ORGANIC PCMs

Novel Organic PCM	**Melting Temp. Deg C**	**Freezing Temp. Deg C**	**Enthalpy of Fusion kJ / Kg**	**Enthalpy Of Freezing kJ/kg**
Tetradecyle Tridecanoate	40.01	38.78	207.89	-207.62
Tetradecyle Pentadecanoate	45.43	44.66	214.81	-215.34
Tetradecyle Hectadecanoate	46.68	46.13	217.19	-217.10
Tetradecyle Nonadecanoate	50.19	49.64	203.23	-203.91

C.Thermo chemical or Bond Heat Thermal Energy Storage (BES)-

In this method using heat to produce certain physicochemical reaction and then storing the energy of the products is done. Absorbing and Adsorbing are the two examples for bond reaction. The heat is released when reverse reaction is made to occur. In this case also storage operates isothermally during the reactions. Bond energy storage systems are being proposed for use in the future for medium and high temperature applications.

III.EXPERIMENTALSETUP

A. Working Principle-

The natural tendency of a less dense fluid to rise above a denser fluid can be used in a simple solar water heater to cause fluid motion through a collector. The density difference is created within the solar collector where heat is added to the liquid.Fig.4 shows closed loop system of SWH.As water gets heated in collector, it rises to the tank and the cooler water from the tank moves to the bottom of the collector, setting up a natural circulation loop. It also called a thermosyphon loop(Fig.3). Since these water heaters not use a pump, it is a passive water heater. For the thermosyphon to work, the storage tank must be located higher than the collector. Since the driving force in a thermosyphon system is only a small density difference and not a pump, larger-than-normal plumbing fixtures must be used to reduce pipe friction losses. In general, one pipe size larger than normal would be uses with a pump system are satisfactory.Since the hot-water system load vary little during a year, the angle of tilt is that equal to the latitude, the temperature difference between the collector inlet water and collector outlet water is usually 8-11°C during the middle of a sunny day. After sunset, a thermosyphon system can reverse its flow direction and lose heat to the environments during the night.

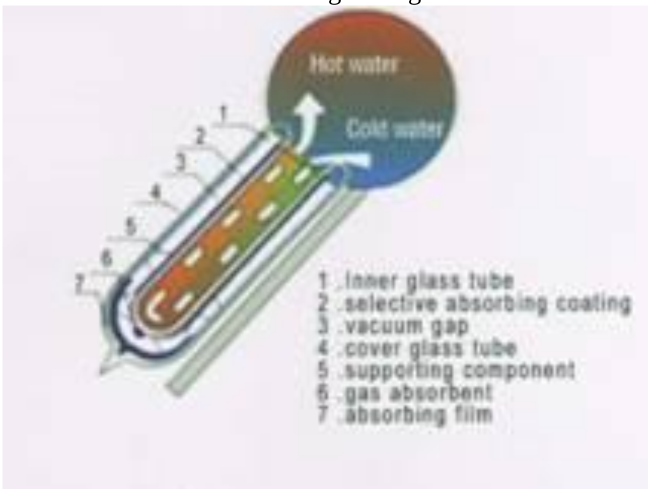

Fig.3-Thermosyphon Effect

To avoid reverse flow, the top header of the absorber should be at least 30cm below the cold leg fitting on the storage tank, as shown; otherwise a check valve would beneeded. Several features inherent in thermosyphon design unitutility. Ifit's to be operated in a freezing climate, a non-freezing fluid must be used, which in turn requires a heat exchanges between collector and portable water storage. (If portable water is not required, the collector can be drained during cold period instead). Heat exchanger of either the shell-and-tube type or the immersion-coil type required higher flow rates for efficient operation thana thermosyphon can provide. Therefore, the thermosyphon is usually limited to non-freezing climates. For mild freeze climates, a heat exchanger coil welded to the outer surface of the tank and filled with antifreeze may work well.Fig.4 shows closed loop system of SWH.

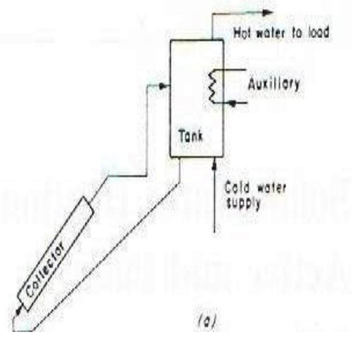

Fig.4-Closed loop system of SWH

B. Components of SWH-

The use of thermosiphon systems is accepted world- wide due to their simple and reliable characteristics .The basic components of the SWH system are shown in Fig.5.

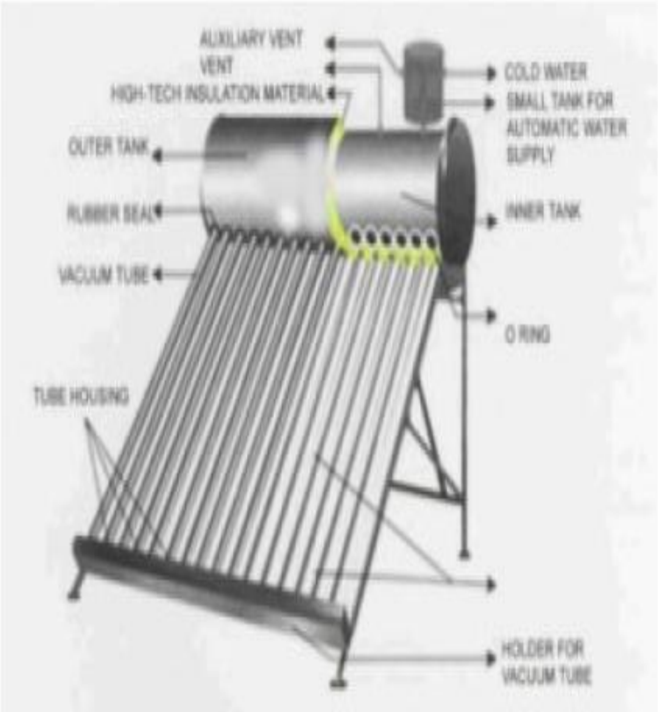

Fig.5- Evacuated tube solar water heater

Main components of evacuated tube solar water heater (open Circuit, non-pressure system)

- Evacuated glass tubes and Barium Getter
- Storage tank
- Mounting frame
- External water supply source

C. Storage tank-

It is a tank which stores the water and come from external water source like water tank. It is mainly consist of two tank i.e. inner tank and outer tank. The inner tank is placed inside the outer tank. The gap is maintained between two tanks. This gap is filled by high tech insulating material (Rock Wool or mineral wool) in order to reduce the heat losses from the heated water exist inside the inner tank heated by the evacuated tube solar water heater. Rock wool is a manmade fibre and has many excellent characters like non-combustible, non-toxic, low thermal conductivity, long service life and so on. Storage tank is placed at the top of frame and tubes. The top open end of the tubes is connected to the storage tank. The bottom end of tubes is placed in a holder provided at bottom of the frame.

D. Working-

As the sun's rays after passing through outer glass tubes falls on the inner glass tubes which are coated with absorbent materials. So these sun's rays are absorbed by the absorbent materials and inner tube and gets converted in to heat after absorption. Due to absorption, surface of inner tubes gets heated up and this heat is transferred to the water exist inside the inner tubes. The temperature of the water in the tubes rises making it less dense or lighter and hot and lighter water naturally moves up to the top of collector and through the evacuated collector tube goes to the storage tank. This makes the colder and heavier water in water tank moves down to the bottom of the collector. That continuous displacement occurs naturally. So the users can get the hot water (30 - 90°C) from the tank. The tilt angle of these collectors varies from 15 - 90°.Capacity of storage tank is depends on the water requirements used by the people. It is normally 200-250 litre for 4-5 adult people.

E.Proposed Work-

We have taken Domestic Hot Water (DHW) System as an application, particularly we will focuson Thermal Energy Storage unit of DHW. In DHW thermal energy is stored in evacuated tubes and in hot water storage tank. A lot of work is already done on evacuated tube thermal analysis.Inside evacuated tube, solar energy is getting absorbed and water gets heated. This heated water is then transferred to hot water storage tank. It is very essential to study the effect of varying water storage tankmaterial, insulationmaterial, insulation thickness and climatic conditions on thermal performance of water storage tank in order to improve performance of solar DHW system.Considering hot water storage tank as Thermal Energy Storage(TES) System, we can work stepwise as following-

1)Review of the work done on the subject under consideration (Thermal Energy Storage, DHW Systems).

2)Selection of any one specific part (e.g.-hot water storage tank of DHW) for the further thermal analysis work.

3)Search for the companies doing the production of similar parts.

4)Find out the scope for optimization.

5)Prepare a mathematical model based on Numerical Methods and by using heat transfer equations, which can give the output values if we change tank (diameter) size, insulation material, insulation thickness, etc.

IV.HEATTRANSFERMATHEMATICAL MODEL-

Inside hot water storage tank of domestic solar water heating system,heat transfer takes place as (Ref.fig.6)-

1) Hot water inside the tank transfers heat to the inner surface of the tank (by convection only as water is opaque to radiation).

2)Heat transfer from tank inner surface to tank outer surface (by conduction).

3) Heat transfer from tank outer surface (which is same as insulation inner thickness) to insulation outer thickness (by conduction).

4) Heat transfer from insulation outer thickness to the atmosphere (by combined convection and radiation).

We have considered a time step of 300 sec. to calculate the valuesfor 460 min.(7.5 hours).We have prepared mathematical model using Excel VBA which can calculate the new values instantly by changing any of the above parameters. We have applied mass balance and energy balance equations.

A. Mass Balance Equation-

$$\frac{dm}{dt} = \text{(m water in)-(m water out)}$$

B. Energy Balance Equations-

1.By Newton's Law of cooling, for convection heat transfer from water to tank material -

$$\frac{d}{dt}\text{(mCpT)water=(-hA}\Delta\text{T)}$$

$$\frac{d}{dt}\text{(mCpT)water= -hA(Twater-Tmetal)}$$

2.For conduction heat transfer from tank inside surface to tank outside surface-

$$\text{hA(Twater-Tmetal)= (K.A.}\frac{dT}{dx}\text{)metal}$$

3.For conduction heat transfer tank outside surface to the insulation-

$$\text{(K.A.}\frac{dT}{dx}\text{)metal=(K.A.}\frac{dT}{dx}\text{)insulation}$$

4. For conduction heat transfer tank outside surface to the insulation-

$$\text{(K.A.}\frac{dT}{dx}\text{)metal=(K.A.}\frac{dT}{dx}\text{)insulation}$$

5.For combined convection and radiation heat transfer from insulation to the atmosphere by an equivalent heat transfer coefficient-

$$\text{(K.A.}\frac{dT}{dx}\text{)insulation=(Q)loss}$$

(Q) loss=(Q) convection+ (Q) radiation

$$(Q)loss = hc.A.(Ts - T\infty) + \sigma.A.\varepsilon.(Ts^4 - T\infty^4)$$

By simplifying second term of the above equation,
Assuming, $Ts \approx T\infty \approx Tm$
And,

$$\sigma = Stefan - Boltzman\ constant$$
$$\varepsilon = emissivity$$
$$(Q)radiation = \sigma.A.\varepsilon.(Ts^4 - T\infty^4)$$
$$(Q)rad. = \sigma.A.\varepsilon.(Ts^2 + T\infty^2).(Ts + T\infty).(Ts - T\infty)$$
$$(Q)rad. = hr.A.(Ts - T\infty)$$

Where, the term `hr' is defined as

$$hr = \sigma.\varepsilon.(Ts^2 + T\infty^2).(Ts + T\infty)$$
$$hr = \sigma.\varepsilon.Tm^3$$

Thus,

$$(Q)loss = (hc + hr).A.(Ts - T\infty)$$
$$(Q)loss = heq.A.(Ts - T\infty)$$

By simplifying above transient equations we get a 4x4 matrix for 4 unknowns -temperature of water at outlet, temperature of tank metal inside surface, temperature of tank metal outside surface and temperature of insulation. By taking values for this time step (300 sec.) as initial values, we have calculated similar values for 460 min.(7.5 Hrs.) after every 300 sec. using Microsoft Excel solver. In the excel sheet,equivalent heat transfer coefficient with combined effect of convection and radiation is evaluated.ss Microsoft Excel Solver uses following methodology-
Mass balance and heat transfer equations can be written in the form-
f1(x,y,….)=0
f2(x,y,….)=0,
f3((x,y,…)=0
f4(x,y,…..)=0,ect.
With some associated error,
d1(x,y,….)
d2(x,y,….)
d3(x,y,….)
d4(x,y,….),ect.
This error has to be minimized.

$$f1+\frac{\partial f1}{\partial x}.dx+\frac{\partial f1}{\partial y}.dy+....=0$$

$$f2+\frac{\partial f2}{\partial x}.dx+\frac{\partial f2}{\partial y}.dy+....=0$$

like -wise we can solve the equations by Gauess Seidel or GauessElimination method. In this method we convert the equations in matrix form and by row or column operations we convert that matrix in either upper triangular or lower triangular form to get the unknowns.

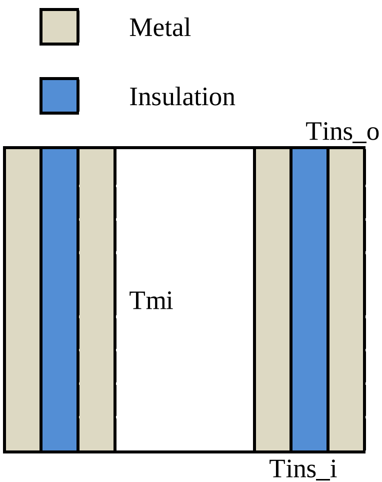

Fig.6- Water storage tank metal inner/outer diameter and insulation layer and respective temperatures

V.RESULTS AND CONCLUSIONS

1)Solar energy through solar water heating (SWH) systems can reduce amount of fossil fuel energy required. This natural energy is absolutely free and the supply is unlimited in the day whenever there is sunlight. The usage of this energy does not produce any pollutant and therefore is most Environment Friendly. Natural circulation solar water heaters are simple in design and low in cost. Forced circulation water heaters are used in freezing climates and for commercial and industrial applications.

2) Apart from being highly polluting, conventional electric heaters consume only a percentage of the actual electricity that is dispatched from the power plants across long transmission distances, which have large transmission losses. A good reason to use SWHS instead of conventional energy based systems, is that it offsets those greenhouse gases that would have been generated had the water been heated by electric power or natural gas.

3)Most of the times, water heating (especially in the domestic sector) coincides with the peak load timings of the grid. This results in higher peak loads if most of the hot water demand is being met from conventional electric heaters.From the point of view of demand side management, it becomes indispensable to adopt non-conventional energy-based and energy efficient technologies, which can generate hot water with minimal requirements and dependence on fossil fuels, thereby contributing to shaving off the peak load.

4) Solar water heaters can save as much as 50-85% annually on the utility bills over the cost of an electric water heater.

5) Besides many advantages of solar water heating systems, there is a need to work on Thermal Energy Storage (TES) devices used in SWH.A lot of work is done on Flat Plate Collectors than only Evacuated Tube Collectors. There is great scope for work on efficiency improvement of thermalenergy storage tank.

6) We have selected hot water storage tank as a thermal energy storage unit of evacuated tube type SWH for analysis.
By applying mass balance and energy balance equations, we have calculated various types of heat transfers from the tank to the surroundings. For getting the values of heat loss for a utility period of 7 hours, we need the heat loss values after some regular intervals (say 300 sec.).These values can be obtained by Microsoft Excel using Solver. These values can further used for plotting various graphs.

7) Once we prepare the Microsoft Excel data sheet, we can easily study parametric variation e.g.-by changing tank diameter, tank material, insulation material, insulation thickness, ambient temperature ,etc., the probable values of heat loss can be easily estimated using the prepared excel sheet.

8) The prepared excel sheet can also be used for comparative study of performance of various tank materials and insulation materials regarding heat loss.

9) The prepared excel sheet can be used to obtain optimized dimensions before actual manufacturing of hot water storage tank.

10) If someone wants the probable results from a hybrid system having both sensible heat storage and latent heat storage using phase change material, the prepared excel sheet can be used.

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