International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

An Analytical Performance Evaluation of Intelligent Hot Water Storage Tank for Solar System

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Submitted: 26/05/2023 **Revised**: 05/07/2023 **Accepted**: 25/07/2023

Abstract: The increase of use of fossil fuels in industrial applications hampers the environmental cycle, hence solar energy is one of the alternate energy source and has been used in various industrial applications due to clean, cheap and easily available almost in all seasons. Solar energy is one of the form of renewable energy, thus it need various comprehensive system to utilize with fullest capacity. Presently design of effective energy storage system is challenging task. For typical application of hot water for domestic usage, a solar hot water system is widely used. Intelligent solar tank can be heated both by solar collectors and by means of an auxiliary energy supply system. In this system, when heat gets stored during day time particularly in winter season, it dissipates considerably to the environment in night due inappropriate use of insulating material around the storage tank. Hence, attempt is made to identify reasons of heat loss and to propose the modifications in the system in order to enhance the performance of solar water system.

So in this work, the temperature drops of the existing system is measured by using thermocouple. The significant drop in temperature was observed due to inappropriate use of insulating material over the storage tank. Hence finite element analysis of existing storage tank is carried out. These results are considered as a base line. Further composite storage tank with different annular supporting rings required for development of region of annular vacuum is proposed. Finite element analysis of composite storage tank is carried out and results are compared. The temperature drop in proposed composite tank is very low and such tanks can be effectively used for domestic applications.

Keywords: *Solar energy; thermal energy; temperature drop; finite element analysis; storage tank*

1. Introduction

In today's era whole world is focused on renewable energy power generation, due to increased prices of crude oil. There is an increased awareness of climate change all over the world. Solar energy is one of the form of renewable energy. However, it is challenging task to convert all the available solar energy into useful energy. Available solar energy can be converted into electrical energy or heat energy. As the sun is only available during day time the solar energy storage and its conservation is very important. Hence, there is a need to improve performance of solar energy storage system (Electrical as well as Thermal energy systems). When it comes to requirement of hot water for domestic usage, a solar hot water system is one of the most viable, economic and energy efficient water heating system. It saves electricity cost as well as protects the environment from harmful gases. In solar water heating system, sun energy is converted into heat for heating water by the use of sun-facing solar thermal collectors. Modern systems are electronically-managed to take maximum advantage of this basic principle to collect and hold all available heat. There are three basic operations involved in solar water heating systems such as collection of thermal energy, energy transmission and storage of energy. Typically, when heat gets stored, it dissipates considerably to the environment, hence there is a need to propose some remedy. It is possible to improve the said drawback by incorporating suitable insulating material around the storage tank.

Many researchers have carried analytical, experimental and finite element analysis to predict the heat loss and optimize the thermal storage tanks. Ganesh Venkatesan et al. (2001) carried out experimental analysis in order to calculate thermal conductivity and heat capacity of polyurethane foam insulation. The obtained experimental results were higher range than that predicted by an existing mathematical model. Gabbrielli R., and Zamparelli C. (2009) have presented an iterative optimizing procedure to design molten salt thermal

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storage tanks used for parabolic trough solar power plants. They used multiple layers of structural and insulating materials in thermal storage tank construction. The optimal design with internally insulated, carbon steel storage tank was proposed. Yang Li, Caili Wang, and Rongshun Wang (2012) have carried out finite element analysis to study thermal stress and structure optimization of a neck tube with vertical cryogenic insulated cylinders subjected to various operating conditions using commercial software. The study results were used as baseline for structure design and optimization of cryogenic cylinders. Fahad Khan, and Brian J. Savilonis (2013) have investigated the benefits of spherical tanks to replace the existing cylindrical tanks used in molten salt thermal energy system. Structural and thermal performance of cylindrical tanks with different H/D ratios and spherical tanks of same volume are compared. Luigi Mongibello et al. (2014) have developed a transient model and validated by simulation results obtained by TRANSYS 17 software in order to achieve the design criteria of domestic solar hot water plants under daily transient conditions. Te-Wen Tu and Sen-Yung Lee (2015) have presented an analytical solution for the heat transfer in hollow cylindrical tubes with time dependent boundary condition and time-dependent heat transfer coefficient at different surfaces. The convergence rate of the present solution was fast and the analytical solution was simple and accurate. Aowabin Rahman, Nelson Fumo & Amanda Smith (2015) have developed a simplified mathematical model to analyses a storage tank containing a stationary fluid with hot and cold heat exchanger coils. Weiqiang Xu, Qianqian Li, and Minjie Huang (2015) have carried out the design of basic structure of airborne cryogenic liquid hydrogen tank. They have analyzed the thermal performance of newly designed tank with conventional tank. The study reveals that designing the insulating support for new tank reduces the leakage of heat more than 85%. Saif ed-Din Fertahi et al. (2017) have carried out the thermo-mechanical analysis on horizontal storage tank used to store hot water for domestic application. They described three studies that were performed to extend the lifespan of the horizontal storage tank by proposing the suitable material and optimum design. From the simulation it was identified that, the optimum fillet radius of storage tank, which results in minimum stress values. Olga V. Shepovalova et al. (2017) have investigated new concept of high vacuum glazing applications for flat plate solar thermal collector. They provided the vacuum insulation. It was concluded that there was no leakage from sealing in proposed design. Willy Villasmil et al. (2019) have discussed on thermal insulation materials and methods suitable for thermal energy storage applications up to 90^0C.By using of evacuated powders in a double wall tank construction can achieve low thermal conductivity of the insulating jacket. Shahram Yari, Habibollah Safarzadeh, and Mehdi Bahiraei (2023) have developed and manufactured the collector and the double walled tank in spherical shape which was capable to tracking the sun irrespective to the placement angle. In this study the water heated by the collector was stored in the inner chamber of the double-walled tank, and the chamber of tank was surrounded by a Phase Change Material (PCM). The result obtained from analysis shows that the maximum storage temperature in the thermal charge process was about 80.3 °C with the maximum thermal efficiency of about 74 %, at a flow rate of 1.75 l/min. Shahab Bazri et al. (2022) have numerically analysed the performance of portable solar water heater using evacuated tube heat pipe solar collectors which was coupled to the latent heat storage tank. The testing was carried out at two different climate conditions viz. the geometry of the fins and different PCMs. Several characteristics were used to evaluate the system's performance, including the geometry of the fins and different PCMs. António Araújo et al. (2023) have numerically analyzed the solar water heating systems using on–off control at different four locations. For analysis two design parameters were considered viz. collector area and the storage volume. The analysis indicated that a small increase in the optimum collector area leads to considerable decrease in the optimum storage volume. Moucun Yang et al. (2023) have designed horizontal shell and tube PCM based Latent heat thermal energy storage which was capable for charging and discharging in solar domestic hot water. Thus providing the vacuum layer over the complete body over the storage tank high thermal resistance can be achieved.

The aim of this work is to study the temperature drop of the existing domestic solar water heating system at night by using thermocouples fitted at the outlet. The significant drop in temperature was observed due to inappropriate use of insulating material over the storage tank. Hence finite element analysis of existing storage tank is carried out. These results are considered as a base line. Further finite element analysis of proposed composite storage tank with different annular supporting rings required for development of annular vacuum region is carried out and results are compared with baseline results.

2. Analysis of Existing Tank

Fig. 1 shows actual photograph of domestic solar water heater system of 100 lit capacities. This solar system is installed in rural area of Indian subcontinent. The results obtained from experimentation i.e. drop in temperature are used for numerical analysis.

Fig. 1 Existing domestic solar water heater system

The material properties of storage tank are represented in Table 1 .

Table 1: Material properties of existing storage tank material (stainless steel)

Material Density	7750 Kg/m^3
Coefficient of Thermal Expansion	1.70E^{-5} per ^{O}C
Young's Modulus	1.93E^{+5} MPa
Bulk Modulus	1.693E^{+5} MPa
Shear Modulus	7.3664E^{+4} MPa
Tensile Yield Strength	2.07E^{+2} MPa
Compressive Yield Strength	2.07E^{+2} MPa
Tensile Ultimate Strength	5.86E^{+2} MPa
Isotropic Thermal Conductivity	16 W/m ^{O}C

These tank specifications are used for FEA simulation of existing tank. In the existing system stainless steel material is used for storage tank and polyurethane foam (PUF) material is used as the thermal insulation over the storage tank. The temperature data is recorded for 14 hours i.e. 6.00 pm to 8.00 am by using probe type thermocouple which is shown in Fig. 2. This temperature data initial temperature (T_{start}) and final temperature (T_{end}) is used for the heat transfer analysis. The temperature is measured for ten days regularly and the average values of the starting and ending temperatures are T_{start} = 80 ºC and T_{end} = 59.2 ºC respectively. Thus in this analysis temperature drop for this period is considered.

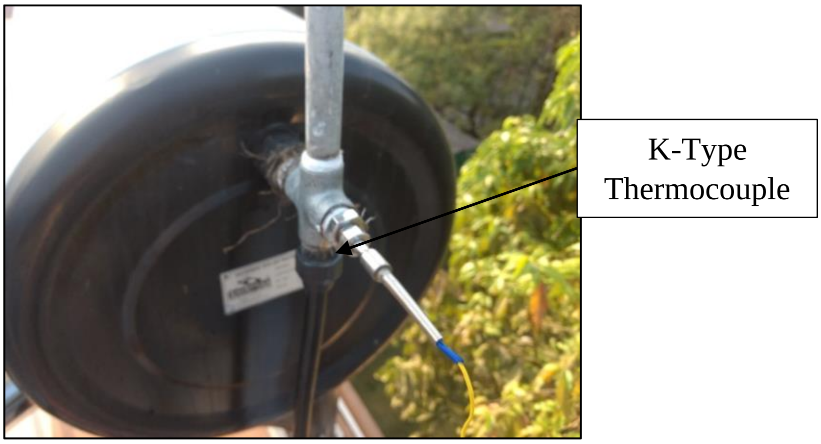

Fig. 2: Position of Thermocouple

3. Design and Analysis of Tank

There are various methods which are useful to optimize heat loss. Among one is replacing the existing insulation with material having less thermal conductivity than that of existing. But it has limitations due to availability of insulating materials having that much lower conductivity. Usually to reduce the loss of heat from large geothermal steam carrying pipes air gap at surrounding is used as a thermal insulator. Air gap have very less thermal conductivity thus provision of air gap between the insulation gives better resistance to heat transfer. Thus air gap is used as thermal insulation. However, for applications like cryogenic storage mechanism it was revealed that instead of making air gap insulation, providing vacuum in annular area as an insulation would be more effective. Thus, it is decided to apply this on thermal storage tank.

3.1 Configuration of proposed tank

In this work, design of new storage tank is proposed, which possess better heat storage capacity. The dimensions of main shell, end closures are calculated based on standard theory of thin pressure vessel. The proposed tank is double layered vacuum sealed storage tank. To provide a vacuum layer one additional layer of metallic tank between the inner storage tank and insulation material is added, which separates the inner storage tank and insulating material by providing vacuum. In cylindrical shell tank two type of stresses are induced i.e. Circumferential or Hoop stress and longitudinal stress as shown in Eq. (1) and (2) respectively.

$$\sigma_c = \frac{PDi}{2ti}; \qquad (1)$$

$$\sigma_L = \frac{PDi}{4ti} \qquad (2)$$

The inner vessel shell thickness can be calculated using Eq. (3)

$$t_i = \frac{P \times ri}{(S \times E - 0.6P)} + C.A. \qquad (3)$$

where,

t_i = Thickness of inner cylindrical shell, mm ; P= Design pressure = 0.075 MPa; r_i= Radius of inner shell ≈ 178 mm; E = Joint efficiency = 0.8; C.A = 0.2 mm. (Assumed); S= Allowable stress N/mm^2

The thickness of the flat circular end is calculated using Eq. (4)

$$t_f = D_i \times \left(\frac{C \times P}{S \times E}\right)^{0.5} \qquad (4)$$

The structural stability of inner tank is the main challenging task while developing vacuum around the internal tank. In cryogenic application the structural stability of inner tank is maintained by providing the supporting blocks between two tanks. Thus, in this work structural stability of internal tank is maintained by providing the hollow pipes of rectangular cross section having ring shape, placed between the inner and middle tank. The circular rings are designed by maintaining 10 mm gap between inner and outer tank. The operating temperature will directly affect structural strength of the supporting ring and storage tank. Hence to consider the effect of temperature and structural load combined coupled thermo-structural (FEA) analysis has been carried out. The number of rings and the positions of rings are varied depending on the induced stress & corresponding deformation values. Here, two cases are considered for positioning of supporting rings as shown in Fig. 3 and Fig. 4.

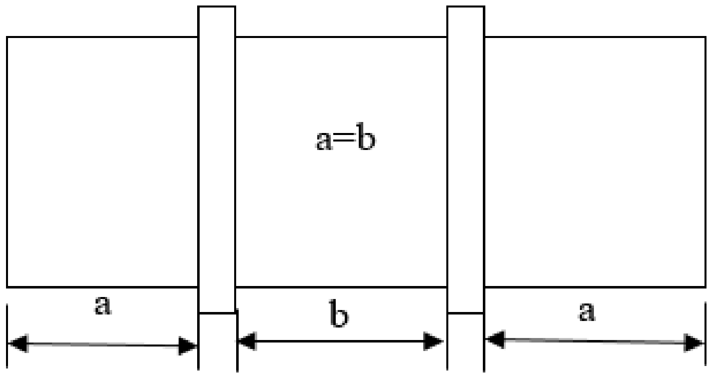

Fig. 3. Case I- The arrangement with 2 rings (Distance of rings from ends of tank is equal to the distance between two rings).

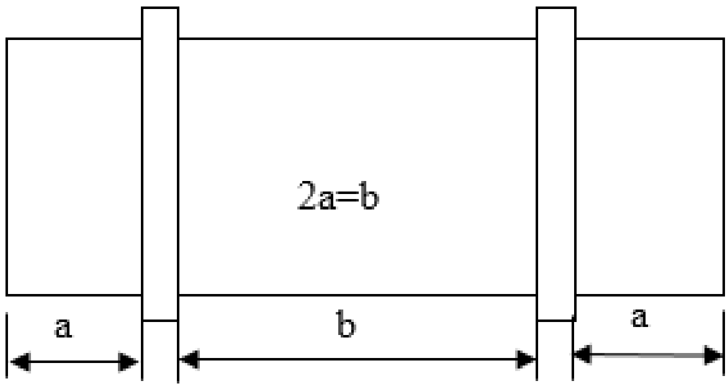

Fig. 4. Case II- The arrangement with 2 rings (Distance of rings from ends of tank is half the distance between two rings).

In proposed tank, at the end cap arrangement, there are three circular disks having varying diameter separated from each other by different insulating medium. The one surface of inner head is in contact with hot water and on other side vacuum is maintained. In vacuum radiation mode is used for analysis. The middle disk is separated by polyurethane insulation with outer end cap disk. The outer surface of outer circular disk is exposed to the ambient air; such arrangement is shown in Fig. 5.

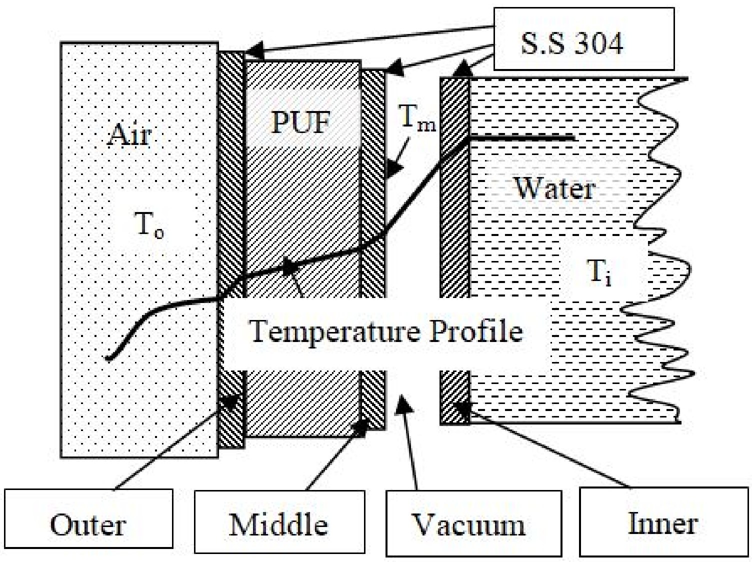

Fig. 5 End cap arrangement of proposed tank

3.2 Thermo-mechanical coupling in FEA

This section is an equation setting of the physical models solved by ANSYS. Heat transfer, stress and compatibility equations and their coupling are written under detailed assumptions knowing that the FEM could be in direct or indirect way. ANSYS software solves the coupled problem based on the finite element method. It is important to consider an interaction between thermal and the mechanical phenomenon also called coupled phenomenon of storage tank & supporting rings. The strategies used to solve coupled set of physics equations can be generally categorized as weak or loose coupling and strong or tight coupling. In tight coupling solution method, a single system of equations is assembled and solved for the full set of coupled physics. The nonlinear iterations operate on the full system of equations simultaneously, taking into account the interactions between the equations for the coupled physics in each iteration. In cases where there is strong coupling between the physics, this approach can have faster convergence rates than loose coupling.

3.3 Thermo-mechanical FEA analysis

The Finite Element Analysis is carried out in ANSYS workbench by using combine thermal stress module. Coupled analysis is carried out to calculate temperature distribution over the body and structural analysis calculates the structural performance on input data given by thermal analysis. Effect of temperature distribution is considered and structural load can be solved according to properties at elevated temperature. To carry out the thermo-structural analysis, the working temperature and operating pressure on the tank surface are applied.

The circular rings are used to maintain 10 mm gap between inner and outer tank. The operating temperature will directly affect structural strength of the supporting ring and storage tank. Hence to consider the effect of temperature and structural load combined coupled thermo-structural (FEA) analysis has been carried out. The number of rings and the positions of rings are varied in order to get less induced stress & deformation values. Here such one case is shown in Fig.6

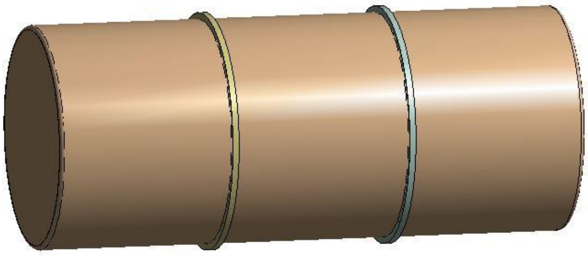

Fig. 6 CAD model of tank with 2 supporting rings

Uniform distributed temperature 80^{O}C is applied on the inner face of cylindrical tank. The operating pressure is hydrostatic pressure of water inside the storage tank.

3.4 Mesh model of tank

In first step the mid surfaces of all parts are generated in space clam and there is bonded contact applied between the ring support and storage tank shown in Fig. 7. The quad elements are used for analysis because it gives better performance of deformation while solving the meshed model. The correct mesh from a numerical accuracy standpoint is one that yields no significant differences in the results when mesh density is increased. Before deciding the element size, we find out the element convergence criteria.

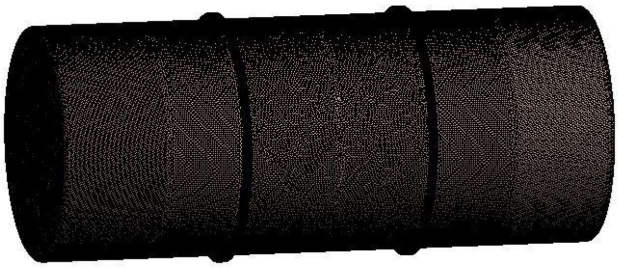

Fig. 7 Mesh model of tank.

3.5 Boundary conditions

Any engineering problem have infinite solutions but to obtain exact solution the boundary conditions are important. In order to find performance of solar tank for given operating condition the temperature load is applied on inner surface of tank. The contact between the tank and rings are assumed to be bounded contact. The outer surface of the ring support is fixed support for one ring and the axially free displacement for other ring as shown in Fig. 8, 9 and 10.

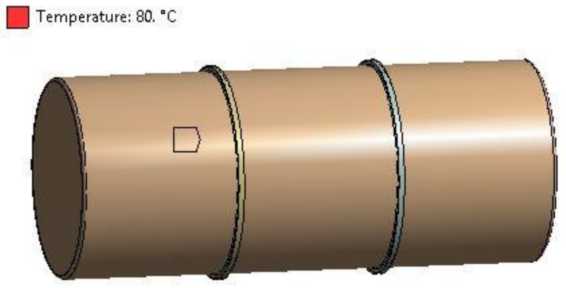

Fig. 8 Thermal boundary condition

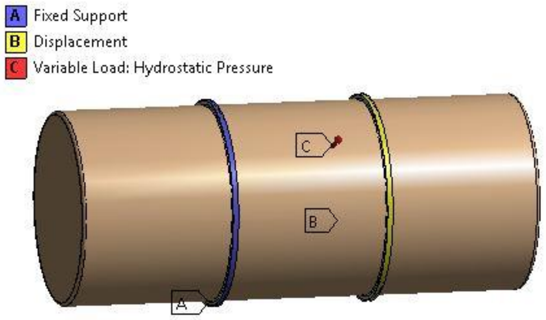

Fig. 9 Structural boundary conditions

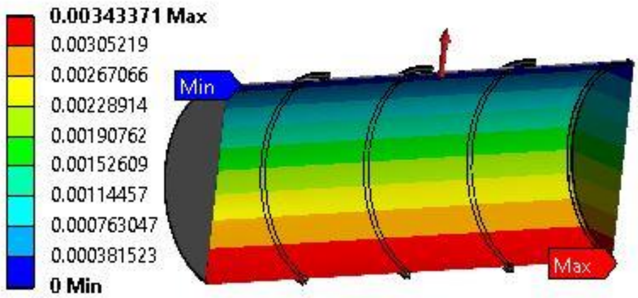

Fig. 10 Hydrostatic pressure inside the tank

3.6 Simulation results for Case -I

The results are based on standard equations of heat transfer and strength of material. Von misses' criteria are used for evaluating maximum principle stress and directional deformation along z axis. The Von Misses stress in each case-I A, B, C.

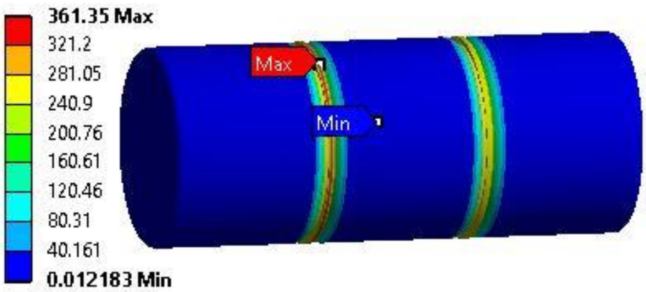

Fig. 11 Von-misses stress for case I-A

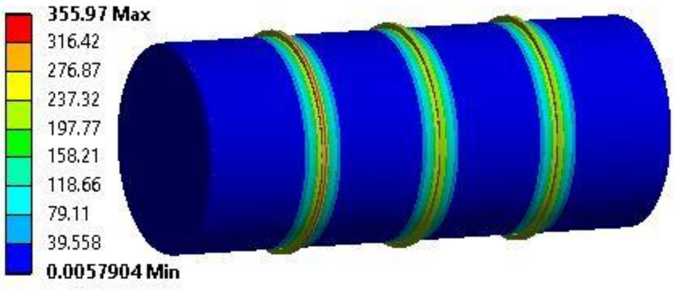

Fig. 12 Von-misses stress for case I-B

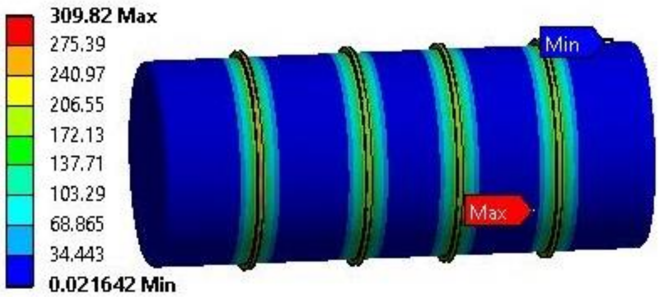

Fig. 13 Von-misses stress for case I-C

From above three cases it is clear that increasing the number of rings results in decreasing the Von misses stress. To find out the deformation in between two supporting rings we apply the standard earth gravity in Z direction and found out the results of Z directional deformation.

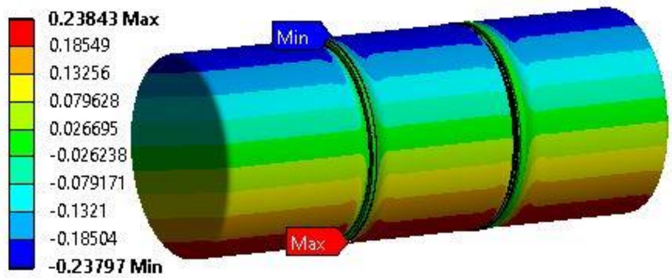

Fig. 14 Total Z directional deformation in case I-A

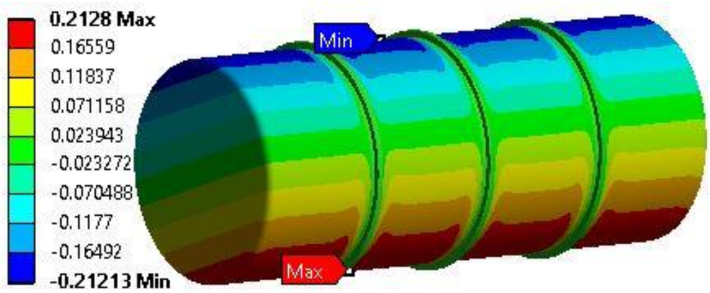

Fig.15 Total Z directional deformation case I-B

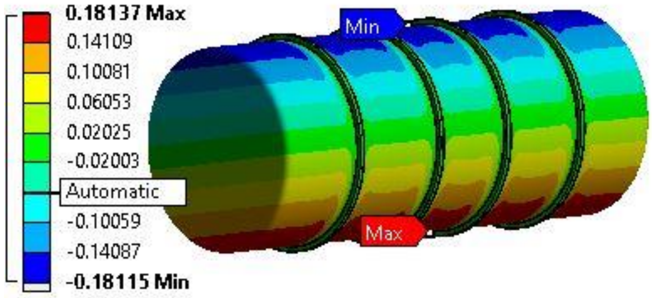

Fig. 16 Total Z directional deformation case I-C

The total deformation for each case is shown in above Fig. 14, 15 and 16. It is observed that as number of supports increases, overall deformation decreases.

3.7 Simulation results for case II

The results are based on Standard equations of heat transfer and strength of material. Von misses' criteria are used for evaluating maximum principle stress and Directional deformation along z axis was calculated as shown in Fig. 17, 18 and 19.

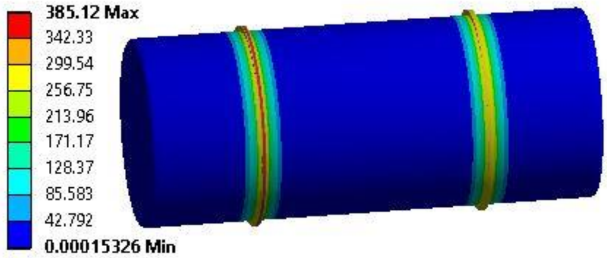

Fig. 17 Von-misses stress for case II-A

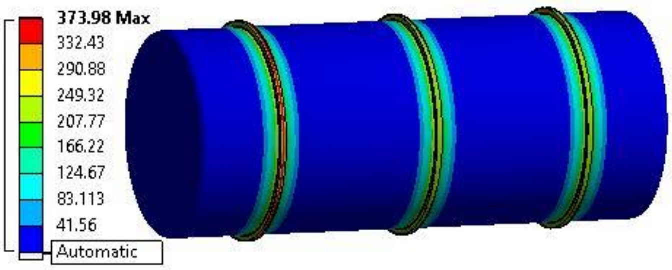

Fig. 18 Von-misses stress for case II-B

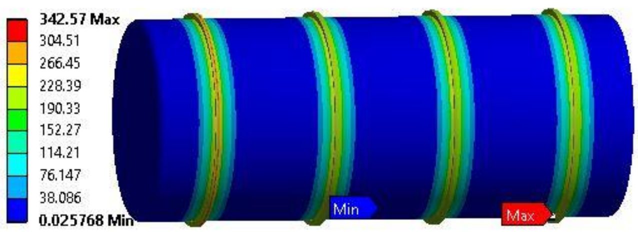

Fig. 19 Von-misses stress for case II-C

To find out the total directional deformation between two supporting rings we applied the standard earth gravity in Z direction and we found out the results of Z directional deformation.

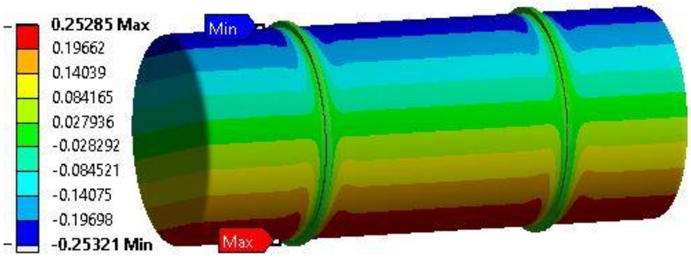

Fig. 20 Total Z directional deformation case II-A

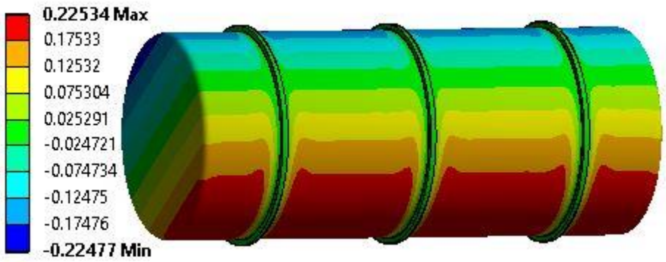

Fig. 21 Total Z directional deformation case II-B

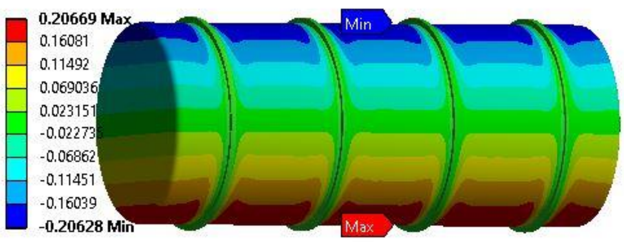

Fig. 22 Total Z directional deformation case II-C

The maximum deformation is observed in case II-b which is 0.245 mm. Minimum deformation is observed in case II-A which is 0.182 mm as shown in Fig. 20, 21 and 22.

Table 2 FEA results in case I

Case I	Max. Deformation (mm)	Max. Stress(MPa)
A	0.2384	361.35
B	0.2128	355.97
C	0.18137	309.82

Table 3 FEA results in case II

Case II	Max. Deformation(mm)	Max. Stress(MPa)
A	0.2528	385.12
B	0.225	373.98
C	0.206	342.53

Hence configuration I-C having least deformation of 0.18137 and lowest von misses stress of 309.82 MPa is proposed for development of composite tank.

4. Analysis of Proposed Tank

The proposed tank is designed with same storage capacity of existing tank. The outer dimensions like diameter and length of existing tank is constant. In proposed design only the thickness of inner tank was changed according to the design. The additional layer of tank is inserted above the inner tank to maintain the 10 mm vacuum gap over the inner tank. Over the middle tank 40 mm thick layer of existing thermal insulation is applied uniformly. Both the thickness of middle and outer tank are 8 mm& 5 mm each. These specifications are used for analysis.

4.1 Finite element analysis of Proposed Tank

The heat storage capacity of proposed tank is analyzed by using steady state thermal module present in FEA. To compare the thermal storage capacity of proposed tank with existing one it is required initially to store same thermal energy data for both of them. Therefore, values of thermal load used in analysis are exactly same as used to analyze storage capacity existing tank. To account the transient effect same procedure is used to perform discrete steady state analysis. The detail procedure to carry out analysis is described as follows.

4.2 Material properties

Properties of selected material are shown in Table 4.

Table 4: Thermal properties of material

Sr. No.	Material	Property	Value
1	Stainless Steel	Thermal conductivity	16 W/m K
2	Stainless Steel	Emissivity	0.16
3	Polyurethane foam	Thermal conductivity	0.11 W/m K
4	Air	Combined Heat transfer coefficient	8 W/m^2 K

4.3 CAD modelling of proposed tank

Initially as per design of proposed tank 3-D CAD model was prepared in same IDEAS 11 NX modular software. As one extra layer of tank is added in original tank, separate parts of system are made and then they were assembled to make complete composite tank as shown in Fig. 23.

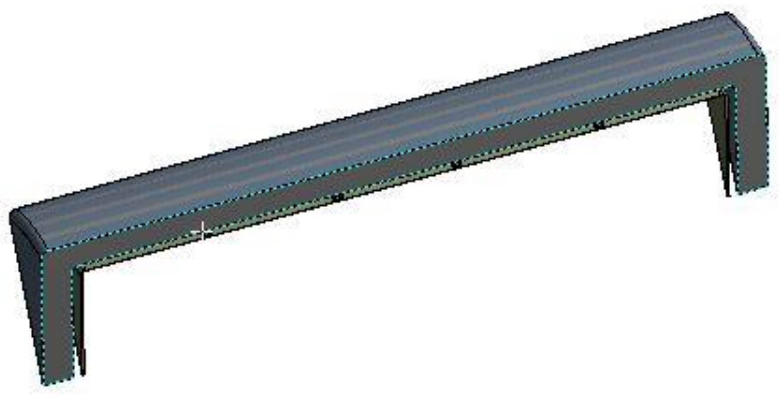

Fig. 23. 1/12th CAD model of proposed tank

4.4 Symmetric loading condition

The time required for solution directly depends on the element count in the problem. The applied thermal load is uniform in the analysis and imported CAD model possess symmetry along its axis. To reduce the mesh count in the solution which ultimately effect the required time for solution only 1/12th CAD model is considered for solution. Initially the1/12th CAD model of the tank was imported in ANSYS in the ".xt" format to perform steady state thermal analysis. After importing the CAD model, it was reviewed for geometry sharing, data loss and corrections are made as per the requirement. The cyclic symmetry condition is applied on geometry by creating new cylindrical coordinate system which is shown in Fig. 24.

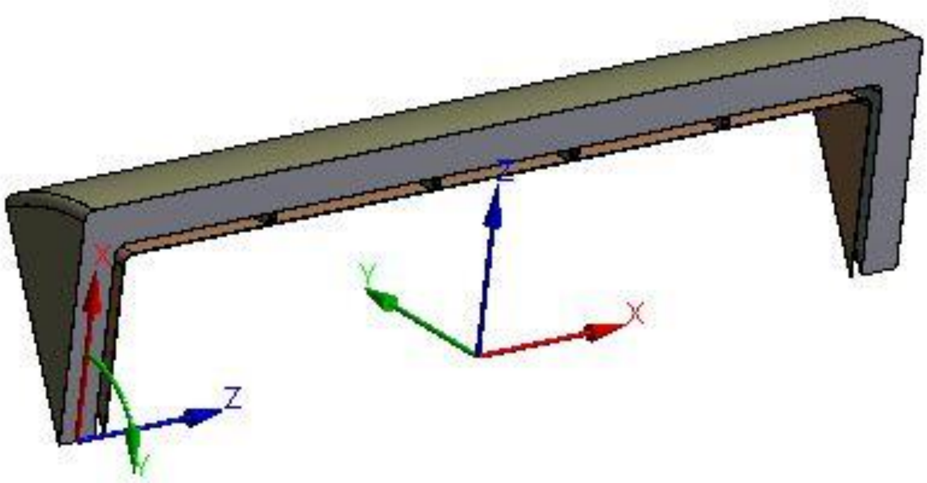

Fig. 24 Proposed tank with coordinate system

4.5 Meshing of tank model selection of element

During analysis cyclic symmetry is being applied on the $1/12^{th}$ CAD geometry of proposed tank. Tetrahedral type of mesh element is selected for meshing due to cyclic symmetry of the CAD geometry. Thus, we use the tetrahedral elements to perform analysis. These hexahedral mesh are economic with the number of elements because the same number of nodes (for 8 nodes) one hexahedra corresponds to six tetrahedral. It is usually more preferred while meshing because it normally reduces the element count in mesh and provides better stability when solving the model. To overcome this, we select appropriate mesh density by selecting optimum element size. The correct mesh from a numerical accuracy standpoint is one that yields no significant differences in the results when mesh density is increased. Appropriate element size was obtained by performing element conversion criteria. The $1/12^{th}$ meshed model is shown in Fig. 25.

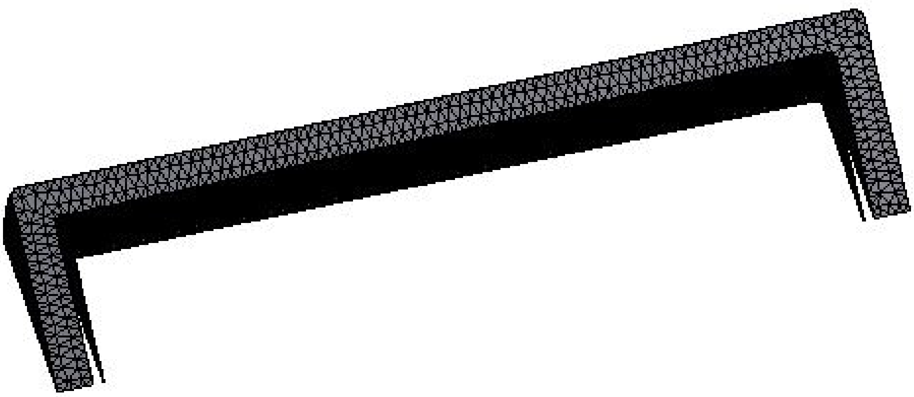

Fig. 25 .$1/12^{th}$ meshed model of proposed tank

4.6 Boundary conditions

Thermal conductivity of material is already specified at the time material is allocated to each composite layer. To account radiation heat exchange between outer surface & atmospheric air, we have applied 0.16 emissivity for outer surface. Apply the heat transfer coefficient for air side is 8 $W/m^{2}\,^{0}C$. To account heat loss through vacuum we have applied the radiation effect in between two vacuum sealed tanks. Due to provision of four support rings there are five perfect enclosures for radiation heat transfer formed. Radiation effect in between each enclosure of vacuum by considering surface emissivity value of 0.16 is applied, which is shown in Fig. 26.

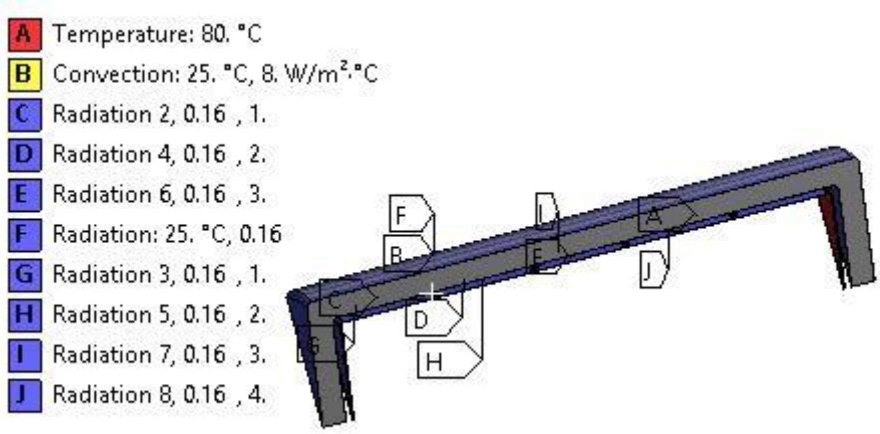

Fig. 26 Boundary conditions of simulation

4.7 FEA results for single iteration

The analysis is carried out to analyze the heat storage capacity of proposed storage tank. The results of temperature distribution through composite tank and total heat flux over the tank body are calculated by FEA analysis. The obtained results for first iteration of discrete steady state analysis are presented in Fig. 27.

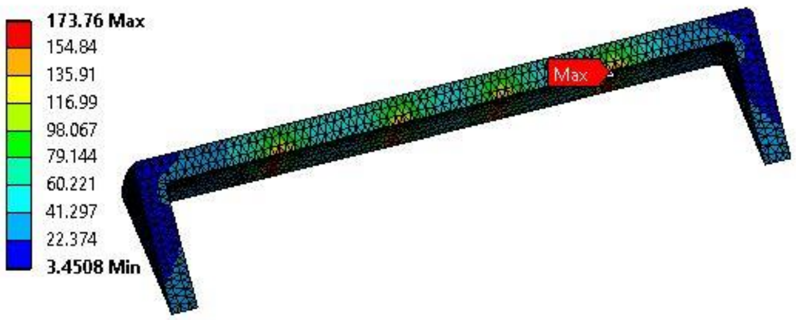

Fig. 27 Total heat flux from PUF insulation

After the completion of analysis, heat flux results are extracted in to excel file format. In this , heat flux values with respect to each element are obtained. To find out the total average heat flux over complete tank body we simply take average of all heat flux results in excel file. Value of average heat flux was calculated & we assume that average heat flux is constant for single hour. From heat flux value, we calculate the temperature drop of water by using energy balance equation. Similar procedure is adopted to calculate the water temperature for subsequent iterations. The FEA results of temperature drop in both tank with starting temperature 73^{0}C is presented in Fig 28.

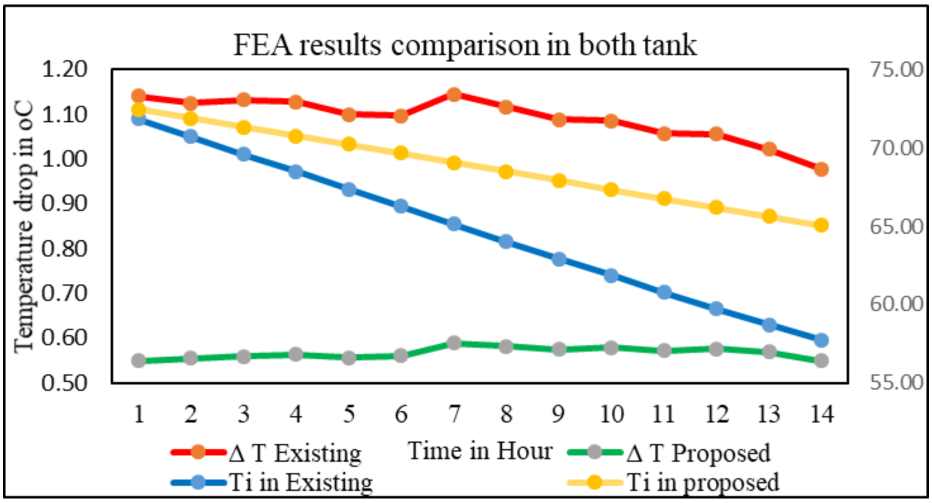

Fig. 28 FEA results of temperature drop

From the Fig. 28, it is clear that the in existing tank temperature drop value for each hour is constant and it is decreases as time increases. The reason is as time increases the temperature of water inside tank is continually decreases. Thus the driving force for heat transfer is decreases as time goes on. In the proposed tank the temperature drop is very less as compared with existing tank. The difference in temperature drop is slightly varies however, the variations is negligible. Here we also noticed, that the slope of temperature drop curve is more in case of existing tank as compare to proposed tank.

5. Conclusion

In order to study the effect of vacuum insulation on the thermal storage performance of domestic solar water heater system, FEA analysis of storage tank has been performed. It is observed that considerable amount of heat loss takes place form the existing storage tank. It is due to the inappropriate use of insulating material. Problem of transient thermal analysis with four annular supporting rings is solved by using steady state analysis and it gives optimum results. By providing vacuum, thermal resistance is increased for heat transfer. By providing the vacuum gap of 10 mm in annular region heat storage capacity is enhanced by 40- 43 %.

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