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Numerical Simulation of Stratified Thermal Energy Storage Tanks

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ABSTRACT

Stratified tanks are being widely used for thermal energy storage (TES), allowing a decoupling between the energy source (commonly a renewable energy source or heat rejected by some industrial process) and the demand. A high degree of stratification is required to make more efficient use of the stored energy, and several design configurations have been developed in order to create and maintain a good stratification. Numerical and experimental approaches are used to monitor and design the process, and also to predict the behavior of these tanks under different conditions. Detailed numerical simulation, however, is computationally expensive and not suitable for the long-time simulations (typically years) required to assess the performance and the economics of energy systems which include TES tanks.

In this paper, a relatively simple, computationally inexpensive numerical approach, called Multi-node model, is used to simulate the energy transfer and the stratification inside the tank. The results obtained are compared to a software package for simulation of energy systems called TRNSYS and some experimental results to validate the model.

1 INTRODUCTION

Stratified tanks allow the storage of thermal energy for long periods of time, acting as decoupling devices between the energy source and the load so they can be employed to balance energy demand between daytime and night time. Storage tanks can be used for heating or cooling purposes, having several applications in renewable energy such as hot water storage in a solar system for heating or cold water storage in a free cooling system. Although the capital cost of such systems is usually high, the investment is recovered through energy savings and carbon emissions savings.

There are two types of operations for storage tanks: forced heat convection and natural convection. Natural convection storage tanks works based on the density and temperature dependence. When the water in the tank gets heated up it becomes lighter and rises up automatically. While cold denser water from the bottom of the tank fills the empty space of the bottom of the tank and a thermocline layer gets formed between the hot water and the cold water (Bhaumik, 2012). This process called the stratification. A high degree of stratification is required to obtain more efficient use of the stored energy. This can be achieved by maintaining a minimum mixing of liquid layers during the charging and discharging processes by proper inlet design, and low flow-rates. Thermal storage efficiency also depends on tank wall material and thickness, and the tank geometry.

TES performance of stratified tanks has been evaluated for the last 25 years by many studies using experimental method or Numerical simulations [i.e. (Ghaddar & Al-Marafie, 1989) (Dammel, Winterling, & Stephan, 2012) (Bhaumik, 2012) (Gu & S.T.Wu, 1985) (Iwamoto, Takayama, & Imano) (Amara, Benyoucef, Nordell, & Benmoussat)]. Experimental investigations can provide valuable and accurate data, but they require high costs, long time and large labor. Detailed numerical simulation is more flexible and less expensive but not exempt of complexities due to the physics involved in the stratification phenomena, represented by Equations 1 to 4, which correspond to the mass balance, the Boussinesq approximation for density, momentum and energy balance, respectively.

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \qquad (1)$$

$$(\rho - \rho_o) = -\rho_o.\beta(T - To) \qquad (1)$$

$$\rho_o\left(\frac{\partial u}{\partial t} + u.\nabla u\right) = -\nabla p + \nabla\{\mu[(\nabla u) + (\nabla v)]\} + \rho_o g[1 - \beta(T - To)] \qquad (3)$$

$$\rho_o c\left(\frac{\partial T}{\partial t} + u.\nabla T\right) = \nabla.(k\nabla T) \qquad (2)$$

The operating conditions for TES are highly variable and, typically, the performance of energy systems including stratified tanks needs to be evaluated for long time periods, usually years. Detailed CFD models are so computationally expensive that are not suitable for such analysis. Consequently, alternative models have been developed to perform long-time performance. These models can be classified into two categories, as follows (Duffie & Beckman, 2006):

The multi-node approach. This approach divides the tank into N nodes (sections) and writes energy balances for each section. The result is a set of N differential equations that can be solved for the temperatures of the nodes as functions of time.

The plug flow approach. In this approach segments of liquid at various temperatures are assumed to move through the tank in plug flow, and the models are essentially bookkeeping methods to keep track of the position, size and temperature of the segments.

Each of these approaches has many variations and the selection of the model depends on the application. Further, the degree of stratification in a real tank will depend on the design of the tank, its size, the design and location of inlets and outlets and flow rates.

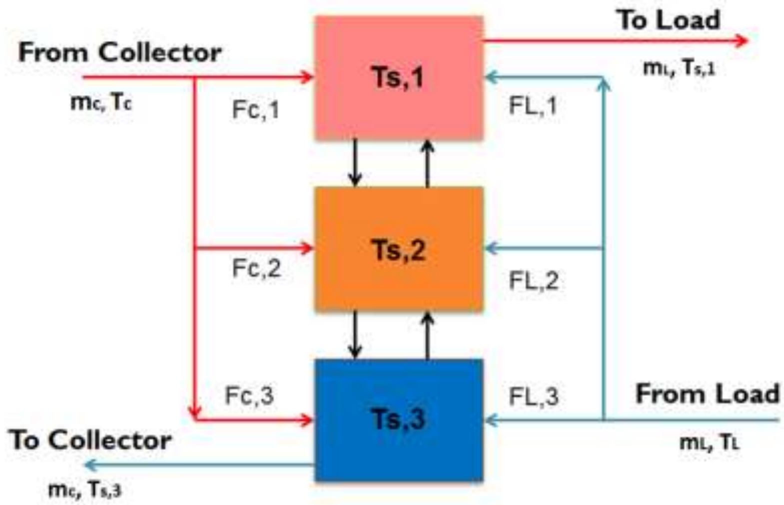
The main objective of this work is to model the performance of stratified tanks using the multi-node approach. A code in MATLAB was developed to automatically simulate the tank model. The results are compared to those obtained from a simulation in TRNSYS. TRNSYS is a software package suitable for simulation of energy systems which includes an extensive library of components such as cooling towers, heat exchangers, pumps, PID controllers and stratified tanks. Type 534 (Cylindrical storage tank) was used for the simulation. Finally, the results were compared with experimental measurements from Adamovsky et. Al.

2 MODELING APPROACH

The multi node approach divides the tank in several cells of nodes. The water in each node is assumed to be completely mixed. Figure 1 illustrates a basic model with three nodes.

During charging process, hot water from the solar collector (or other heating source) is injected in the top of the tank at temperature T_C, while cold water is extracted from the bottom to be re-heated in the collector and returned to the top. The model assumes that the water from the collector flows directly into the node that has the closest but lower temperature, so its density nearly matches that of the entering water. An array of control functions F_C is defined to indicate which node receives the incoming water. The control function F_C takes the value of one for the node that receives the water from the collector and zero for the other nodes.

During the discharging process, the opposite occurs: hot water flows out from the top of the tank to the load and then is returned to the bottom of the tank, at the lower temperature T_L. The previous assumption also applies to this case: the water from the load flows directly into the node that has the closest but lower temperature and a corresponding array of control functions, F_L, is defined to indicate which node receives the water coming from the load. Note that the flow from the collector always leaves from the bottom, node 3, and the flow to the load always leaves from the top, node1.



Three Node-Stratified Storage Tank Model

The control functions $F_{c,i}$ and $F_{L,i}$ are described by equations 5 and 6.

$$F_{c,i} = \begin{cases} 1, \; if \; i = 1 \; and \; T_{c,o} > \; T_{s,1} \\ 1, \; if \; T_{s,i-1} \geq T_{c,o} > \; T_{s,1} \\ \;\; , \; if \; i = 0 \; or \; if \; i = N+1 \\ \qquad 0, \; Otherwise \end{cases} \tag{3}$$

$$F_{L,i} = \begin{cases} 1, \; if \; i = N \; and \; T_{L,r} > \; T_{s,N} \\ 1, \; if \; T_{s,i-1} \geq T_{L,r} > \; T_{s,i} \\ 0, \; if \; i = 0 \; or \; if \; i = N+1 \\ \qquad 0 \, , \quad Otherwise \end{cases} \tag{4}$$

For convenience, a net mass flow rate $m_{m,i}$ to each node from the upper node is defined by Equation 7, so the energy balance for each node is given by Equation 8.

$$m_{m,i} = m_{c.} \sum_{j=1}^{i-1} F_{c,j} - m_{L.} \sum_{j=1}^{N} F_{L,j} \tag{7}$$

$$m_i.\frac{dT_{s,i}}{dt} = \left(\frac{UA}{Cp}\right)_i \left(Ta - T_{s,i}\right) + F_{c,i}.m_c.(Tc - Ts,i) + F_{l,i}.m_l\left(T_l - T_{s,i}\right)$$
$$+ \frac{kA_{cs}}{\Delta h.Cp}\left(T_{s,i-1} - 2T_i + T_{s,i+1}\right)$$
$$+ m_{m,i}(Ts_{i-1} - Ts_i) \qquad if \quad m_{m,i} > 0 \qquad (8)$$
$$+ m_{m,i+1}(Ts_i - Ts_{i+1}) \qquad if \quad m_{m,i+1} < 0$$

The discrete equation 8 includes the mass balance and implies upwind scheme for the convection terms, and CDS (central difference) for the diffusion term. Crack Nicolson method was used for advancing in time. The time step used for the model is a fraction of the critical time step defined by Equation (9).

$$\Delta t_{crit} = \frac{2m_S}{\frac{UA}{Cp} + \max(m_C, m_L)} \qquad (9)$$

3 RESULTS AND DISCUSSION

Two models of stratified tank were simulated. The first one is a cylindrical tank to model the charge and discharge cycles and compare the results with a simulation in TRNSYS using Type 534 (Cylindrical storage tank). The second model is a rectangular cross-section tank to compare the discharge cycle with experimental measurements from Adamovsky et. al.

3.1 Cylindrical Tank Model

The model consists of a cylindrical tank with a height of 1.5 m and 0.36m diameter filled with water. The heat loss coefficient between the tank and the environment is 1.45 W/m^2-K and the ambient temperature is assumed to be 20°C. For the charging cycle the tank is initially filled with water at a uniform temperature of 20°C and water at 80°C is injected at the top of the tank at a flow rate of 120 kg/h. For the discharging cycle, the same flow rate is used and the return temperature of the water to the bottom of the tank is 20°C. Cycle times of 2 hours with time increments of 1 minute were selected for the model.

First, the effect of number of nodes on the degree of stratification was studied by performing a simulation of the charging cycle and varying the number of nodes from 5 to 30. The temperature profiles (Temperature at different heights of the tank) obtained at the end of 1 hour of simulation is presented in Figure 2. It can be seen that, as the number of nodes increases, the model predicts a higher degree of stratification. However, the difference between the curves is less pronounced for models with 15 or more nodes.

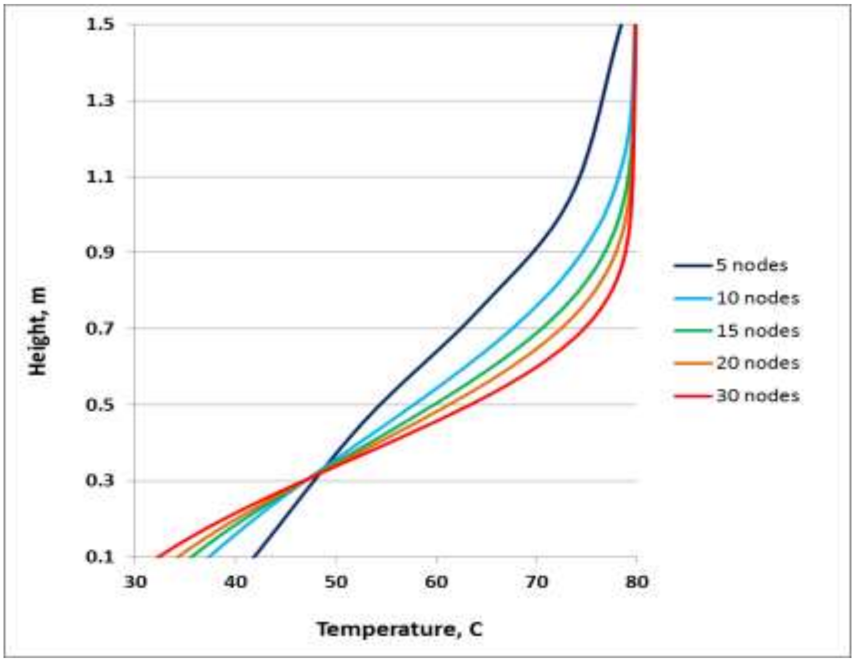


Fig. 1. **Temperature Profile after 1 hour of Charge for Different Number of Nodes**

A number of 10 nodes were selected for modeling the charge and discharge cycles. The same parameters and conditions were modeled in TRNSYS in order to compare the models. The results are presented in Figures 3 and 4. There is a strong agreement between our results and the results obtained from TRNSYS simulation. It is possible to observe that during the charging process the temperature of the nodes at the top of the tank rises much faster than the nodes near the bottom. Similarly, during the discharge the temperature of the nodes near the bottom of the tank decreases faster. The time required for the temperature to become uniform in the tank depends on the flow rate of the return water and the magnitude of heat loss through the walls. Finally, Figure 5 presents the stratification effect of the tank on specific times during the charging cycle.

3.2 Rectangular Tank Model

The model, developed to compare simulation with experimental results from Adamovsky et. al (Adamovsky, Kabrhel, Kabele, & Urban). consists of a rectangular shape tank with horizontal dimensions of 0.60x0.70 m and height of 1.65 m filled with water. The heat loss coefficient between the tank and the environment is 1.16 W/m^2-K and the ambient temperature is assumed to be 20°C. A 202 minute discharging cycle is simulated using a 10 node model with time increments of 1 min. Through the first 57 minutes of discharge thermal output is 6kW, then for the following 53 minutes decreases to 2.6 kW and during the last 92 minutes increases to 4.5

kW. Ambient temperature and return fluid inlet temperature are assumed to be 20°C and 15°C, respectively, as they are not specified in the experiment. The fluid mass flow rate is calculated each time step based on the energy withdrawal and the assumed return temperature. A comparison of the simulation and the experimental results is provided in Figure 6. During the first 110 minutes simulation results show considerable agreement with the experimental data, however, when the thermal output increases in the last 92 minutes, the simulation predicts a much lower destratification rate than the experiments.

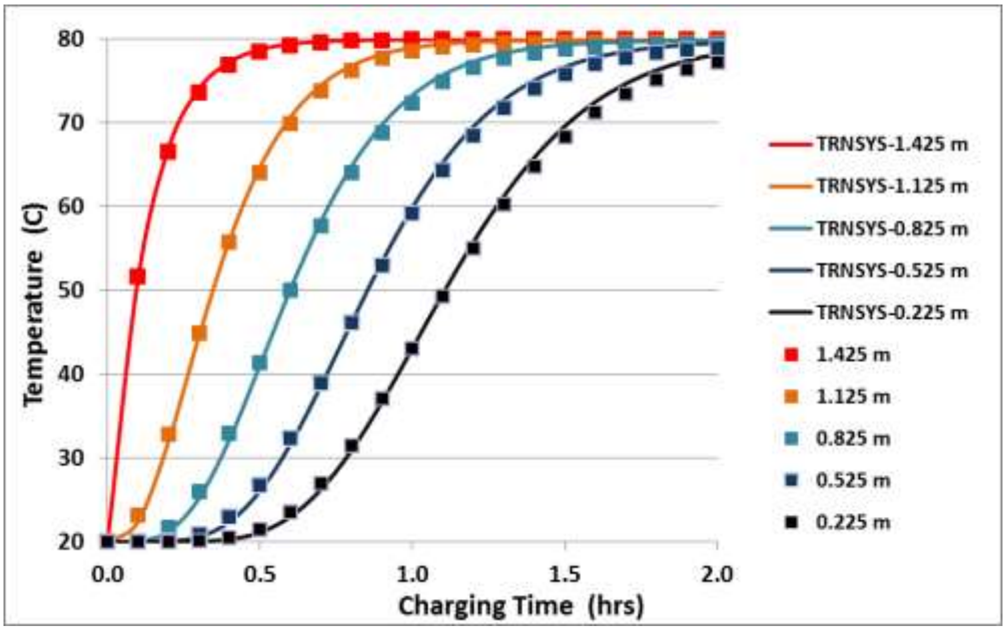


Fig. 2. **Temperature of Nodes vs. Time during Charging Cycle**

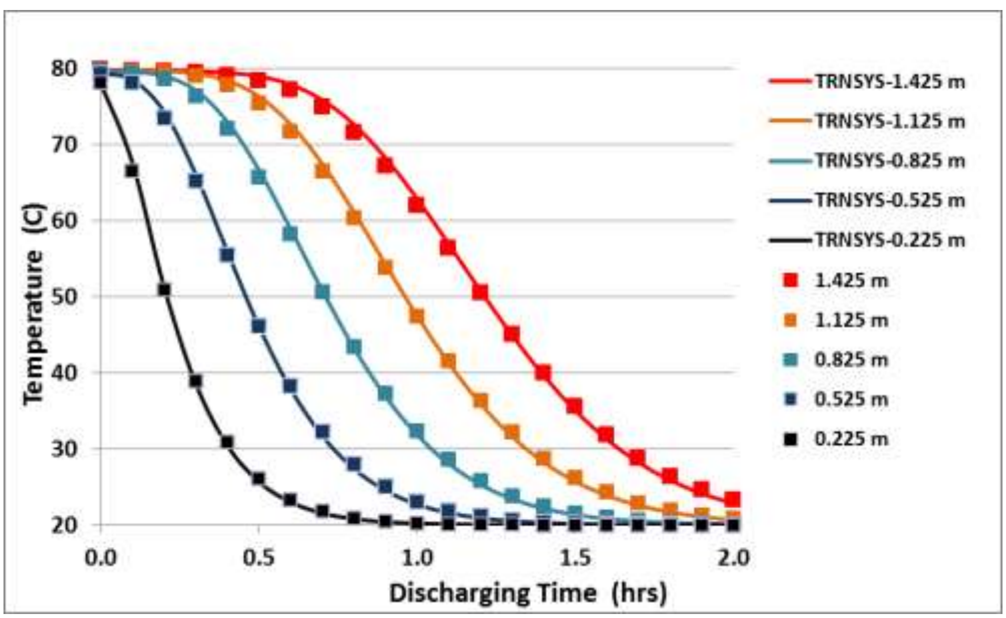


Fig. 3. **Temperature of Nodes vs. Time during Discharging Cycle**

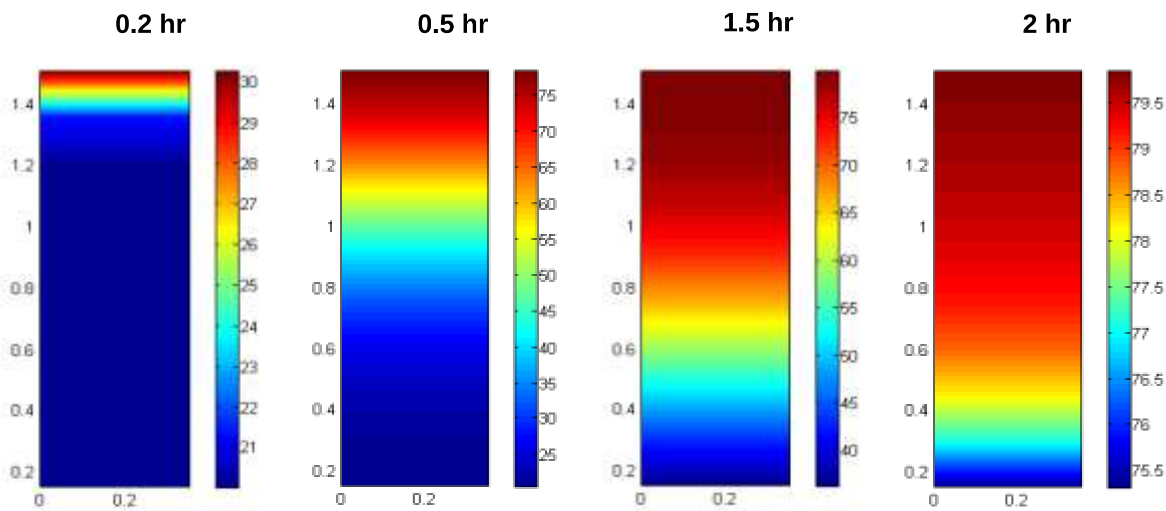


Fig. 4. **Stratification Effect During Charging Cycle**

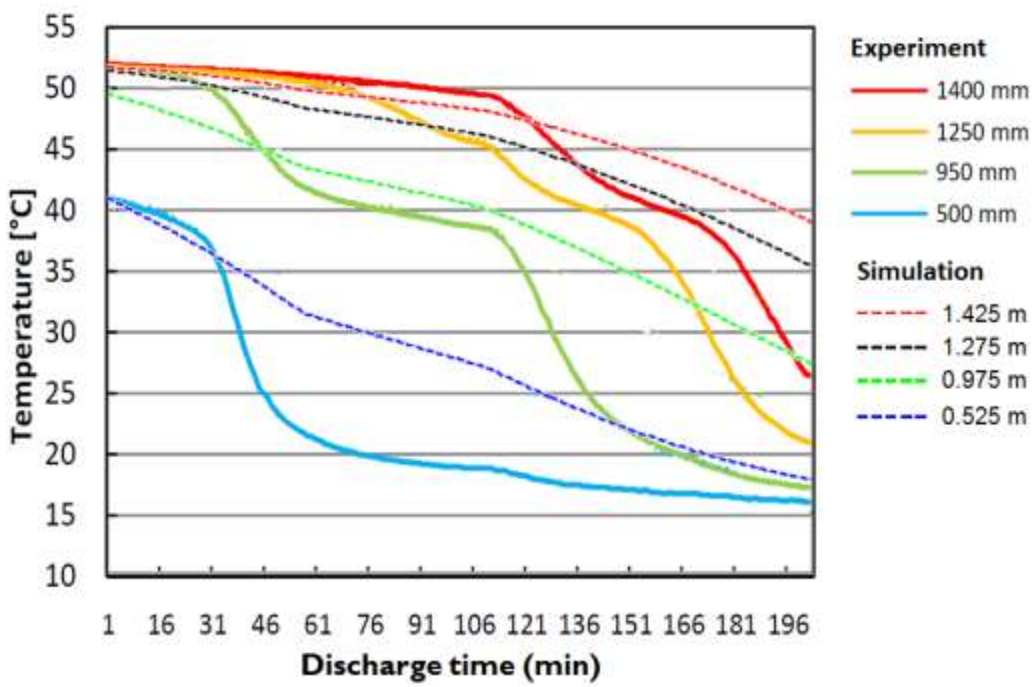


Fig. 5. **Comparison of Simulation and Experimental Data**

4 CONCLUSIONS

The model developed showed strong agreement with the TRNSYS simulation results. However, the comparison with experimental results reveals considerable deviation in the degree of stratification after 202 minutes of discharge of the tank.

Detailed numerical simulation is required to describe accurately the performance of stratified tanks; However, CFD models are computationally expensive and not suitable for long-time simulations. One-dimensional models based on multinode approach, although inaccurate for detailed modeling of the tank, shows acceptable performance for the long-time simulations typically required to evaluate the performance of energy systems involving stratified tanks.

The number of nodes selected for the multinode model was found to have a significant effect on the degree of stratification. Since, in real conditions the degree of stratification depends on the design of the storage tank and operating conditions (i.e. inlet and outlet velocities), previous knowledge from experiments or accurate simulation is required to select the number of nodes that better describes the degree of thermal stratification of the tank, in order to avoid unrealistic estimations of the performance of the system.

NOMENCLATURE

A = Area of surface of each tank segment, m^2

A_{cs} = Tank cross sectional area, m^2

Δh = Distance between adjacent nodes, m

C_p = Specific heat of fluid, J/Kg-K

K = heat conductivity of the fluid, W/m-·K

m_c = Mass flow rate of return flow from collector, kg/s

m_L = mass rate of return flow from load, kg/s

$m_{m,i}$ = net mass flow rate to node i from node i-1, kg/s

m_s = Mass of fluid stored in each node, kg

T_a = Environment temperature, C

T_c = Collector return flow temperature, C

T_L = Load return flow temperature, C

$T_{s,i}$ = Node temperature, C

U = Overall heat loss coefficient, W/m^2-K

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