Effect of Insulation on the Performance of Wrapped-Coil-Tank Heat Pump Water Heater Deploying Low GWP Refrigerants.

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Domestic water heating accounts for 18% of all residential and commercial building site energy used in the United States. Heat pump water heater is one of the most efficient water heating technologies compared to other conventional electric resistance or gas-based water heating technologies. For heat pump water heaters, the water in the storage tank absorbs heat rejected by the condenser of the heat pump system. To accomplish this indirect heat transfer, condenser in form of a coil is wrapped around the water tank and the whole assembly is covered with thermal insulation. Tank insulation plays an important role in controlling the amount of heat loss from the tank and from the condenser coil and consequently the thermal stratification inside the tank is continuously impacted by the heat loss to the environment. The thermal stratification is critical to achieve improved Unified Energy Factor (a performance parameter often used to characterize the water heater efficiency). This current study is focused on the impact of thermal insulation over the wrapped tank coil water heater on the storage tank. The various thermal-physical properties of the insulation material and thickness are studied to determine their potential effect on water heating process. The boundary conditions are established based on the refrigerants' (R32, R1234ze and R1234yf) behavior inside the condenser tube as it goes through super-heated, two-phase flow and sub-cooled phased.

1. Introduction

Water heating is considered as one of the buildings' highest energy consumption services. Water heating accounts for 18% of all residential and commercial building site energy use in the United States, making it the third largest user of energy in homes [Harris et al, 2005]. To increase the water heaters efficiency, heat pump water heaters (HPWH) have been used as a replacement for the low efficiency conventional gas fired or electrical water heaters. Fundamentally, the HP is essentially a reverse Rankine cycle which absorbs energy from a source at lower temperature (ambient air, geothermal energy, solar energy, and waste heat) and utilizes the energy to heat cold water. However, the system becomes significantly complex when the practical implications are considered such as sizing the compressor, selecting appropriate heat exchangers etc [Chua, 2010]. The utilization of HP for water heating adds to the complexity of the system and makes the water tank design and performance a very critical factor in the system performance [Morrison et al, 2004; Baxter et al, 2011; Franco, 2011; Shah and Hrnjak, 2014; Nawaz et al., 2016]. Several preliminary studies have been conducted to predict the performance of HPWH. Researchers have investigated working fluid, thermodynamic cycle, tank size and water draw [Nekså, 2002; Sienel et al., 2007; Hepbasli and Kalinci, 2009; Bowers et al., 2012]. Individual components and whole system have been analyzed using different analysis methods including energy analysis, entropy analysis and exergy analysis system [Sarkar et al, 2005; Zhang et al., 2007;Liapradit et al., 2008; Fernandez et al., 2010]. It has been concluded that HPWH efficiency is affected by many factors, such as, , water tank size, environmental condition, working fluid, refrigerant charge, opening degree of thermal expansion valve and compressor frequency [Hepbasli and Kalinci, 2009]. However, there are rare studies to model and optimize the water tank which is an integral part of all Storage-HPWH systems [Shah and Hrnjak, 2014].

A concept system was presented by Ohkura et al., [2015] to extract tepid water from the side of the storage tank to avoid the degradation of system performance due to heat loss through the tank. Numerical simulation was deployed to study the performance enhancement of a CO_2 heat pump water heating system with reconfigured storage tank. The concept relied on the fact that water extraction makes the temperature gradient in the storage tank large, and makes the area of tepid water small. It was found that the water extraction increased the heat pump coefficient of performance (COP) but decreased the storage efficiency. Since the water tank is a critical component of any HPWH,

several studies have focused on the water tank characterization. Cecchinato et al. [2005] conducted a theoretical study to compare the performance of a CO_2 HPWH to an HFC (R134a) HPWH. The model analyzed two approaches to represent the performance of the HPWH; a perfect mixing and perfect stratification. They concluded that better system efficiency will result when there is more stratification. The perfect mixing case showed that CO_2 system's performance was more adversely affected than the R134a. Stene [2005] conducted an analytical and experimental study for brine-to-water heat pump for combined space and hot water heating and concluded that thermal stratification is important and directly impact the performance of the system. Yokoyama et al. [2010] studied the performance of a CO_2 HPWH under simulated standard hot water demand. It was concluded that since CO_2 heat pump performance is extremely sensitive to water inlet temperature, it is important to maintain temperature distribution in the tank for an improved performance of HPWH under various water demand scenarios over. An oversized tank and heat pump resulted in higher standby losses, leading to inefficient reheating of the system [Kim et al., 2010].
Insulated wrapped coil tanks are used to heat the water. The insulation has a very important role in reducing the heat losses from the tank which will contribute to the efficiency increase. Thermal insulations are used in a wide range of equipments and in buildings. The thermal insulation thickness should to be optimized to achieve lower cost and higher efficiency. Different insulations and thicknesses can be used. We are investigating numerically the thermal insulation thickness effect on the thermal stratification inside the tank for a better performance and to reduce the system cost. Figure 1 shows a detailed schematic of the heat pump system [Baxter et al., 2011].

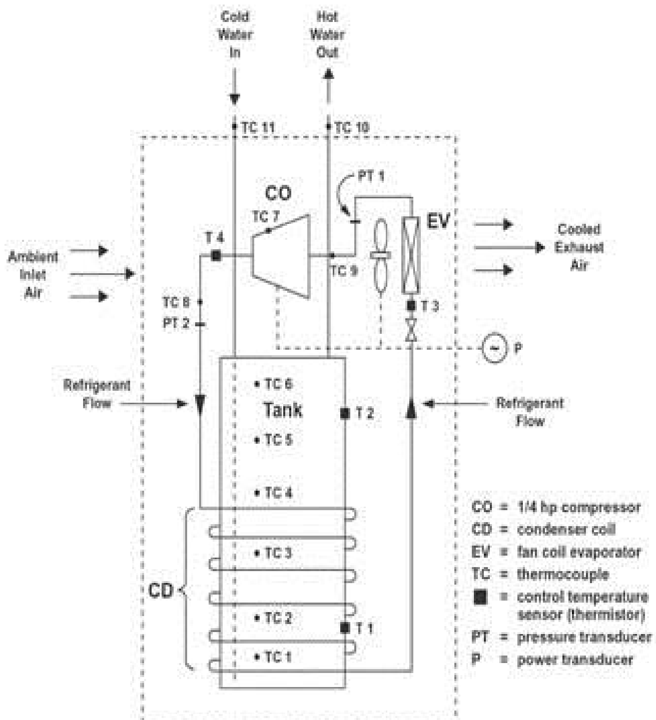


Figure 1: Schematic of heat pump system with wrapped coil tank.

2. Numerical Modeling

A 45 Gallon insulated water tank exposed to room temperature was modeled and simulated using ANSYS FLUENT 17.2. The recovery and supply tubes are 0.5 inch in diameter. The tank dimensions are shown in Figure 2. The insulation thermal conductivity is considered 0.45 W/m. K and density of 37.5 kg/m^3. The condenser is a wrapped coil around the water tank which is the heat sink. According to the refrigerant state at various locations along the height of the tank, the wrapped coil can generate a stratified thermal profile in the water tank during the heating process. Accordingly, the domain was divided into 6 segments and the initial temperature for each segment is shown in table 1. The sections start with section #1 at the bottom and increases going upwards.

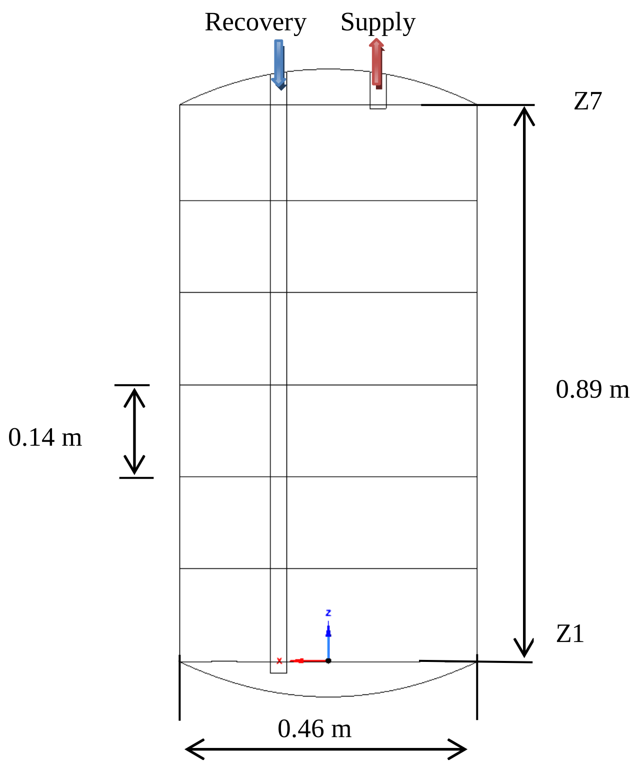


Figure 2: Water tank (Z1 to Z7 are the seven heights for temperature monitoring).

Table 1: Initial Temperatures

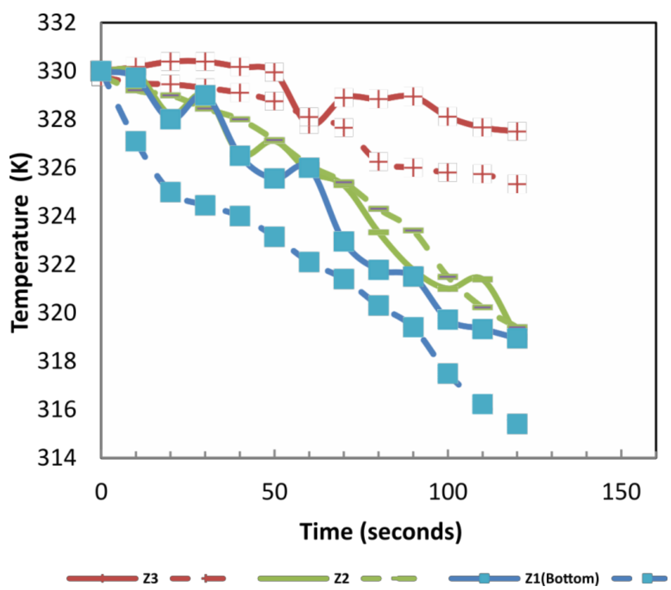
Section #	Initial Temperature (K)
1	311
2	313.7
3	316.5
4	319.3
5	322
6	324.8

The mesh was refined at the supply and recovery tubes inlets and along the tank wall and the insulation thickness. In addition, the adjacent region to the tank inner wall and insulation outer surface was also refined to capture the heat convection mechanism accurately. The simulation was transient and gravity force was included. Navier-Stokes and energy equations were solved and realizable k-ε turbulence model was used to simulate the flow turbulence [Wilcox, 2006]. SIMPLE scheme was used for pressure-velocity coupling with second order implicit transient formulation.

The time step was 0.01 seconds and the maximum iterations per time step was 15 with a residual of 1×10^{-5}. An Intel Xeon processor E5-1607 at 3.1 GHz and 32 GB of memory was used to run the simulations. The tank wall temperature was 338.7 K from the bottom to 0.58 m height (i.e. till the upper edge of section 4) then the wall temperature was 324.8 K to the top of the tank. Constant wall temperature was selected due to the phase change conditions in the condenser which reduces the wall temperature change. The selected wall temperature values are based on the report by Nawaz et al. [2016]. The boundary condition represents a wrapped coil water tank where refrigerant condenses at constant temperature for about 2/3 of the tank height from the bottom. A medium withdraw pattern was selected for the simulations (i.e. flow rate of 1.7 x 10^4 m^3/s and withdraw time of 90s).

The experimental data by Baxter et al., [2011] for a wrapped tank water heater were used to validate the numerical model. For the baseline case, the water initial temperature was 330 K all over the tank, the recovery water inlet temperature was 288 K and the supply water temperature was 330 K. The water temperature was measured at six different heights inside a wrapped coil HPWH during the charging and discharging process. Figure 3 shows the temperature profiles as a function of time for both the experimental and the numerical data. The temperature profiles show similar trend for both the numerical and experimental data with close agreement in the upper half of the tank while the water temperature in the lower half of the tank has higher deviation. The deviation can be attributed to the error associated with the single phase heat transfer observed in experiment.

(a)



(b)

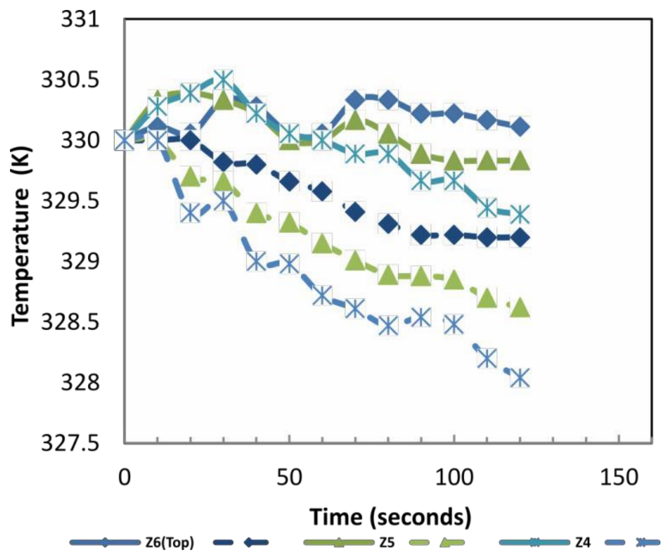


Figure 3: Comparison between measured values (solid lines) and numerical predictions (dotted lines) of water temperature along different heights (a)Z1=0, Z2=0.19 and Z3=0.36) and (b) Z4=0.53, Z5=0.7 and Z6=0.89 m)

The refrigerant entered as superheated vapor and exited as liquid so a contact temperature boundary condition is not a realistic condition but it was adopted since a major part of the wrap tank contained two-phase refrigerant going through condensation. The maximum error between the numerical and experimental data is 3.5 K and the average error is 1.3 K. These results show a satisfactory performance for the CFD model.

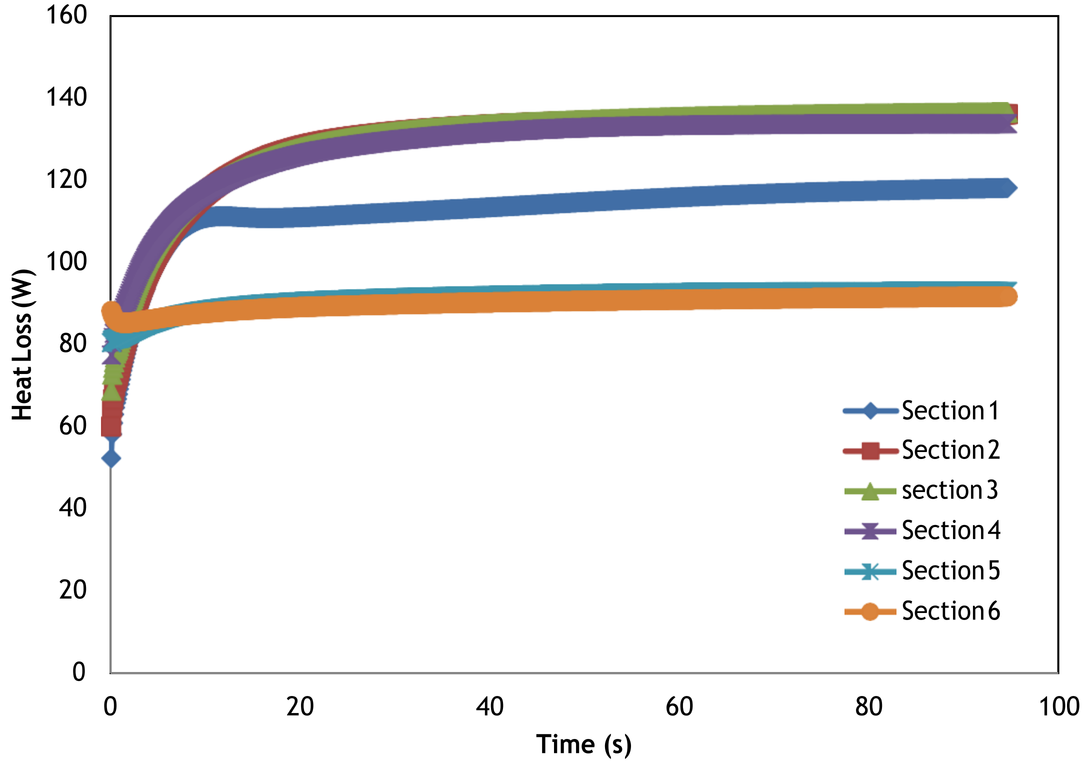
3. Results

Insulated water heater tank was simulated numerically. Three different insulation thicknesses were considered, 0.5, 1 and 2 inch. The tank top and bottom walls were assumed adiabatic. The tank wall was considered as a thin wall. The heat loss rate across the tank wall and insulation is calculated using Fourier's equation:

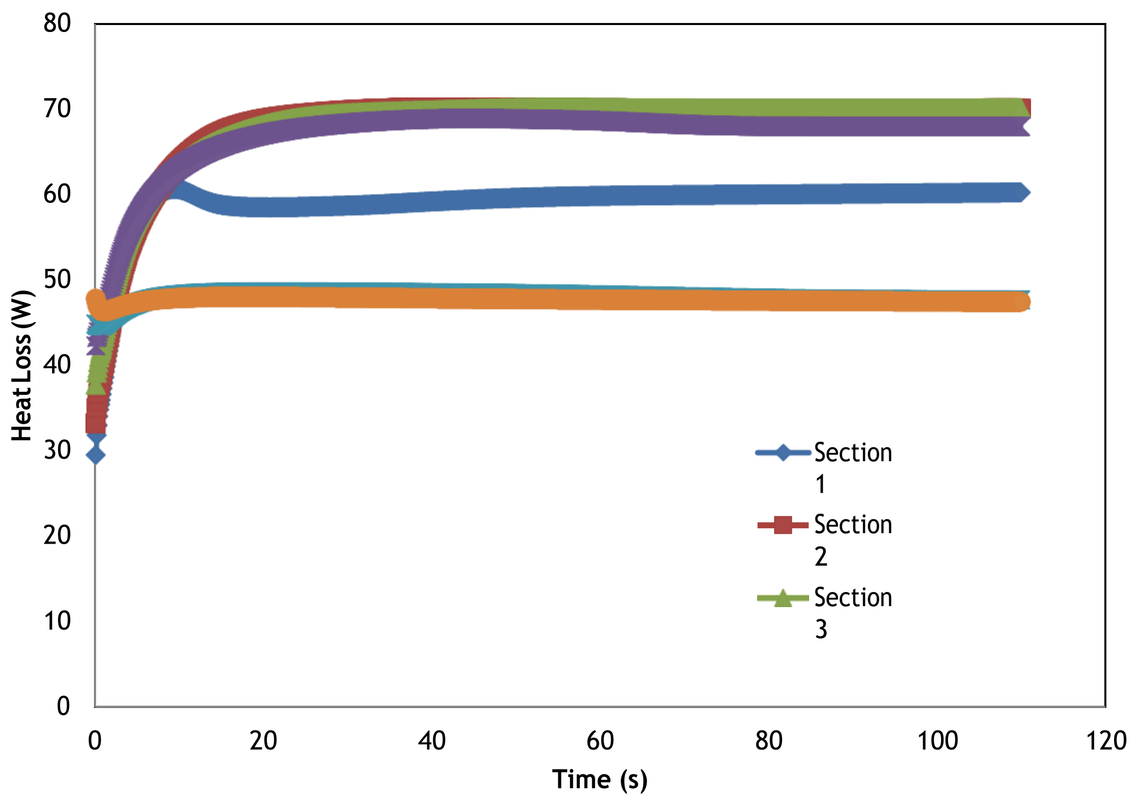
$$\frac{Q}{A} = -k\frac{\Delta T}{\Delta X} \tag{1}$$

Where *K* is the insulation thermal conductivity (W/m.K) and $\frac{\Delta T}{\Delta X}$ is the temperature difference across the insulation thickness *X*. Figure 4 presents the heat loss at each section of the tank wall along the tank height. The highest heat lost rate occurs at section 2,3 and 4 while the lowest heat lost is observed in section 5 and 6 at the top part of the tank. This behaviour is observed for all insulation thicknesses. The plots show that increasing the insulation thickness is reducing the heat losses. This means that thicker insulations should be investigated to reach the optimum insulation thickness.

(a)


160
140
120
100
80
60
40
20
0
Heat Loss (W)
0
20
40
60
80
100
Time (s)
Section 1
Section 2
section 3
Section 4
Section 5
Section 6

(b)


80
70
60
50
40
30
20
10
0
Heat Loss (W)
0
20
40
60
80
100
120
Time (s)
Section 1
Section 2
Section 3

(c)

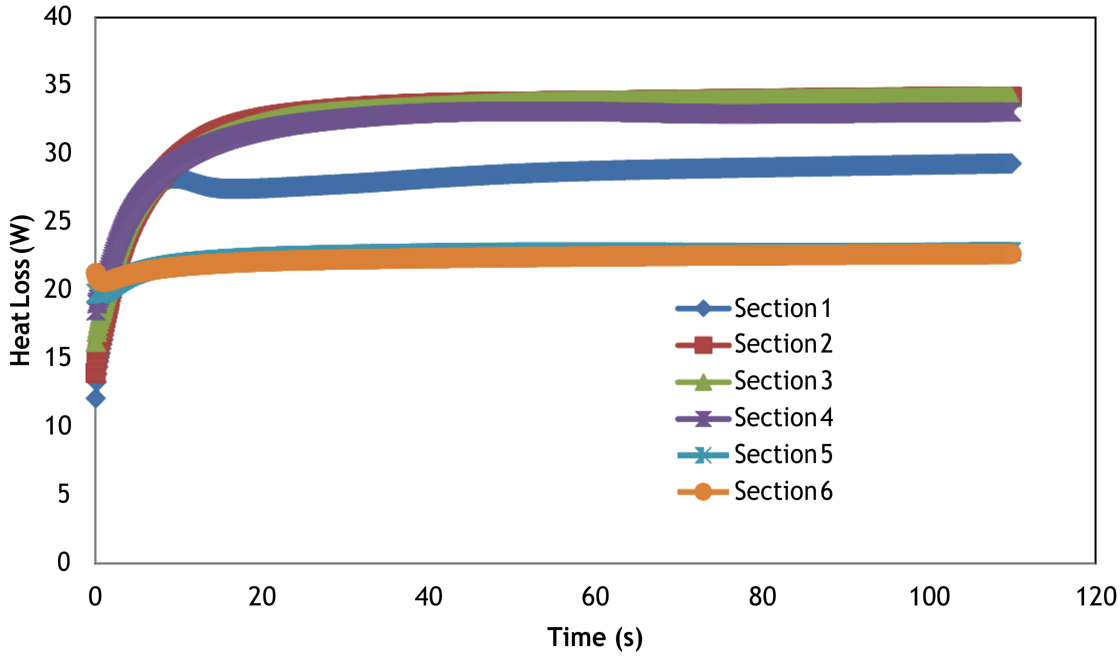


Figure 4: Average heat losses across the tank wall for (a) 0.5 insulation thickness, (b) 1 inch insulation thickness and (c) 2 inch insulation thickness.

The insulation thickness did not show a significant effect on the average tank temperature although the difference in the heat loss rate. Figure 5 shows the average tank temperature with 0.5 inch insulation for the 6 sections along the tank height. It is found that tank average temperature have a similar behavior to for the three insulation thicknesses (figures for 1 and 2 inch cases are not shown here).

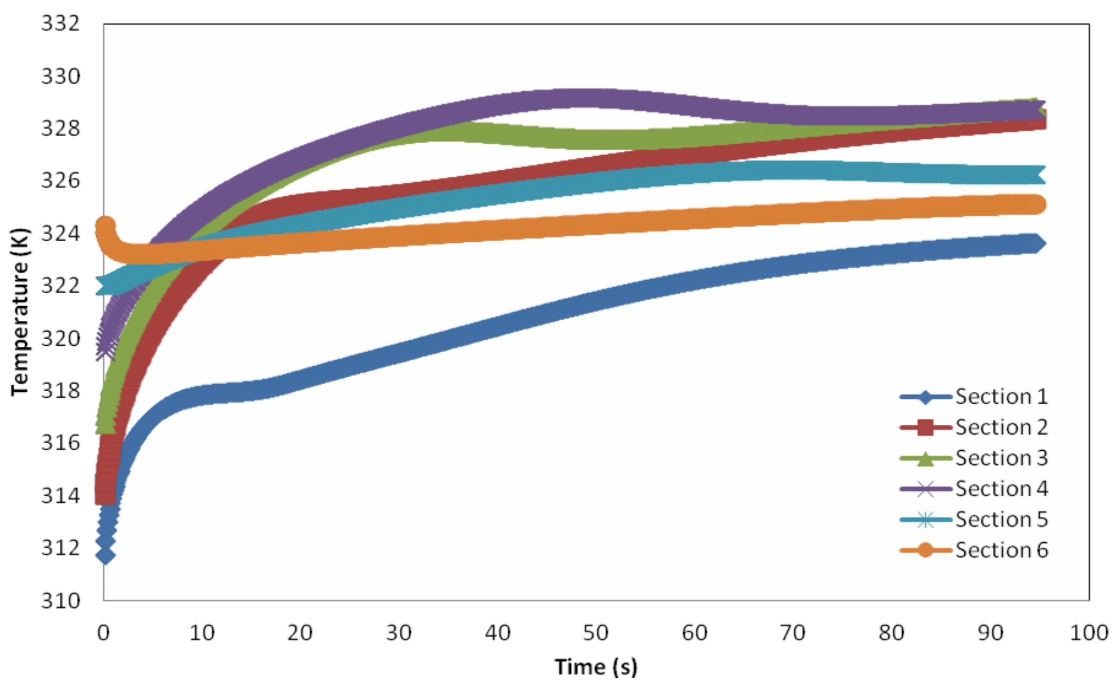


Figure 5: Average tank temperature with 0.5 inch insulation.

The insulation thickness average temperature is shown in figure 6 for the smallest insulation thickness. It was observed that the effect of the insulation thickness is not prominent on the average insulation temperature. The insulation average temperature decreases with time as seen in the figure and that is observed along the tank height. However, the temperature drop during 90 seconds is around 0.5 K and 1.25 K for the bottom and top half of the tank respectively. The temperature drop can be attributed to the increase of heat loss with time.

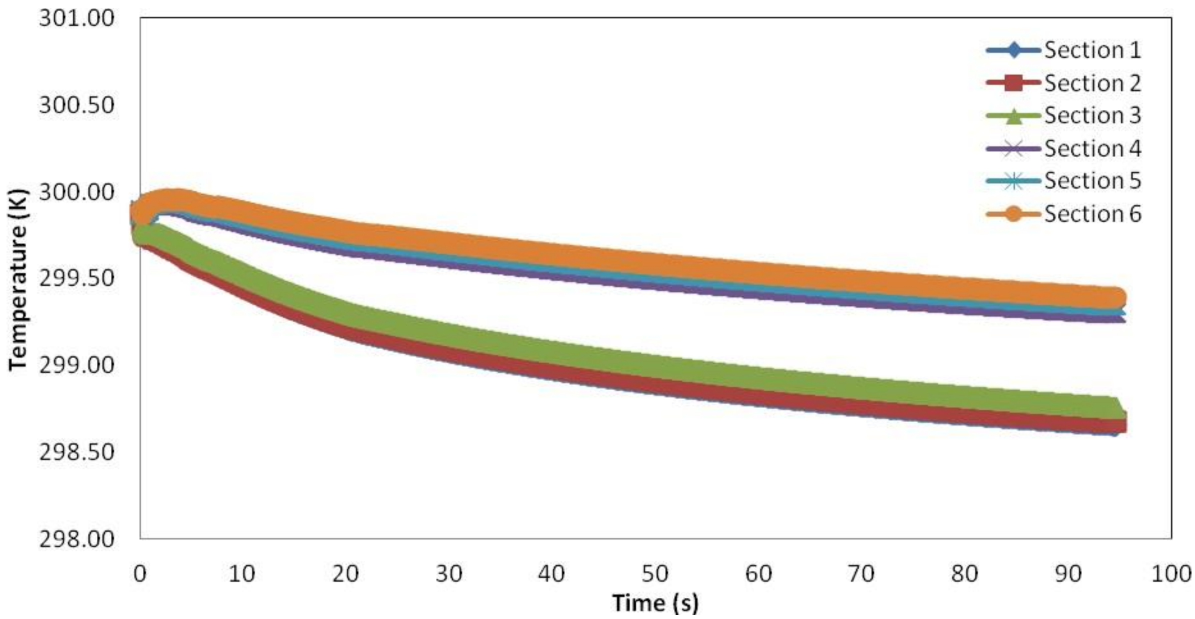


Figure 6: Average Insulation temperature for 0.5 inch insulation tank.

4. Conclusion

It can be concluded from the numerical investigation that:

- Increasing the insulation thickness to 2 inch reduces the tank heat loss.
- Insulations with higher thickness need to be investigated to find the optimum insulation thickness.
- The insulation thickness does not have a noticeable effect on the tank average temperature.

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