Performance Analyses of Multiple inlet Modes of a Bottom Supply Hot Storage Tank

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Abstract

The storage tanks are high energy containing devices, its main role is to reserve the hot fluid for later use. Hot storage tanks enroll two energy wasting mechanisms; one of which energy wasting due to insulation and the second is energy wasting due bad mixing between the hot and cold fluid streams. In this work the performance of a bottom supply hot storage tank under multiple supply modes was analyzed. The analyses were done for two bottom supply modes namely (covered and uncovered) under different supply flow rates (3, 6, 8 and 9 l/min). The performance of the tank was measured using most recent quantifying parameters (Thermocline thickness, Mixing number, Discharge efficiency and Exergy efficiency). It has been found that hot storage tanks that enroll high flow rates must be supplied with smoothing cover over the bottom supply to eliminate the turbulent mixing between hot and cold fluids, whereas for low flow rate supply mode the tank performs well even without cover. High thermocline thickness was achieved for the uncovered high flow rate 9 l/min. Mixing number was increasing by increasing the flow rate dislike the covered mode where the Mixing number values are close to each other's. The Discharge and Exergy efficiencies show similar behavior as both efficiencies are maximum for the low flow covered mode and minimum for the high flow uncovered mode. It is valuable to identify the workability nature of the hot storage tank to maximize the beneficial energy from the tank.

Keywords: Hot Storage Tank, Bottom Supply, Thermocline thickness, MIX number, Discharge Energy Efficiency, Exergy Efficiency, Heat transfer.

Introduction

Energy Storage Tanks (EST) are vessels that store energy for special usage purpose. It is important in residential applications as electric heater Hot Water Storage Tanks (HWST) or solar heating HWST, commercial and industrial sectors such as manufacturing the hot storage cylinders for domestic hot water usage, solar hot water cylinders for district heating systems and even in solar power generation. The highly efficient hot water storage tanks are favored for its effect on energy saving, its role in creating new applications and the competition it creates in the markets. Many researches were done to understand the nature of the hot water mixing with cold water, furthermore different tank supply conditions and different tank applications were considered (F. J. Oppel et. al. and Y. H. Zurigat et. al.). In their research, they predicted the temperature by accounting for turbulent mixing at the inlet region of the HST; they introduced an effective diffusivity factor for this purpose. Many researchers quantitate the performance of HST such as J. H.

Davidson et al. (1994), Jose Fernandez et. al. (2007) and N. Gopalakrishnan and S. Srinivasa Murthy (2009). García et. al. (2013) compared between two water inlet devices in a HWST during a thermal charging process: a sintered bronze conical diffuser (SBCD) and a conventional inlet elbow (E). The temperatures were recorded by the thermocouples; the MIX numbers as well as the thermocline thickness were used to quantify the performance of stratification in their research. More quantifying parameters were then used for HST such as charging efficiency and the exergy concept, Petr Švarc (2014) studied two different supply inlets into the HST the side and the downward inlets, the measured data during charging process were compared with the help of the thermocline thickness, *MIX* number, equivalent lost height (*ELH*) and efficiency based on the exergy concept. These quantifying parameters are sufficient to evaluate the HST performance. Due to the importance of HST in the recently new applications; increasing concern was given to HST, accelerated researches were conducted in the last few years. Njoku et. al. (2014), executed an extensive survey on the performance methods based on energy, entropy and exergy analyses, he proposed the entropy generation ratios, which are based on second law considerations, as effective quantifying parameters to measure the performance of stratified thermal energy storage systems. Heming Yuna, Fangfang MA, Xunhu Guo and Baoming Chen, (2017) studied the thermal storage effect of solar energy storage tank. They suggested entropy generation number (Ns) for performance analysis. Furthermore in 2018 Alva G., Lin Y. and Fang G. made an overview of the HST usage in domestic, power generation applications and thermal energy storage materials. The current study is directed toward analyzing the performance of multiple supply modes of a bottom supply HST, the analyses were performed by measuring the most effective performance parameters including the Mixing number, Discharge efficiency, Exergy efficiency in addition to the thermocline thickness. The covered and uncovered supply modes were analyzed for different flow rates (3, 6, 8, and 9 l/min).

Experimental Setup

The HWSTs are usually provided by different inlets and exits locations; many are using centered bottom supply of cold water and centered top exit of hot water, others are using a side supply again from the top or the bottom of the tank. The widely used bottom cold water supply is analyzed in this paper for both covered and uncovered modes Figure 1. Figure 1 shows a schematic of the bottom cold water supply for the covered and uncovered modes. The uncovered mode allows the direct mixing between cold and hot water whereas the covered mode forces cold water to be uniformly distributed in the bottom region of the HST.

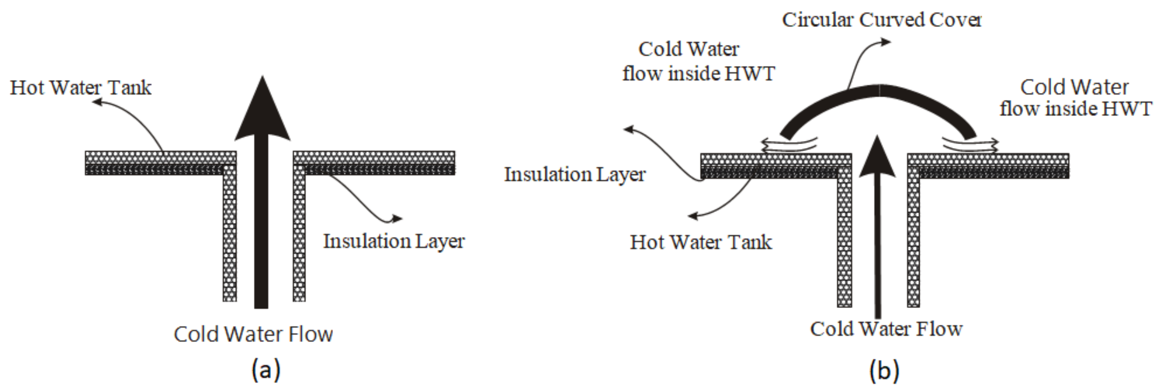

Figure. 1. Schematic diagram of the hot water tank bottom supply modes (a) uncovered (b) Covered.

To analyze the thermal performance of such a HST, an experimental setup was construct shown in Figure. 2. The setup was equipped with two constant temperatures water containers, the cold one as a source of cold water and the hot container represents the source of hot water in the system. The water in the hot water container is heated using a gas heater for its fast heating and high energy value. These two water containers are connected to a main HWST by means of piping network, water pump and control valves to manage the circulation process i.e. filling the hot tank with the required temperature and recirculating until reaching a uniform temperature all over the tank, then supply the test tank with the required flowrate of cold water under the selected supply mode to perform the pre-specified experiment.

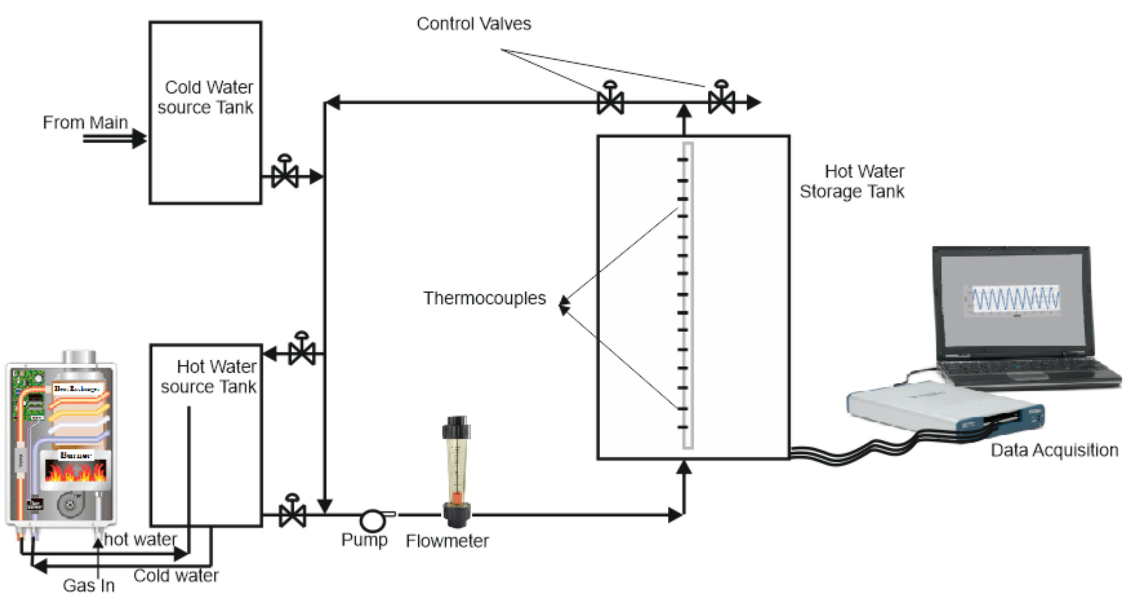

Figure. 2. Schematic diagram of the experimental setup.

The constructed system is provided by a flowmeter to measure and adjust the required flow rate (3, 6, 8 and 9 l/min). The main test tank (HST) is equipped with fifteen K-Type thermocouples set in a vertical line with 5 cm distance a part to sense the temperatures all over the HST, one extra thermocouple is used to measure the outside temperature of air. A computerized data acquisition system is used to record the collected data from the sixteen thermocouples each period of time and saving these data in a proper file by the end of the experiment. The different control valves are used to control the direction of the flow and when maintenance is required.

The experimental device (HST) design dimensions and experimental parameters are listed in table 1.

Table 1: HST design dimensions and experiments parameters.

Hot Water Storage Tank Dimensions	
Tank Height	78 cm
Tank Internal Diameter	42 cm
Total Number of thermocouples	15
Distance between thermocouples	5 cm
Tank Insulation thickness	4 cm
Tank total capacity	108 L
Experimental Parameters	
Cold Water Flow rates	3, 6, 8 and 9 l/min
Hot Water Initial Temperature	60 ^{o}C
Features considered	Bottom flow Covered and Uncovered Supply

The experiments have been performed for different water usage flow rates, bottom supply feature; covered and uncovered modes as listed in previous table.

Experimental Results

To be able to analyze the performance of the HST; the HST was filled with uniform temperature hot water then supplied with bottom flow cold water at (3, 6, 8 and 9 l/min) both with the supply inlet uncovered and then with the covered supply inlet. The data for the eight experiments was recorded in separate files for analyses. A sample data file for 8 l/min flow rate uncovered mode is shown in table 2.

Table 2. Sample Data File for 8 l/min uncovered supply mode.

Time	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
10.0	60.8	61.0	60.9	60.8	61.1	61.0	61.0	60.8	61.1	61.0	60.9	61.2	61.1	60.5	60.2
20.0	60.4	60.8	60.8	61.0	61.0	61.1	60.8	60.9	61.2	61.0	60.9	61.2	61.0	60.5	60.3
30.0	60.7	60.8	60.8	61.1	60.9	61.2	60.9	61.1	61.1	61.1	61.0	61.2	61.1	60.5	60.3
40.0	60.5	60.7	60.7	61.0	61.1	61.2	60.7	61.1	61.3	60.3	60.9	61.0	58.8	59.0	59.2
50.0	60.5	60.9	60.9	60.8	61.0	60.9	61.1	60.5	60.6	59.6	59.9	59.0	58.2	57.6	57.5
60.0	60.3	60.8	60.9	60.8	60.8	61.2	60.9	61.1	61.2	57.7	57.5	57.9	57.0	55.8	55.8
70.0	60.3	60.4	60.9	61.0	61.0	60.9	60.6	60.5	59.5	57.8	56.9	56.6	55.6	55.7	55.7
80.0	60.6	60.6	60.9	60.7	60.7	60.8	60.9	60.7	58.0	56.1	55.4	54.9	54.0	54.7	54.5
90.0	60.4	60.6	60.6	60.7	60.8	61.0	60.9	60.8	55.7	54.9	54.5	54.0	54.1	53.6	53.0
100.0	60.3	60.4	60.6	60.7	60.7	60.9	60.4	60.4	55.4	54.5	54.0	52.9	52.3	52.0	52.0
110.0	60.6	60.4	60.9	60.5	60.7	60.8	60.5	55.8	51.6	52.1	53.0	52.4	52.0	51.7	51.5
120.0	60.4	60.3	60.5	60.8	60.6	60.8	60.0	54.9	52.6	52.3	51.9	51.2	51.9	51.2	50.9

To visualize the temperature distribution differences between covered and uncovered bottom supply modes, the temperature distribution for uncovered bottom supply mode for flowrate (nearly 9 l/min) and covered mode for the same flowrate are shown in figure 3 and figure 4 respectively.

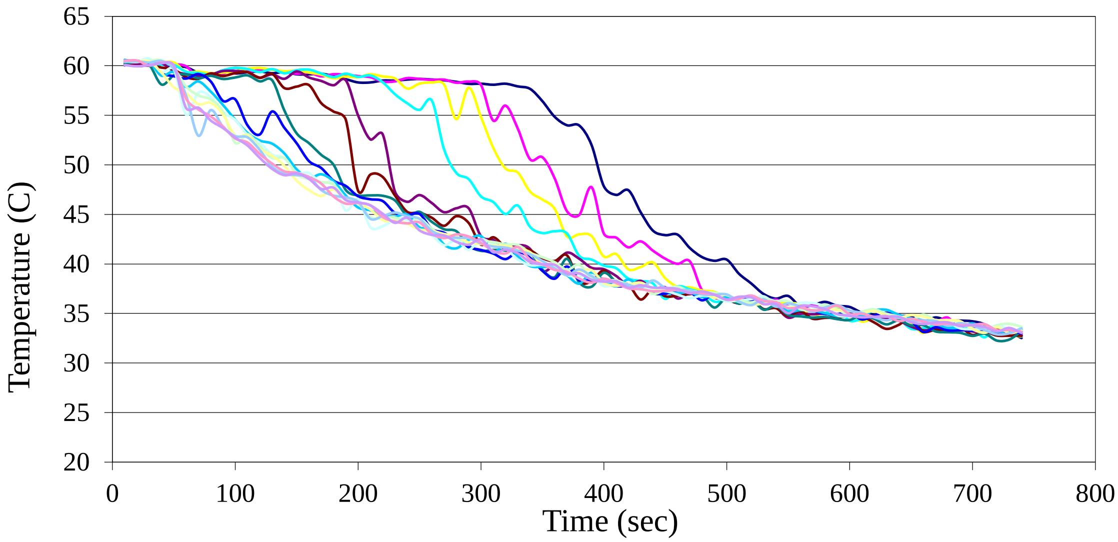

Figure 3. Temperature distribution versus time for uncovered bottom supply mode for 9 l/min flow rate.

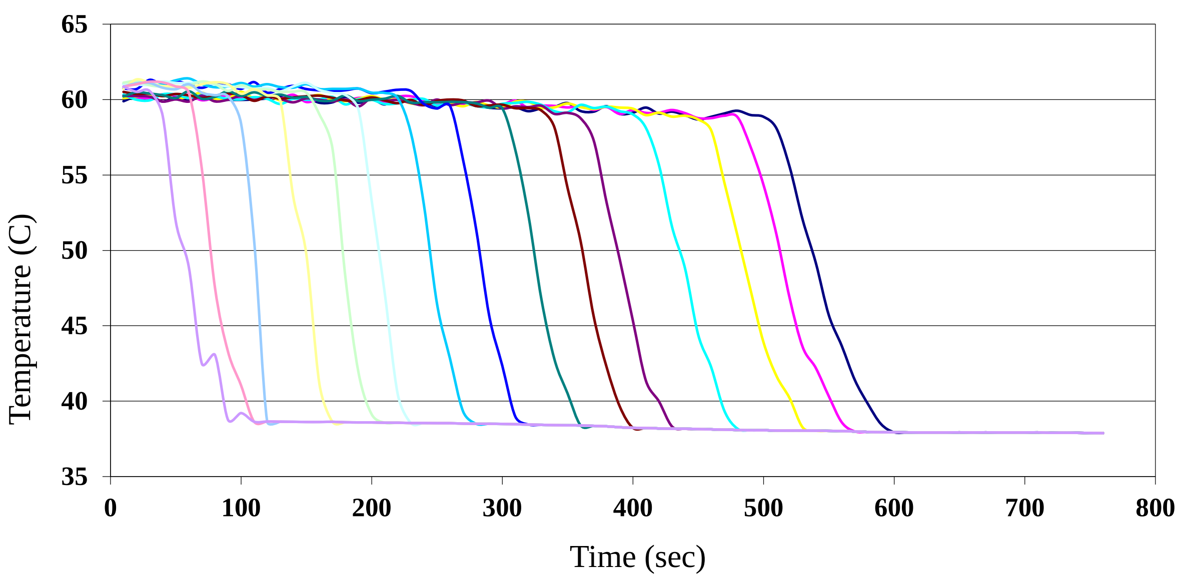

Figure 4. Temperature distribution versus time for covered bottom supply mode for 9 l/min flow rate.

Figure 3 shows the temperature distribution for 9 l/min uncovered supply mode, it is clear from the figure that turbulent mixing is effective in such high flow rate, the thermocouples values are fluctuating through the tank and exit temperature drops down in a relatively short time period. On contrast figure 4 shows the temperature distribution for the same flow rate (9 l/min) but for the covered supply mode, there is a clear difference if compared to figure 3. In Figure 4 the thermocouples values are more stable and uniform, the exit temperature from the HST takes longer time to dropdown. This behavior is interesting and valuable. To quantify these differences different quantifying parameters will be considered in the performance analyses.

Performance Analyses

To quantify the performance of the HST, thermocline thickness, mixing number, discharging efficiency and exergy of the HST will be considered.

As the different experimentations consumes different time periods; the consumed time should be non-dimensioned. First the mean residence time (t') that is the time necessary to fully fill the storage tank with water volume equal to the tank's volume is defined as;

$$t' = \frac{Tank\ volume\ (m^3)}{volume\ flow\ rate\ (^{m^3}/_{s})} \qquad (1)$$

Dimensionless time parameter can been defined as;

$$\tau = \frac{t}{t`} \qquad (2)$$

Where τ is the dimensionless time, t time in seconds and t' is the residence time consumed in the specified experiment.

Whenever there is a temperature variation in the experimental inlet or exit temperatures; a dimensionless temperature should be used to eliminate these differences as,

$$\theta = \frac{T - T_\infty}{T_{max} - T_\infty} \qquad (3)$$

Where θ is the dimensionless temperature, T_∞ is the ambient temperature, T_{max} is the maximum water temperature, T is the water instantaneous temperature.

These non-dimensional parameters are basics to compare the quantifying parameters of the different tests.

Thermocline thickness

The thermocline thickness represents the length of the stratified region in the HST. As the cold water enters the HST from the bottom supply inlet; the cold water mixes with the hot water inside the tank, causing a temperature variation throughout the HST. The temperature distribution inside the HST can be divided into three different regions; hot water at the top, cold water at the bottom and stepped thermocline region in the middle. Position of the thermocline region is defined by the boundary lines of cold water and hot water in the tank. To quantify this parameter the thermocline thickness is defined as,

$$Thermocline\ Thickness = L_h - L_c \quad (4)$$

Where $L_h$is the height of the first hot water layer and L_c is the height of the last cold water layer.

Figure 5 shows the thermocline thickness for 9 l/min flow rates for both covered and uncovered bottom supply modes. As it is clear from figure 5 the thermocline thickness for uncovered mode is much higher than the covered mode, this indicates the high turbulent mixing if the cover is not used at high cold water flow rates. Figure 5 also indicates the valuable use of the bottom supply cover in reducing the thermocline thickness in the HST.

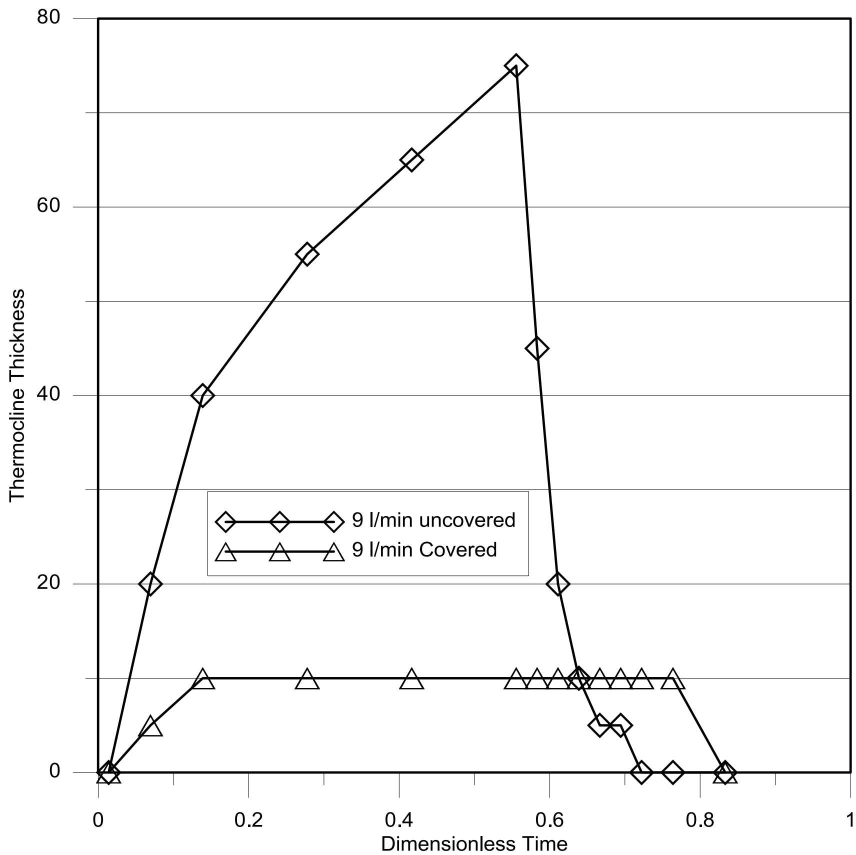

Figure 5 shows the thermocline thickness for flow rates (Uncovered mode 9 l/min and Covered 9 l/min).

Mixing Number

Mixing number (MIX) is used to measure the mixing effect in hot water storage tanks; it is given by the equation, N. Gopalakrishnan (2009),

$$MIX = \frac{M_{ideal} - M_{actual}}{M_{ideal} - M_{fully\ mixed}} \quad (5)$$

Where

$$M = \sum_{i=1}^{i=n} \rho_i V_i c_p T_i Y_i \quad (6)$$

ρ_i fluid density, V_i sub-volume, T_i sub-volume temperature, Y_i distance to the node n and n is the number of nodes in the HST.

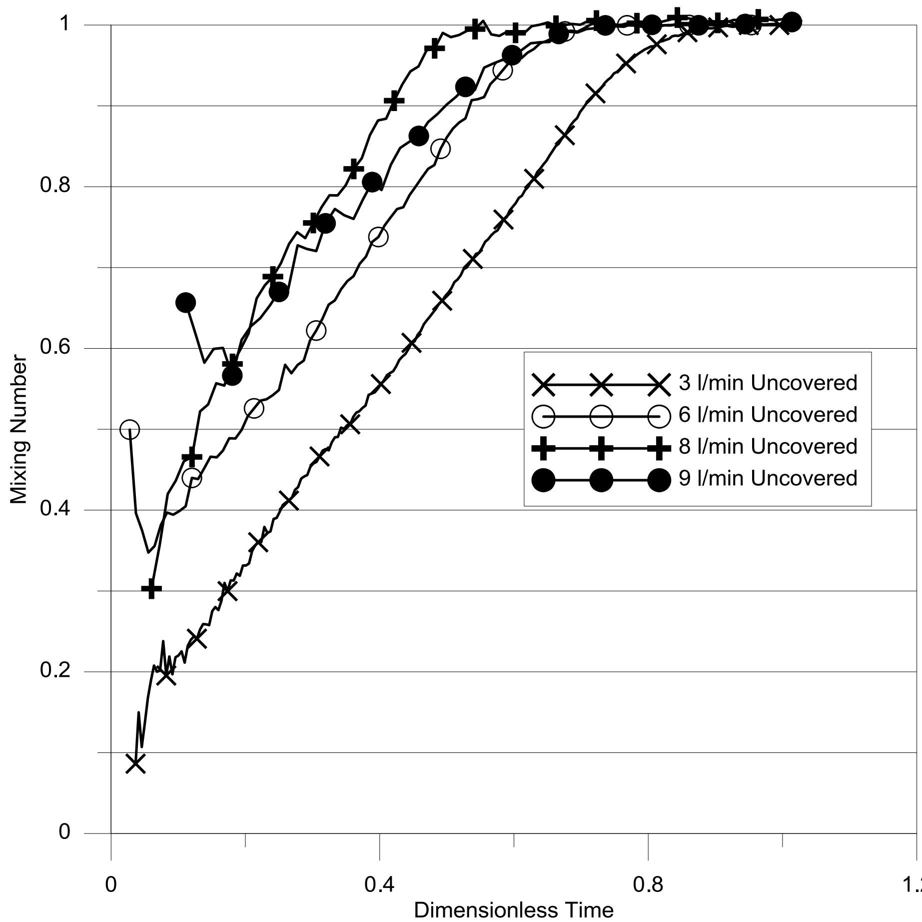

Figure 6 Mix number for Uncovered supply Modes (3, 6, 8 and 9 l/min flow rates).

Figure 6 shows the mixing number with dimensionless time for 3, 6, 8 and 9 l/min for uncovered supply mode. This figure includes three valuable notations the first notation is that the mixing number increases from zero to one as expected from the definition of the mixing number. The second notation is that mixing number is minimum for low flow rates and increases by increasing the supply flow rate. The third notation is observed from the fluctuation at the starting values of the mixing number, which are due to the recorded temperature values which are not ideal to have zero mixing number from the calculations unless interfered. In the actual values for a very small time period the M_{actual} may be greater than M_{ideal} here it gives a negative mixing number or nominator is greater than denominator, after few seconds the actual mixing number behavior appears clearly.

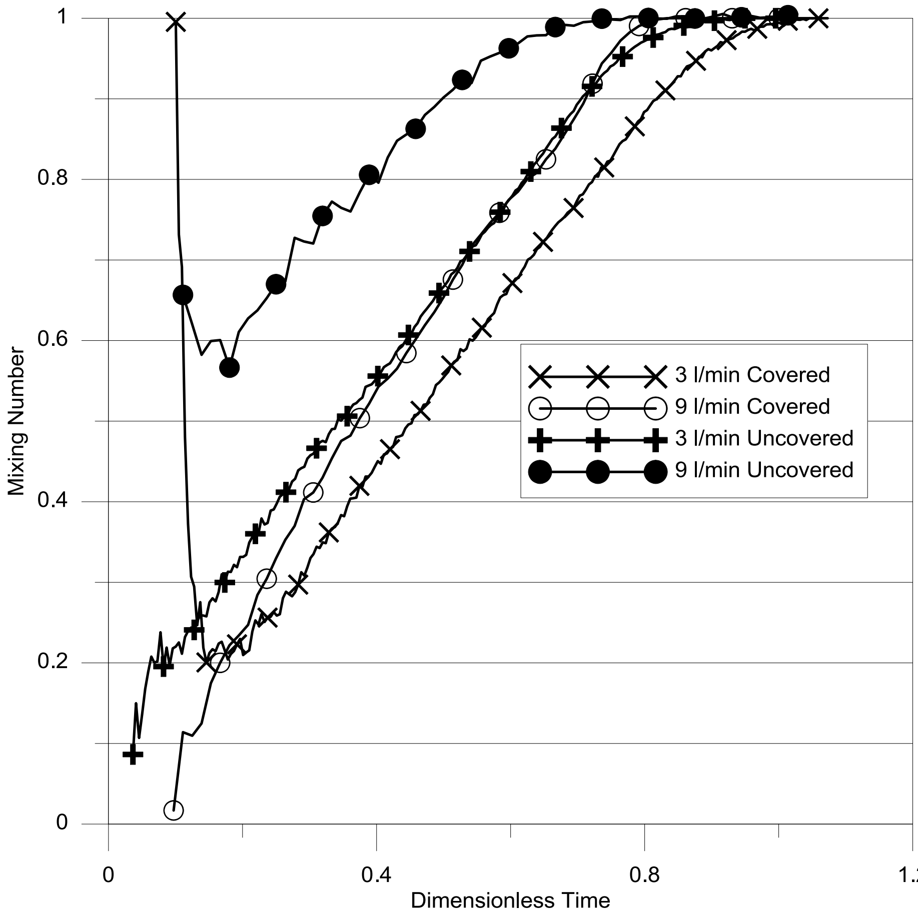

Figure 7 shows the effect of different flow rates 3 and 9 l/min for the covered supply mode and 3 and 9 l/min for the uncovered supply mode on the mixing number with time.

Figure 7 shows the effect of different flow rates 3 and 9 l/min for the covered supply mode and 3 and 9 l/min for the uncovered supply mode on the mixing number with time. The lowest mixing number is achieved at the covered low uncovered flow rate 3 l/min. this clearly emphasize the important effect of the used cover. The mixing number for high uncovered flow rate is obviously apart from the low covered values.

Discharging Energy Efficiency

The Discharge Energy Efficiency (η_d) which is defined as the ratio of the thermal energy delivered by the water leaving the HST ($Q_{out}(t)$) to the initial thermal energy in the HST ($Q_{in}(0)$).

$$\eta_d = \frac{Q_{out}(t)}{Q_{in}(0)} \tag{7}$$

The thermal energy delivered by the water leaving the HST ($Q_{out}(t)$) is calculated as;

$$Q_{out}(t) = \sum_{t=0}^{t} \rho \dot{V} c_p (T_{out}^{\cdot} - T_{in}) \tag{8}$$

Where ρ is the water density, $\dot{V}$ water volume flow rate, c_p water specific heat, T_{out} outlet temperature from the HST, T_{in} inlet temperature to the HST and t is the time.

The initial thermal energy in the HST ($Q_{in}(0)$) is calculated as

$$Q_{in}(0) = \sum_{n=1}^{n=N} \rho \dot{V} c_p (T_n^{\cdot} - T_{in}) \tag{9}$$

Where n is the node number and N is the last node number.

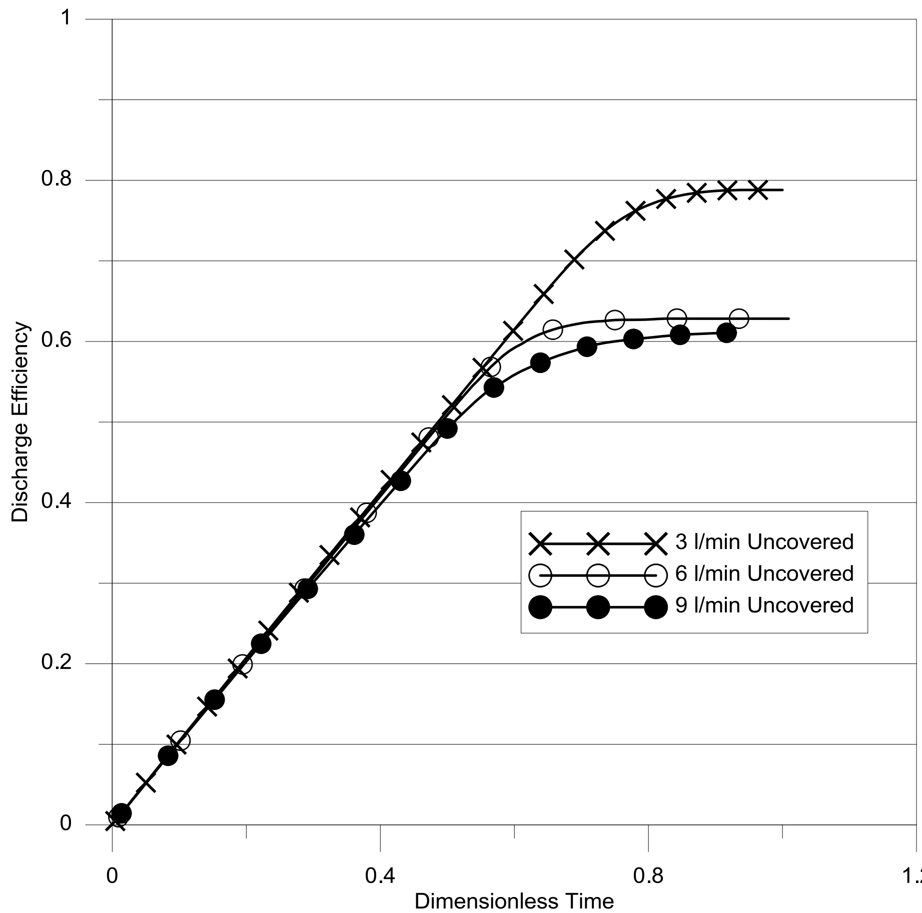

Figure 8 shows the Discharge Energy Efficiency η_dVersus Dimensionless time for (flow rates 3,6 and 9 l/min for the uncovered supply mode).

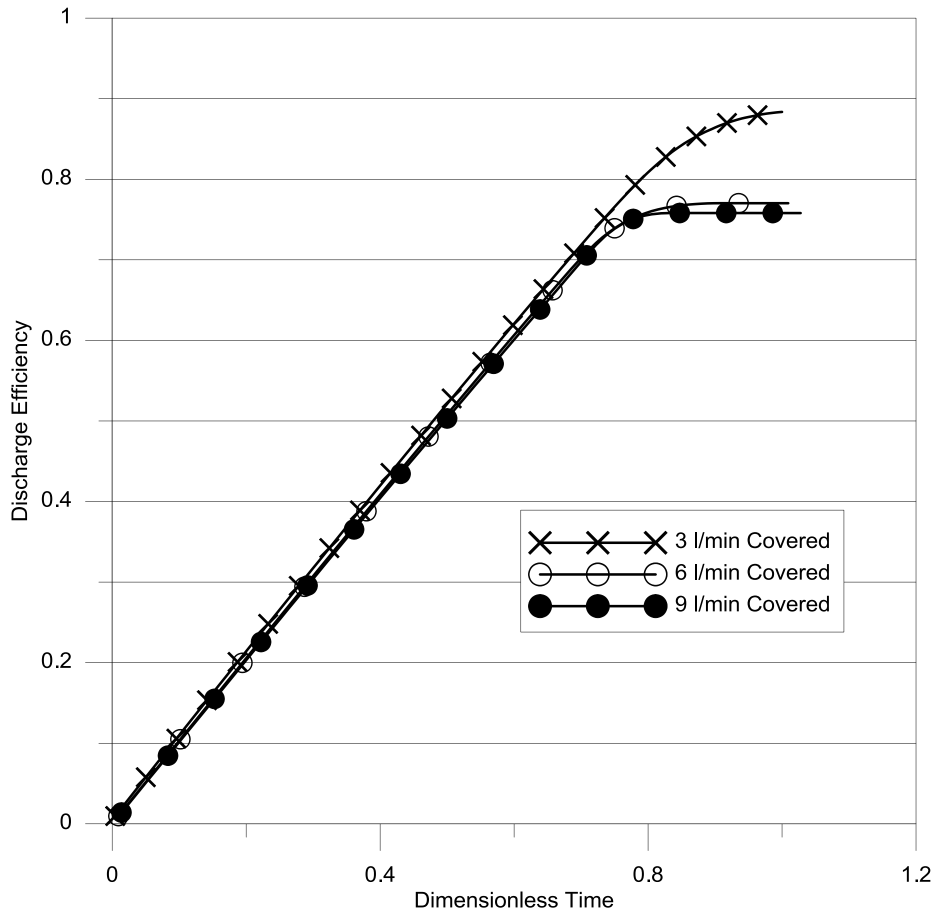

Figure 9 shows the Discharge Energy Efficiency η_dVersus Dimensionless time for (flow rates 3, 6 and 9 l/min for the covered supply mode).

Figure 8 and Figure 9 show the η_d Versus τ for flow rates 3, 6 and 9 l/min for the covered and uncovered supply modes. The covered flow mode achieved the maximum efficiency η_d= 88% for 3 l/min, and η_d=76% for 9 l/min, whereas the maximum uncovered discharge efficiency was η_d=78% for 3 l/min and η_d=62% for 9 l/min.

Exergy Efficiency

Exergy efficiency (η_{ex}) is defined as the ratio of the cumulative exergy in discharging process from the HST to initial exergy of charging process.

$$\eta_{ex} = \frac{Ex_{out}(t)}{Ex_{in}(0)} \tag{10}$$

The exergy delivered by the water leaving the HST ($Ex_{out}(t)$) is calculated as;

$$Ex_{out}(t) = \sum_{t=0}^{t} \rho \dot{V} c_p [(T_{out} - \dot{T_{in}}) - T_{in} \ln \frac{T_{out}}{T_{in}}] \tag{11}$$

Where ρ is the water density, $\dot{V}$ water volume flow rate, c_p water specific heat, T_{out} outlet temperature from the HST, T_{in} inlet temperature to the HST and t is the time.

The initial exergy in the HST ($Ex_{in}(0)$) is calculated as

$$Ex_{in}(0) = \sum_{n=1}^{n=N} \rho \dot{V} c_p [(T_n - \dot{T_{in}}) - T_{in} \ln \frac{T_n}{T_{in}}] \quad (12)$$

Where n is the node number and N is the last node number.

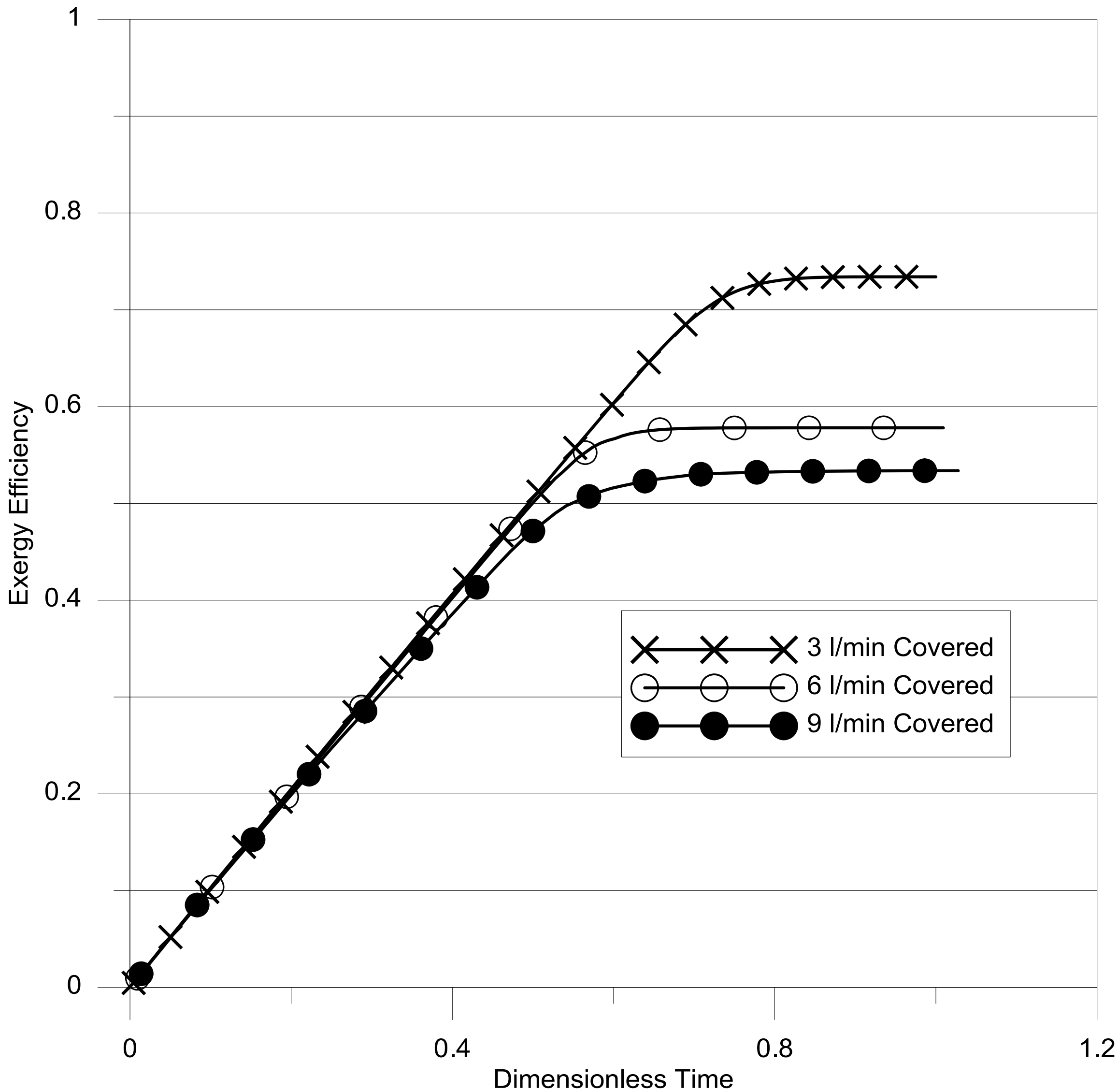

Figure 10 shows Exergy Efficiency Versus Dimensionless time for (flow rates 3, 6 and 9 l/min for the covered supply mode).

The behavior of the exergy efficiency is as expected in line with the Discharge Energy Efficiency as both are performance quantifying parameters in the HST.

Conclusion

In this study the uncovered and covered bottom supply modes in HST were studied for 3, 6, 8 and 9 l/min flow rates. The thermocline thickness, mixing number, discharge efficiency and exergy efficiency were selected to compare the performance of the HST under the different supply modes and supply flow rates. It has been found that the covered mode of the HST has a smaller thermocline thickness compared to the uncovered supply mode. The mixing number is much better for the covered mode even at high flow rates. 88% discharge efficiency was achieved in the covered mode compared to a maximum 78% for uncovered supply mode. The exergy efficiency was in line with the discharge efficiency behavior. All the quantifying parameters favor the covered supply mode on the uncovered supply mode. More analyses could be done for the HST in combination with the solar collector which is expected to have more advantages specially due to the higher collector efficiency at lower supply temperatures which is achieved in the covered mode HST system.

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