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Final Report Part II

EFFECTS OF PLUMBING ATTACHMENTS ON HEAT LOSSES FROM SOLAR DOMESTIC HOT WATER STORAGE TANKS

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PREFACE

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SUMMARY

Thermal storage tanks are widely applied in most solar domestic water heating systems sold in the United States. Study of heat loss mechanism of the storage tanks is necessary to develop more accurate tank heat loss models for solar domestic water heater system. Such models will enhance the accuracy of system ratings published by the Solar Rating and Certification Corporation and lead towards improved system efficiency via better design. Previous heat loss studies have consistently shown that the actual losses are about twice the predicted values using

$$Q=U \cdot A \cdot \Delta T.$$

Heat losses from a storage tank and its plumbing fittings involve three different operating modes: charging, discharging and standby. In the charging mode, the tank receives energy from the solar collector. Typically, the water flows between solar collector and storage tank by means of pumping or thermosyphon. In the discharge mode, water flows from the storage tank through the distribution pipes to the faucets and cold city water enters the tank. In the standby mode, there is no forced water flow into or out of the tank. The motion which takes place within the storage tanks used in solar domestic water heating systems generally combines the effect of forced and natural convection. When the storage tank is under no flow condition, nature convection is the main factor governing the heat transfer, (1) from the hot layer to cold layer in the tank, (2) between the water and inner tank wall, (3) between the ambient and tank surface. In this experimental study, only the standby mode was considered.

The experiments were considered two system configurations: the reference tank heat loss with no plumbing attachment, as well as the tank with typical shaped plumbing. Efforts are made to understand the facts that affect the overall heat loss of the system. About 200 tank heat loss measurements were completed for seven different pipe arrangements under several test conditions.

The salient results were:

- During the standby mode, the water body inside the storage tank whose temperature was initially uniform become stratified by heat losses from the water to tank wall and tank wall to ambient, as well as the result from heat and mass transfer within the water body itself. The stratification and the decay are linear with vertical height and time, respectively.
- For the 50-gallon storage tank, there is a distinct transient region at the bottom where the heat transfer is relatively active. For the 2-gallon storage tank, the heat transfer between the water and the side-walls dominates the overall heat loss of the system.
- The average surface temperature for water filled in both tank and pipe fittings is higher than that for water filled in the tank only, that is, the heat transferred to the pipe fittings and dissipated to ambient is significantly increased when the pipe is filled with water.
- The heat losses from the plumbing fittings attached to the thermal storage tank are relatively small compared to the heat loss from the tank itself. This result was unexpected.

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INTRODUCTION

BACKGROUND

The Solar Rating and Certification Corporation (SRCC) has established a standardized methodology for determining the performance rating of the Solar Domestic Hot Water (SDHW) systems it certifies under OG-300 [1]. Measured performance data for the solar collector component(s) of the system are used along with numerical models for the balance of the system to calculate the system's thermal performance under a standard set of rating conditions. SRCC uses *TRNSYS* to model each of the components that comprise the system. [2] Obviously the uncertainty of the SDHW system performance predictions is directly related to the accuracy of the *TRNSYS* models.

The majority of the SRCC certified systems include a thermal storage tank with an auxiliary electrical heater. The most common being a conventional fifty gallon electric tank water heater. Presently, the thermal losses from these tanks are calculated using $Q = U \cdot A \cdot \Delta T$.

Unfortunately, previous heat loss studies have shown the actual losses are about twice the predicted values. [3,4] This is because this generalized formula does not adequately address temperature stratification both within the tank as well as in the ambient air surrounding the tank, non-uniform insulation jacket, thermal siphoning in the fluid lines attached to the tank, and plumbing fittings attached to the tank.

At this point in time, the basic heat loss model for thermal storage tanks is not under question. Its uncertainty is in the input conditions and parameters that are applicable to a particular design and operating condition. This study is intended to address only that part of the problem that deals with the plumbing fittings attached to the tank.

Heat losses from a storage tank and its plumbing fittings involve three different operating modes: charging, discharging and standby. In the charging mode, the tank receives energy from the solar collector. Typically, the water flows between solar collector and storage tank by means of pumping or thermosyphon. In the discharge mode, water flows from the storage tank through the distribution pipes to the faucets and cold city water enters the tank. In the standby mode, there is no forced water flow into or out of the tank. The motion which takes place within the storage tanks used in solar domestic water heating systems generally combines the effect of forced and natural convection. When the storage tank is under no flow condition, nature convection is the main factor governing the heat transfer, (1) from the hot layer to cold layer in the tank, (2) between the water and inner tank wall, (3) between the ambient and tank surface. In this experimental study, only the standby mode was considered

PROJECT OBJECTIVES

The specific objective of this study is to determine the effect that plumbing attachments have on the overall heat loss coefficient for thermal storage tanks used in SDHW systems. To accomplish this objective, an experimental study will be designed and completed to conduct heat loss tests for a variety of plumbing arrangements found in solar domestic water heaters.

All the testing procedures for the heat loss from inlet/outlet fittings will be the same as that for the heat loss from tank itself except that some fittings have been added to the tank. Obviously there are an infinite number of different piping/insulation configurations. An attempt was made to select those that represent the range of fittings found in the market place.

Heat loss tests will be completed for the following configurations:

- tank set up pursuant to DOE test procedures for residential tank water heaters
- heat trap fittings using those supplied by tank manufacturer
- U-tube heat traps
- vertical inlet/outlet pipes
- horizontal inlet/outlet pipes
- piping with and without valves

Three insulation configurations will be used:

- minimum requirements in OG300
- with extra insulation (adiabatic)
- without insulation

For evaluation of the thermosyphon effects, some tests will be run with the water only in the tank and leave the fittings empty. Other tests will have all of the inlet/outlet pipes filled with water.

LITERATURE REVIEW

The motion that takes place within storage tanks used in solar water heating systems generally results from the effects of forced and natural convection. Presently, studies by other researchers, which show that thermally stratified storage can improve the performance of the solar systems significantly compared to that of thermally mixed storage, are considerably concentrated on the charging and discharging modes, or the static decay of stratification.

The stratification could be influenced by: (1) forced convective flow through the storage tank, (2) thermal mixing at the inlet and outlet, (3) natural convective flow near the inner tank wall induced by heat loss to the ambient air, (4) natural convective flow generated by heat transfer from hot layer to cold layer via highly conductive tank wall, and (5) heat diffusion due to temperature gradient. When the storage tank is under no flow condition, only the last three mechanisms control the stratification.

Jaluria and Gupta [5] examined the decay of thermal stratification with time in the absence of external convection flow that might cause mixing in the storage tank. In their experiments, an initially isothermal water body is thermally stratified by means of thermal discharges into it and also statically by adding hot water at the top of cold fluid contained in a tank. The decay of the stratification with time due to heat transfer to the environment and within the water body is studied for various initial and heat loss conditions. They studied the temperature distributions in the tank, the decay of the surface temperature and the dependence of the decay on the initial temperature and the dependence of the decay on the initial temperature distribution and on the energy loss. They found the temperature distribution is largely one-dimensional, with variation in the vertical direction.

Viskanta and Hale [6] examined the thermal energy storage (TES) system after charging and discharging. They found that natural separation typically exists in the liquid due to the stable thermocline that is established and the degradation of the thermocline due to heat conduction between the hot and cold fluids is small because the thermal conductivity is low. Buoyancy forces produced by temperature differences as a result of heat loss from the side-walls and by heat conduction along the container walls generates free circulation which degrades the thermocline. A transient two-dimensional model was developed to predict thermal and fluid kinetics in a rectangular cavity simulating a stratified sensible TES tank that is cooled from the side-walls and/or the top.

Hess and Miller [7] studied the effect of thermally conducting side walls of a tank on the rate of heat transfer in the enclosed stratified fluid. His research revealed that, if the conductivity of the fluid is low, the degradation of the thermocline due to the heat transfer between the hot and cold fluids is low; if the fluid is stored in a container made from a material of a thermal conductivity vastly different from the fluid, convection currents will be generated at the fluid-wall interface inside the container, causing degradation of the thermocline at a faster rate than anticipated. The flow field of the fluid was found to fill the entire tank and was not confined to the vicinity.

However, no investigations on the effects of the plumbing attachments on the overall heat loss coefficient of the thermal storage system were found.

DESCRIPTION OF EXPERIMENTAL APPARATUS

SDHW AUXILIARY 50-GALLON REFERENCE TANK WATER HEATER

An electric water heater, Richmond Miser 8V52-2B was used as the reference storage tank water heater for this study. This model, described in Table 1, is actually the same as the "SRCC Supplemental Tank Rheem 81-V-52D". It represents the typical auxiliary backup tank water heater used in the majority of SDHW systems[9]. The size of the 50-gallon tank is shown in Figure 1.

Table 1. Tank specifications for *Richmond Miser* include:

Rated Storage Volume	50 gallons
Foam Insulation R Value(manufacturer)	R11.5
Jacket Height	57.1 inches
Jacket Diameter	19 inches
Tank Outside Height	55 inches
Tank Outside Diameter	16 inches
Two Electrical Heating Elements	4.5 kW/each
Openings on the Top	four ¾" NPT
Other Opening(s)	one ¾" at the bottom

Figure 1. Dimension size of the 50-gallon tank

TWO-GALLON REFERENCE TANK FOR HEAT LOSS TESTS

A smaller electric water heater with a two-gallon capacity was used to obtain a larger differential between the tank heat losses and losses through the different piping and fitting configurations. The time cycle for each experiment on the 50-gallon tank is generally 4 or 5 days. Using a relatively small tank, will enable the heat losses contributed to the plumbing attachments to be of the same order of magnitude as the losses from the tank itself as well as reduce the testing cycle time to 1-2 days. A two gallon *Reliance* 121SUS4-FK electric tank water heater was selected as the test tank for all of the heat loss tests with plumbing fittings. Its specifications are given in Table 2.

Table 2. Tank specifications for *Reliance* two-gallon test tank.

Rated Storage Volume	2 gallons
Foam Insulation R Value(manufacturer)	R11.5
Jacket Height	12 inches
Jacket Diameter	10 inches
Tank Outside Height	9.2 " inches
Tank Outside Diameter	8 inches
One Electrical Heating Elements	1.44 kW
Openings on the Top	one ¾" NPT, two ½" NPT
Other Opening(s)	one ¾" NPT on side wall (4" above the jacket bottom)

INSTRUMENTATION

Thermocouples

Copper/Constantan thermocouples (Type T) were used to measure the water temperatures within the tank and the ambient air temperature, as well as the surface temperature of the plumbing attachments. Comparing to other commonly used thermocouples, such as Iron/Constantan (Type J) or Chromel/Alumel (Type K); type T thermocouple has the highest accuracy as illustrated in Table 3.

Table 3. Specifications of commonly used thermocouples

Types	T	J	K
Alloy Combination	Cu/Cu-Ni	Fe/Cu-Ni	Ni-Cr/Ni-Al
Maximum Temperature Range	-200 – 350 °C -328 – 662 °F	0 – 750 °C 32 – 1382 °F	-200 – 1250 °C -328 – 2282 °F
Limits of Error (above 0 °C)	1.0 °C or 0.75%	2.2 °C or 0.75%	2.2 °C or 0.75%
Special Limits of Error	1.1 °C or 0.4%	1.1 °C or 0.4%	1.1 °C or 0.4%

Data Acquisition System

A Fluke 2635A Hydra Data Bucket (FHDB) was used for the data acquisition system.

The FHDB is a 21-analog input channel data logging instrument that can measure and record the following electrical and physical parameters: DC volts, AC volts, resistance, frequency and temperature. When the FHDB scans channels configured for measurement, readings can be displayed, printed out and recorded. The inputs for channels 1 through 20 are via a Universal Input Module (UIM), which plugs into the rear of the unit for a quick connect/disconnect capability. The basic specifications of model 2635A are listed in Table 4.

Table 4. Fluke Hydra Data Bucket Data Acquisition System Specifications

Measurement	
Thermocouples	9 Types
DC Voltage Ranges	100 MV – 150V, 300V
AC Voltage Ranges	300 MV – 150V, 300V
Max DC Resolution	1 μ V
DC Current	4 – 20 mA
Status(Contacts)	Yes
Counter	To 1 MHz
Event Totalize	Yes
Features	
Analog Input Channels (max.)	21
Basic Accuracy (V DC)	0.01%
Speed Channels/second	4/17
Instrument Set-up & Operation	Front Panel or Computer I/F
RS-232C/IEEE-488/Ethernet	Std/NA/NA
12V DC Operation	Yes
Permanent Data Storage	PC card
Battery Back-up	Program, Clock, Data

At the beginning of this project, a Keithley Metrabyte's DAS-8 and an EXP-16 data acquisition board was used to record the data. This DAS was abandoned in favor of the FHDB.

EXPERIMENTAL PROCEDURE

Heat losses from a thermal storage tank and its plumbing attachments involve three different fluid flow modes: charging, discharging and standby. In the charging mode, solar energy heats the water in the tank primarily by pumped flow or by thermosyphon flow. In the discharging mode, water flows through the tank and distribution pipes to the faucets and cold city water enters the tank. In the standby mode, there is no forced water flow go into or out of the tank.

The motion which takes place within storage tanks used in solar domestic water heating systems generally combines the effect of forced and natural convection. When the storage tank is under no flow condition, nature convection is the main factor governing the heat transfer, (1) from the hot

layer to cold layer in the tank, (2) between the water and inner tank wall, (3) between the ambient and tank surface.

The experiments were focused on two system configurations: the reference tank heat loss with no plumbing attachment, as well as the tank with typical plumbing attachments.

50-Gallon Tank Heat Loss Experiments

The insulation foam is filled between the outer cover and inner storage tank. The average thermal conductivity of insulation foam is 0.018 Btu-in./ft. $^{\circ}$ F. The water tank has been equipped with a circulation loop and thermocouple tree as illustrated as Figure 2.

Three thermocouple trees are positioned inside the tank. One is set in the center; the other two are set with equal distances to the center. Thermocouples are positioned on a 1.0 mm diameter steel bar. PVC caps and clear sealant silicone are applied to seal the openings on the top of the tank. Figure 2 shows the detailed locations of the thermocouples and a schematic of the experimental system.

Figure 2. Schematic of test apparatus and thermocouple locations.

Referring to Figure 2, the detailed test procedure for the 50-gallon tank is as follows:

1. Install a temporary PVC joint on the top of the tank, hook up the expansion tank and the hose to the tank.
2. Open valve V1, V2 (drainage valve), V4 and V5, close V3. City water goes into the tank via V1, V2, the air inside the tank is exhausted via V4, V5.
3. When water overflows V5 and is about half of the volume of the expansion tank, close V1, open V3.
4. Turn on the circulation pump and the electrical power of the heating elements.
5. Turn off the heating power when the water temperature reaches the preset point. Keep the pump working for a little longer until all of the temperature readings are uniform and stable with time.
6. Close V1, V2 and V3, wait for the air bubbles to float up to the expansion tank, then close V4 and V5.
7. Disconnect the hose and the PVC joint, use a PVC cap for that opening to avoid unnecessary heat loss.
8. Periodically record the temperatures of the water within the tank and the ambient air outside of the tank.

Two-Gallon Tank Heat Loss Experiments

One thermocouple tree with three temperature sampling points was placed inside the tank as shown in Figure 3. For the cool-down testing method, the initial uniform water temperature in the system is very important especially to the relative smaller tank because the initial system energy calculation is dependent on the mean temperature. A good initial uniform temperature means a more accurate calculated mean temperature. Like the system for 50-gallon, an expansion tank and circulation pump are used. The system is configured as illustrated in Figure 4.

Figure 3. Dimensions of 2-gallon tank and thermocouple locations

Figure 4. Schematic of experimental setup for reference test

The detailed test procedure for 2-gallon tank is as follows:

1. Install a temporary PVC joint on the top of the tank, hook up the expansion tank and hose to the tank.
2. Open valve V1 (drainage valve), V2 and V3, charge the system until city water is observed in the expansion tank.
3. Stop the water when the water comes out from the side opening of the expansion tank.
4. Turn on the circulation pump and the electrical power of the heating elements.
5. Turn off the heating power when the water temperature reaches the preset point. Keep the pump working for a little longer until all of the temperature readings are uniform and stable with time.
6. Stop the pump, wait for the air bubbles to float up to the expansion tank, then close V2 and V3.
7. Disconnect the hose and the PVC joint on top of the tank, use a PVC cap to block the opening so that the unnecessary heat loss is avoided.
8. Periodically record the temperatures of the water within the tank and the ambient air outside of the tank.

In order to increase the accuracy of the temperature measurements, the heat shrink tubing and clear sealant silicone were used to keep the thermocouples from contacting the water, so that the possible electric-chemical reaction with hot water at the alloy junction could be avoided.

Since the UA value based on these tests will serve as a base line reference for calculating the heat loss coefficient of attached pipe and fittings, it is important that the water level in the tank be maintained at the correct position to ensure that the total amount of the water in the tank is constant for all tests.

Heat Loss Experiments with Varied Plumbing Attachments

Several typical plumbing configurations have been tested. To evaluate the thermosyphon effects inside the tank, some tests were run with the water only in the tank and leave the plumbing empty. Other tests were conducted with the plumbing fittings filled with water. Table 5 lists the typical plumbing attachments that were tested.

Table 5. Typical plumbing configurations that were evaluated

Plumbing Types	Water Filled in Tank Only		Water Filled in both Tank and Pipe	
	Pipe not insulated	Pipe insulated	Pipe not insulated	Pipe insulated
18" straight pipe	X	X	X	X
24" straight pipe	X	X	X	X
Two U-turns with straight pipes	X	X	X	X
Two straight pipes connected by 90° elbow	X	X	X	X
Long horizontal pipe connected with short pipe by 90° elbow	X	X	X	X
Long vertical pipe connected with short pipe by 90° elbow	X	X	X	X
Two short pipes connected by 90° elbow	X	X	X	X

Type L hard copper tube with $\frac{3}{4}$ inch diameter was used for all the tests. The T type thermocouples were soldered on the outside surface of the pipe. The insulation material was Elastomeric Insul-tube with black color. The model number is TC $\frac{7}{8}$ in. IDX $\frac{1}{2}$ in. NOM WALL 25/50. The wall thickness is 12.7mm ($\frac{1}{2}$ in.) The inside diameter is 22.2 mm ($\frac{7}{8}$ in.). The R value is approximately $0.49 \text{ m}^2\text{C/W}$ ($2.8 \text{ ft}^2\text{F/Btu/hr}$).

For the condition of water filled in tank only and with plumbing empty, special attention was required to ensure that the water level remained the same from one test to another. The water level should not be lower than the intersection between the tank top wall and the fittings base. Due to a large cross section area in the tank compared to the pipe cross section, a small air gap in the tank could cause a significant error on the total water volume in the system. This could cause an unacceptable error on the total energy calculation in the system. Also, the temperature at the pipe base or the top wall of the tank may not be the same temperature of the water in the tank.

For the condition of water filled in both tank and the plumbing fittings, it was important to make sure there is no air bubble inside the system, not only in the tank, but also in the pipes. This is because the air bubble will act as an uncertain factor to the heat and mass transfer inside the system. As the result, the measured temperature and the resulting computations will not be correct.

The entire experimental apparatus is situated in a closed laboratory where the temperature and the relative humidity is automatically controlled by the central air conditioning system. During the test, the area around the tank is kept clear so that the nature convection between the ambient and the outside wall of the tank will not be disturbed. Care was taken to ensure that no residual water remained on any exterior surfaces of the plumbing attachments.

The following test procedure is applied for the plumbing configuration shown Figure 5.

1. Open V1(drainage valve), V2(PVC valve), V3 and V4, connect the side openings of the tanks by transparent hose. Charge the city water from the bottom opening of the expansion tank.
2. Close V1 when the water level reaches V1. Stop the water and close V3 when the amount of the water in the expansion tank is $\frac{1}{2}$ of the volume capacity.
3. Disconnect the city water, connect the V2 and V3 with transparent hose. Open all the valves, turn on the pump and power of the heating element.
4. Turn off the heating power when the water temperature reaches the preset point. Keep the pump working for 2-3 minutes to make the temperature uniform. Then stop the circulation pump.
5. For the tests when water is filled in tank only:
 - close V2 and V3, disconnect the hose between V2 and V3. Disconnect the hose from V4.
 - Open V2, hold the hose which is connected to the pump vertically, check the water level in the clear hose. It should be the same as the preset mark on the outside wall of the tank. If not, adjust the hose to get the water at proper level.
 - Close V1. Use a metal rod and a piece of cloth to eliminate any extra water stored in the upper U-turn.
 - Close V1 and V2, disconnect the pump and hose connected to V1, start the Data Bucket and record data every five minutes.
6. For the test when water is filled in both the tank and pipes:
 - Vibrate the tank and the hose between V2 and V3 gently until there is no air bubble in the clear hose.
 - Close V2 and V3 first, then close V1 and V4. Disconnect the expansion tank and the hoses. Start the Data Bucket and record data every five minutes.

The experimental procedure for the other plumbing attachments shown in Figures 6-10 is similar.

Figure 5. Two U-turns with straight pipes

Data Collection Methodology

For each experiment, to minimize the uncertainty of the data, the water is heated up to the 5°C above the intended temperature collecting point. The Data Bucket scans and records the temperature for each channel every 5 minutes. Five of the 21 channels are used to measure ambient temperature.

The reference heat loss tests with no plumbing attachments are conducted under two temperature conditions: 80°C – 40°C and 50°C – 40°C . The tests for the tank with plumbing attachments are conducted under one temperature condition: 50°C – 40°C .

Figure 6. Straight pipes

Figure 7. Long horizontal pipe connected with short pipes by 90° bent

Figure 8. Two straight Pipes with 90° bent

Figure 9. Two short Pipes with 90° bent

Figure 10. Long vertical pipe connected with short pipe by 90° bent

EXPERIMENTAL RESULTS

REFERENCE TESTS

50-Gallon Tank

As the tank is well insulated, the time cycle for the reference heat loss test on the 50-gallon tank is normally two days when it is initially at a uniform temperature and it is allowed to cool down by 15°C from 55°C with an average ambient temperature of 24°C .

Figure 11 shows the vertical temperature distribution for one of the reference tests which takes 45 hours to get the average tank temperature cooled down from 57.42°C to 40.28°C at the bottom of the tank. The thermocouple sampling positions are shown on the x-axis. The mean temperatures at different sampling planes (7.5 inches, 17.5 inches, 27.5 inches, 37.5 inches and 47.5 inches) are shown on y-axis. The temperature distribution is found to be essentially uniform at time $t = 0$. This is accomplished at the beginning of the test by employing the circulation pump. The distribution curves are steeper at the bottom of the tank between 7.5 inches to 17.5 inches. From 17.5 inches to the top of the tank, the distribution lines become straight lines parallel to the x-axis, which suggest the temperature inside the tank is stratified and decays linearly.

Figure 11. Mean temperature profiles as the function of tank height during the decay of stratification (Data set 50gal_ref_1.xls)

Figure 12 shows the profiles of temperature vs. time for each sampling point. It is noticed that the temperature decay is at same rate for the positions at thermocouple No.4 to No.15, which is from 17.5 inches to the top of the tank in vertical direction. It suggests there is no heat transfer in the radial direction. For the profiles of thermocouple No.1-No.3, the steeper slopes indicate the heat transfer is more active at the bottom of tank. Since there is a slight difference of the thermocouple position along the vertical direction, which is restricted by the experimental accuracy, there is a slight difference

among the profiles. It suggests that there is a transient region at the bottom of the tank while the vertical heat transfer rates are the same in the upper tank

Figure 12. Temperature profiles as the function of time at each sampling point (Data set 50gal_ref_1.xls)

2-Gallon Tank

Reference test on 2-gallon tank is conducted under two selected temperature ranges (for UA calculation), 80°C – 40°C and 50°C – 40°C , to study the influence of the initial temperature on the heat loss coefficient UA.

Figure 13. Temperature profiles as the function of tank height during the decay of stratification (Data set 2gal_ref_4.xls, higher temperature range)

Figure 13 shows the vertical temperature distribution for the reference tests at the large temperature range. The tank is initially heated up to 85.74°C. It takes 35 hours and 30 minutes to get the tank cooled down to 38.31°C at the average ambient temperature of 25.14°C. Figure 14 shows the similar profiles with the temperature between 54.91°C to 36.98°C at the ambient temperature of 22.80°C

It is observed that the profiles are parallel to each other in both figures respectively. However, the profiles in Figure 14 have more curvature compared to Figure 13. A comparison between Figures 13 and 14 suggests that the transient region in the smaller tank is insignificant even with a high average initial tank temperature.

Figure 14. Temperature profiles as the function of tank height during the decay of stratification (Data set 2gal_ref_1.xls, lower temperature range)

Figure 15. Temperature profiles as the function of time at each sampling point (Data set 2gal_ref_4.xls, higher temperature range)

Unlike Figure 12, the profiles of temperature vs. time in Figures 15 and 16 for the 2-gallon tank have similar slope. The parallel profiles suggest the rate of heat transfer is nearly the same everywhere inside the small tank.

Figure 16. Temperature profiles as the function of time at each sampling point (Data set 2gal_ref_1.xls, lower temperature range)

Heat Loss Test with Plumbing Attachments

Figures 17 and 18 show the heat trap surface temperatures at different positions as a function of time. The average surface temperature for water filled in both tank and pipe fittings (Figure 17) is much higher than that for water filled in the tank only, that is, the heat transferred to the pipe fittings and dissipated to ambient is significantly increased when the pipe is filled with water.

Figure 17. Two U-turns, water filled in both tank and pipe, with tank Insulated only (Data set MTU_04.xls)

Figure 18. Two U-turns, water filled only in tank, with tank Insulated only (Data set MTU_06.xls)

Temperatures in Figures 17 and 18 show different patterns. For water filled in pipe fittings (Figure 17), the temperature drop from the tank (location 0 mm) from the top of first U-turn (location 325 mm) is not so pronounced as that in empty pipe fittings (Figure 18). This can be explained by the phenomenon that the negative temperature gradient (cold on top and hot on bottom) in this portion enhances the natural convection inside the pipe. While the temperature drop from the top of first U-turn to the bottom of the second U-turn is more similar in these two figures. This also can be explained by the phenomenon that the positive temperature gradient (hot on top and cold on bottom) in this portion reduces the natural convection and the heat transfer is dominated by conduction in both situations.

Figure 19. Two U-turns, water filled only in tank, with both tank and pipe insulated (Data set 11.xls)

The temperature distribution in Figure 18 indicates the heat transfer is dominated by pipe wall conduction, so the distance to the tank plays a strong role.

Figure 19 shows the temperature changes on pipe surface at different locations with insulated heat trap with water only filled in tank. The average ambient temperature is 23.71°C, the average relative humidity throughout the test was 25.4%. Figure 20 shows the temperature differences between pipe wall temperature and ambient temperature at different times with the same conditions as those of Figure 19.

Figure 20. Two U-turns, water filled only in tank, with both tank and pipe insulated (Data set 11.xls)

Figure 21. Two U-turns, water filled in pipe, with both tank and pipe insulated (Data set 8.xls)

The smooth temperature distributions in Figures 19 and 20 indicate the heat transfer rate in the cross-section of the heat trap decreases as pipe length increases. The heat dissipation rate decreases progressively along the pipe and appears to be independent of the pipe shape.

Figure 21 shows the temperature changes on pipe surface at different locations with insulated heat trap and with water filled in both tank and pipe, the average ambient temperature is 23.64°C, and the relative humidity is 24.3%.

Figure 22 shows the temperature differences between pipe wall temperature and ambient temperature for the same test conditions as those of Figure 21.

Figure 22. Two U-turns, water filled in pipe, with both tank and pipe insulated
(Data set 8.xls)

The temperature distributions in Figures 21 and 22 compared to those in Figures 19 and 20 suggest that the water in the pipes has a significant effect on the heat losses from the tank even when the pipes are insulated.

Compared to the Figures 17 and 18, the temperature reduction per unit time of the pipe without the insulation is significantly greater than that with the insulation as would be expected.

HEAT LOSS CALCULATION AND ANALYSIS

As stated earlier, heat losses from the storage tank and its plumbing fittings involve three different modes: charging, discharging and standby. For this experimental study, only the heat losses during the standby mode were considered.

The UA value of the tank will be measured without any plumbing fittings attached to its outlet ports. The tests will be conducted in such a way to ensure that there is no air gap inside the top of the tank. It is obvious that an air gap could cause a considerable error on the heat loss measurement. Therefore the proposed testing will be conducted with two well insulated valves attached to the tank openings. The UA value will serve as a base line reference to calculate the heat loss coefficient of attached pipe and fittings.

Reference Heat Loss Calculations From The Tank

The heat loss for the tank during i th interval can be computed as:

$$Q_i = M \cdot C_p \cdot (\bar{T}_i - \bar{T}_{i-1}) \quad (1)$$

Where

$\bar{T}_i$: Mean tank temperature at the instant time of i th record. ($^{\circ}\text{C}$)

$\bar{T}_{i-1}$: Mean tank temperature at the instant time of $i-1$ th record. ($^{\circ}\text{C}$)

M : Mass of the water in the tank. (kg)

C_p : Specific heat of water at the average temperature $\frac{(\bar{T}_i + \bar{T}_{i-1})}{2}$ ($\text{kJ/kg} \cdot ^{\circ}\text{C}$)

Q_i : Heat loss from the tank during the i th interval. (kJ)

Assuming a mean heat transfer coefficient, the heat loss from tank surface during i th interval:

$$Q_i = (\overline{UA})_i \cdot (1/n) \sum_{i=1}^n (\bar{T}_{\text{tan } ki} - \bar{T}_{\text{ambi}}) \cdot \tau \quad (2)$$

Where

$(\overline{UA})_i$: Mean heat loss coefficient during the i th interval. ($\text{W}/^{\circ}\text{C}$)

$\bar{T}_{\text{tan } ki}$: Mean temperature in the tank during the period between the initial time to the instant of i th record. ($^{\circ}\text{C}$)

$\bar{T}_{\text{ambi}}$: Mean ambient temperature during the period between the initial time to the instant of i th record. ($^{\circ}\text{C}$)

τ : The time interval of each record. $\tau = 300$ Sec.

The mean heat loss coefficient $(\overline{UA})_i$ in i th interval can be computed as:

$$(\overline{UA})_i = \frac{M C_p (\bar{T}_i - \bar{T}_{i-1})}{(1/n) \sum_{i=1}^n (\bar{T}_{\text{tan } ki} - \bar{T}_{\text{ambi}}) \cdot \tau} \quad (3)$$

Thus, the overall mean heat loss coefficient during the test period UA is:

$$UA = \frac{1}{n} \sum_{i=1}^n \overline{UA}_i \quad (4)$$

where

n: Total time intervals during the selected temperature range .

The heat loss from the surface of the tank is :

$$Q_{\tan kloss} = UA \cdot \overline{\Delta T} \cdot n \cdot \tau \quad (5)$$

Where:

$\overline{\Delta T}$: Average temperature difference between the mean tank water temperature and the mean ambient temperature in the interval from selected temperature range

$$\overline{\Delta T} = \frac{1}{n} \sum_{i=1}^n (\overline{T}_{\tan ki} - \overline{T}_{ambi})$$

Heat Loss Calculations for The Tank With Plumbing Attachments

$$Q_{totalloss} = M_{sys} \cdot C_p \cdot (\overline{T}_w - \overline{T}_m)$$

$\overline{T}_w$: Weighted mean tank and piping temperature difference during the test period. (°C)

$$\overline{T}_w = \frac{1}{n} \sum_{i=1}^n \frac{T_{\tan ki} \cdot M_{\tan k} - T_{pipei} \cdot M_{pipe}}{M_{sys}}$$

$\overline{T}_m$: Average water temperature of chosen period.

M_{sys} : Mass of the water in the tank with plumbing attachments. (kg)

C_p : Specific heat of water at the average temperature $\frac{(\overline{T}_w + \overline{T}_m)}{2}$. (kJ/kg.°C)

Thus, the heat loss from the piping during selected period can be calculated as:

$$Q_{pipeloss} = Q_{totalloss} - Q_{\tan kloss}$$

Analysis

Figures 23 and 24 show the profiles of UA as the function of time. Figures 25 and 26 show the UA as the function of mean tank temperature.

Figure 23. UA as a function of time (2-gallon tank, data set 2gal_ref_1.xls)

Figure 24. UA as a function of time (50-gallon tank, data set 50gal_ref_2.xls)

It is found in both Figures 23 and 24 that for a given initial point, the UA values calculated from first few time intervals are not stable. If we reselect the initial point in the stable region, the UA values of first few time intervals based on the new initial point become unstable again. This indicates the instability is not

caused by physical phenomenon associated with experiment apparatus. This is because, at the beginning of the test, convective heat transfer between the hot water and tank wall dissipate energy to the ambient air, and the water near the wall is cooler compared to the water in the center. Thus, the buoyancy force is induced to drive the hot water moves upward to the top of the tank and cold water moves down to the tank bottom. Since the initial temperature is made uniform, there is no domain movement of the water body at the beginning. The non-uniform movement causes the non-stable heat transfer between the water and wall as well as water to water. As the internal circulation developing, water is stratified in the tank. The heat transfer between moving water dominates the overall heat transfer. Since there is no forced convection inside the tank, nor between the ambient air and outer wall, the weights of these two heat transfer processes are at same order. In other words, any uncertainty in one of these two processes will heavily influence the other. However, if an increased time interval is selected, the uncertainty has less and less contribution to the accumulated heat loss. Thus, the data dots will converge finally, and just scatter at the first few intervals.

It is interesting to notice that the scatter region in Figure 23 is above the average for 2-gallon tank while it is below the average in Figure 24 for 50-gallon tank. It could be explain that, at the beginning of the test, the convection between the ambient and the wall dominates the overall heat transfer of small tank while the convection of the water body is the domain for large tank. This is because the circulation driven by the buoyancy force is more easily induced in the large tank with longer height.

The similar curve shape is seen in the Figures 23 and 25, 24 and 26 respectively. This reveals the weight (order) of the tank temperature on the UA is same as that of time.

Figure 25. UA as a function of mean tank temperature (2-gallon tank, data set 2gal_ref_1.xls)

Figure 26. UA as a function of mean tank temperature (50-gallon tank, data set 50gal_ref_2.xls)

Tables 2 and 3 show the UA and heat loss from the reference test of 2-gallon tank and 50-gallon tank respectively. Tables 4-9 show the heat loss from the tank for varied plumbing fittings attached to the 2-gallon thermal storage tank which is well insulated. The selected period covers from the beginning to 360 minutes.

Table 2. Reference heat loss and UA for 2-gallon tank

Date Time	Ttankavg (°C)	Tambavg (°C)	Q_5min (KJ)	UA (W/ °C)
8/8/96 14:24	50.005	22.772		
8/8/96 14:29	49.936	22.789	2.234	0.274
8/8/96 15:29	49.001	22.948	2.524	0.315
8/8/96 16:29	47.940	23.076	2.701	0.346
8/8/96 17:29	47.086	22.913	2.579	0.337
8/8/96 18:29	46.279	22.856	2.486	0.331
8/8/96 19:29	45.411	23.360	2.462	0.334
8/8/96 20:29	44.563	22.950	2.437	0.337
8/8/96 21:29	43.861	23.218	2.363	0.332
8/8/96 22:29	43.099	23.113	2.328	0.333
8/8/96 23:29	42.429	22.815	2.272	0.331
8/9/96 0:29	41.823	22.864	2.211	0.327
8/9/96 1:29	41.127	22.786	2.182	0.328
8/9/96 2:29	40.464	22.777	2.151	0.329
8/9/96 3:19	40.018	22.626	2.107	0.326

Table 3. Reference heat loss and UA for 50-gallon tank

Date Time	Tm1 (°C)	Tm2 (°C)	Tm3 (°C)	Tm4 (°C)	Tm5 (°C)	Tambavg (°C)	Tmeanavg (°C)	Q 5min (KJ)	UA (W/°C)
6/7/97 1:49	50.029	54.838	54.908	55.205	54.895	24.356	53.975	21.910	2.228
6/7/97 4:49	49.002	54.017	54.067	53.827	54.232	24.359	53.029	21.632	2.234
6/7/97 7:49	47.624	53.013	53.419	53.628	53.413	24.353	52.219	21.069	2.209
6/7/97 10:49	46.840	51.893	52.744	52.491	52.516	24.086	51.297	20.889	2.223
6/7/97 13:49	45.948	51.532	51.716	51.722	52.046	24.189	50.593	20.291	2.191
6/7/97 16:49	44.969	50.550	51.213	51.124	51.430	23.984	49.857	19.861	2.175
6/7/97 19:49	44.223	49.666	50.189	50.023	50.323	23.960	48.885	19.912	2.211
6/7/97 22:49	43.486	48.955	49.619	49.773	49.792	24.243	48.325	19.293	2.173
6/8/97 1:49	42.720	48.113	48.971	48.574	48.856	23.999	47.447	19.237	2.197
6/8/97 4:49	42.201	47.196	48.401	48.388	48.087	24.231	46.854	18.790	2.177
6/8/97 7:49	41.518	46.789	47.488	47.539	47.507	24.057	46.168	18.521	2.175
6/8/97 10:49	40.882	46.018	46.744	46.834	47.007	24.123	45.497	18.266	2.175
6/8/97 13:49	40.484	45.592	46.395	46.389	46.472	23.944	45.066	17.759	2.143
6/8/97 16:49	39.743	44.523	45.663	45.914	45.926	24.290	44.354	17.615	2.154
6/8/97 17:19	39.903	44.734	45.880	45.590	45.828	24.128	44.387	17.426	2.135

Table 4. Heat loss from two U-turns heat trap vertically connected to 2-gallon tank

	Water filled in tank only		Water filled in both tank & pipe	
	Pipe not insulated	Pipe insulated	Pipe not insulated	Pipe insulated
File Name	mtu6#.xls	11.xls	5.xls	6.xls
M _{tankwater} (kg)	7.816	7.816	7.816	7.816
M _{pipewater} (kg)	0	0	0.212	0.212
M _{totalwater} (kg)	7.816	7.816	8.028	8.028
C _p (kJ/kg.°C)	4.183	4.183	4.183	4.183
Total time elapsed (s)	32400	42600	33000	37500
T _{tankavg} (°C)	44.66	44.53	44.61	44.60
T _{tankavg} at t=0 min (°C)	50.14	50.02	50.06	50.03
T _{tankavg} at t=360 min (°C)	43.81	44.23	42.92	43.65
T _{pipeavg} (°C)	28.34	30.96	34.74	36.11
T _{totalavg} (°C)	44.66	44.53	44.35	44.38
T _{ambavg} (°C)	22.25	23.71	23.45	23.41
Q _{totalloss} (kJ)	329.56	327.59	333.46	332.45
Q _{tankloss} (kJ)	243.02	297.41	233.70	266.45
Q _{pipeloss} (kJ)	86.54	30.19	99.76	66.00

Table 5. Heat loss from 18" vertically connected to 2-gallon tank

	Water filled in tank only		Water filled in both tank & pipe	
	Pipe not insulated	Pipe insulated	Pipe not insulated	Pipe insulated
File Name	mt22#.xls	mt24#.xls	mt21#.xls	mt25#.xls
$M_{\text{tankwater}}$ (kg)	7.816	7.816	7.816	7.816
$M_{\text{pipewater}}$ (kg)	0	0	0.198	0.198
$M_{\text{totalwater}}$ (kg)	7.816	7.816	8.014	8.014
C_p (kJ/kg.°C)	4.183	4.183	4.183	4.183
Total time elapsed (s)	41100	41100	32700	39000
T_{tankavg} (°C)	44.60	44.59	44.64	44.63
T_{tankavg} at t=0 min (°C)	50.02	50.00	50.12	50.13
T_{tankavg} at t=360 min (°C)	44.12	44.22	42.85	43.90
T_{pipeavg} (°C)	31.13	31.86	39.67	40.73
T_{totalavg} (°C)	44.60	44.59	44.52	44.60
T_{ambavg} (°C)	22.86	22.59	22.77	24.31
$Q_{\text{totalloss}}$ (kJ)	327.11	326.94	336.00	337.24
Q_{tankloss} (kJ)	299.27	302.96	239.57	264.96
Q_{pipeloss} (kJ)	27.84	23.98	95.88	72.28

Table 6. Heat loss from 24" vertically connected to 2-gallon tank

	Water filled in tank only		Water filled in both tank & pipe	
	Pipe not insulated	Pipe insulated	Pipe not insulated	Pipe insulated
File Name	mt31#.xls	mt32#.xls	mt18#.xls	mt20#.xls
$M_{\text{tankwater}}$ (kg)	7.816	7.816	7.816	7.816
$M_{\text{pipewater}}$ (kg)	0	0	0.213	0.213
$M_{\text{totalwater}}$ (kg)	7.816	7.816	8.047	8.047
C_p (kJ/kg.°C)	4.183	4.183	4.183	4.183
Total time elapsed (s)	40200	41100	34200	32100
T_{tankavg} (°C)	44.73	44.66	44.63	44.69
T_{tankavg} at t=0 min (°C)	50.16	50.05	50.07	50.07
T_{tankavg} at t=360 min (°C)	44.19	44.29	43.11	43.00
T_{pipeavg} (°C)	30.52	31.08	39.67	39.54
T_{totalavg} (°C)	44.73	44.66	44.49	44.54
T_{ambavg} (°C)	23.06	22.73	22.66	21.66
$Q_{\text{totalloss}}$ (kJ)	329.56	324.98	335.60	333.24
Q_{tankloss} (kJ)	291.83	301.94	251.71	247.65
Q_{pipeloss} (kJ)	37.73	23.04	83.89	85.59

Table 7. Heat loss from two straight pipes connected by 90°elbow connected to 2-gallon tank

	Water filled in tank only		Water filled in both tank & pipe	
	Pipe not insulated	Pipe insulated	Pipe not insulated	Pipe insulated
File Name	19.xls	24.xls	18.xls	30.xls
$M_{\text{tankwater}}$ (kg)	7.816	7.816	7.816	7.816
$M_{\text{pipewater}}$ (kg)	0	0	0.635	0.635
$M_{\text{totalwater}}$ (kg)	7.816	7.816	8.451	8.451
C_p (kJ/kg.°C)	4.183	4.183	4.183	4.183
Total time elapsed (s)	40800	43200	28800	31500
T_{tankavg} (°C)	44.61	44.58	44.64	44.64
T_{tankavg} at t=0 min (°C)	50.00	50.00	50.09	50.09
T_{tankavg} at t=360 min (°C)	44.11	44.35	42.08	42.63
T_{pipeavg} (°C)	25.69	26.49	31.29	32.01
T_{totalavg} (°C)	44.61	44.58	43.64	44.69
T_{ambavg} (°C)	23.42	23.54	24.12	23.07
$Q_{\text{totalloss}}$ (kJ)	325.64	326.94	346.08	351.03
Q_{tankloss} (kJ)	288.53	304.64	197.49	228.25
Q_{pipeloss} (kJ)	37.11	22.30	148.59	122.78

Table 8. Heat loss from Long Horizontal pipe connected with short pipe by 90° bent

	Water filled in tank only		Water filled in both tank & pipe	
	Pipe not insulated	Pipe insulated	Pipe not insulated	Pipe insulated
File Name	32.xls	44.xls	36.xls	46.xls
$M_{\text{tankwater}}$ (kg)	7.816	7.816	7.816	7.816
$M_{\text{pipewater}}$ (kg)	0	0	0.431	0.431
$M_{\text{totalwater}}$ (kg)	7.816	7.816	8.247	8.247
C_p (kJ/kg.°C)	4.183	4.183	4.183	4.183
Total time elapsed (s)	35100	41400	24900	41100
T_{tankavg} (°C)	44.63	44.63	44.57	44.65
T_{tankavg} at t=0 min (°C)	50.05	50.05	50.10	50.11
T_{tankavg} at t=360 min (°C)	43.33	44.21	41.28	44.08
T_{pipeavg} (°C)	28.38	29.61	33.78	30.06
T_{totalavg} (°C)	44.63	44.63	44.01	43.89
T_{ambavg} (°C)	23.10	23.00	23.12	23.17
$Q_{\text{totalloss}}$ (kJ)	325.96	324.33	341.87	333.93
Q_{tankloss} (kJ)	253.16	299.88	178.93	295.80
Q_{pipeloss} (kJ)	72.80	24.45	162.94	38.13

Table 9. Heat loss from two short pipe connected by 90° bent

	Water filled in tank only		Water filled in both tank & pipe	
	Pipe not insulated	Pipe insulated	Pipe not insulated	Pipe insulated
File Name	62.xls	70.xls	66.xls	71.xls
$M_{\text{tankwater}}$ (kg)	7.816	7.816	7.816	7.816
$M_{\text{pipewater}}$ (kg)	0	0	0.052	0.052
$M_{\text{totalwater}}$ (kg)	7.816	7.816	7.868	7.868
C_p (kJ/kg.°C)	4.183	4.183	4.183	4.183
Total time elapsed (s)	39300	38100	34200	36900
T_{tankavg} (°C)	44.73	44.67	44.42	44.66
T_{tankavg} at $t=0$ min (°C)	50.03	50.09	50.04	50.07
T_{tankavg} at $t=360$ min (°C)	44.00	43.72	42.68	43.49
T_{pipeavg} (°C)	38.03	39.45	41.31	42.43
T_{totalavg} (°C)	44.73	44.67	44.40	44.65
T_{ambavg} (°C)	22.50	19.61	20.23	19.51
$Q_{\text{totalloss}}$ (kJ)	324.98	329.56	329.12	329.44
Q_{tankloss} (kJ)	292.55	319.90	277.13	310.73
$Q_{\text{pipe loss}}$ (kJ)	32.43	9.66	51.99	18.71

CONCLUSIONS

An experimental study is presented for investigating the effects of plumbing attachments on the thermal storage system. Two sets of test designs are completed, one is the reference heat loss for the tank itself, the other is for the system with plumbing attachments.

The salient results were:

- During the standby mode, the water body inside the storage tank whose temperature was initially uniform become stratified by heat losses from the water to tank wall and tank wall to ambient, as well as the result from heat and mass transfer within the water body itself. The stratification and the decay are linear with vertical height and time, respectively.
- For the 50-gallon storage tank, there is a distinct transient region at the bottom where the heat transfer is relatively active. For the 2-gallon storage tank, the heat transfer between the water and the side-walls dominates the overall heat loss of the system.
- The average surface temperature for water filled in both tank and pipe fittings is higher than that for water filled in the tank only, that is, the heat transferred to the pipe fittings and dissipated to ambient is significantly increased when the pipe is filled with water.
- The heat losses from the plumbing fittings attached to the thermal storage tank are relatively small compared to the heat loss from the tank itself. This result was unexpected.

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