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An Experimental Investigation Of Perforated Manifolds To Enhance Stratification In A Solar Domestic Hot Water Tank

Topic Area: Solar Thermal Systems

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Abstract— **An experimental study was conducted to develop and test three perforated manifolds designed to enhance thermal stratification in a solar domestic hot water tank. The perforated manifolds extend from an immersion heat exchanger to the top of the tank. Experimental results were analyzed for each manifold to determine the most effective design. The thermal performance of the manifolds was evaluated in terms of the exergy and entropy of the water in the tank at the end of each test. It was found that perforated manifolds perform better than a conventional non-perforated manifold that delivers hot water to the top of the tank. Further work, especially using CFD tools, will help in identifying favorable perforated manifold designs.**

Index Terms: Solar domestic hot water tank, tank stratification, stratification enhancement, perforated manifold

I. INTRODUCTION

Solar domestic hot water (SDHW) systems perform three basic operations: collecting energy with a solar collector, transferring the energy to water through a heat exchanger, and storing the energy in a storage tank until needed for domestic use. The water in the storage tank should be thermally stratified to the highest possible degree to maximize system efficiency and economic feasibility. The thermal performance of a tank can be improved by enhancing thermal stratification because a stratified tank is a lower entropy system than a non-stratified tank, and lower entropy systems naturally have higher exergy (availability). Thermal stratification takes place naturally due to the lower density of the water at higher temperature. However, as a SDHW tank is charged and discharged, stratification is compromised. Thus, it is desirable to design a manifold that will enhance stratification inside a storage tank.

To be able to evaluate the performance of a device in enhancing stratification, first it is necessary to characterize stratification. The characterization of stratification is an area of research that has been going on for several decades. Since stratification has to do with temperature distribution, the second law of thermodynamics is often utilized to assess the level of stratification. For example, Rosen and Hooper [1] concluded that if only the first law of thermodynamics is used, it is not possible to distinguish a stratified tank from a mixed one. However, a second law analysis allows different temperature distributions to be quantified in terms of the exergy content, which is function of the temperature of the liquid and the reference environment (dead state) temperature (T_0). Rosen and Hooper [1] and later Rosen et al [2] calculated the exergy content of the tank based on the tank temperature as a function of height and T_0. Rosengarten et al. [3] used the second law to characterize thermally stratified hot water storage, with application to solar water heaters, and developed a method of comparing different levels of stratification in liquid thermal storage devices using a "stratification efficiency" parameter which is the ratio of the exergy to the heat content of the water stored in the tank. Several researchers evaluated stratification by taking into comparing the entropy [4, 5] and moment of energy [6, 7] of an actual tank to that of a perfectly stratified tank and a fully mixed tank.

Since exergy is an effective measure to evaluate stratification, the choice of T_0 is critical because exergy is a function of this temperature. Based on the work of Hermansson [6], Rosengarten et al. [3] indicate that T_0 depends on the application, but do not specify what it should be. They state that in some cases, the temperature used is the tank bottom temperature and in others the mains cold water temperature. Haller et al [9] point out that with systems that are not used to produce work, the choice of T_0

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is arbitrary. However, as also pointed out by Rosengarten et al. [3] and Hermansson [4], arbitrary choices of T_0, without a physical justification, could confuse and lead to misleading comparisons because exergy is highly dependent on this temperature. An in-depth review and discussion of methods to characterize stratification in thermal storage tanks is given in Haller et al. [9] and Panthalookaran et al. [5].

II. OBJECTIVE AND SCOPE

The objective is to develop a new immersion-type shell-and-coil heat exchanger (ISCHX) to enhance stratification in a SDHW tank.

In an earlier work [10], stratification was observed with a simple manifold supplying heated water only at the top of the tank (reference manifold #1), as seen in Figure 1. However, since the heated water was supplied only from the top, when the temperature of the heated water was lower than the temperature of the water at the top of the tank, the temperature at the top of the tank dropped as seen in Figure 1 between 8:00 and 10:00. In an effort to eliminate or reduce this cooling effect, three perforated manifolds were designed and tested. All three perforated manifolds extend from the top of the heat exchanger to the top of the tank to promote the delivery of the water heated by the immersion heat exchanger to the tank at the level where the temperature of the water in the tank matches the temperature of the heated water, thereby enhancing stratification. The performance of each manifold was compared with that of the reference manifold (Manifold #1) which is a simple non-perforated manifold with only horizontal water delivery ports at the top to deliver the heated water to the top of the storage tank. All four manifolds were made from 19 mm inner diameter and 22 mm outer diameter (¾ inch nominal) copper tube.

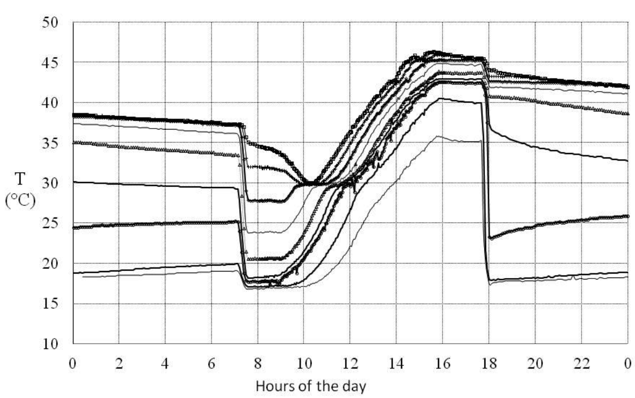


Figure 1. Temperature distribution in the SDHW tank using Manifold #1 (the constant temperature lines from the bottom to the top in the figure correspond to the temperature readings obtained from the bottom to the top of the tank)

The three perforated manifolds are as follows:

Manifold #2 has seven ports, six of them 9 mm in diameter and one (at the top) 19 mm in diameter, as shown in Figure 2.

Manifold #3 is similar to manifold #2, with 3 mm ports in place of the 9 mm ports.

Manifold #4 also has seven ports, with port diameters increasing from 5 mm at the bottom to 19 mm at the top of the manifold. The aim with this design is to reduce the undesired backflow of water into the manifold through the lower ports under some operating modes. The size of each port was determined to match the differential pressure that decreases gradually from the bottom to the top of the manifold as described in Alsagheer [11].

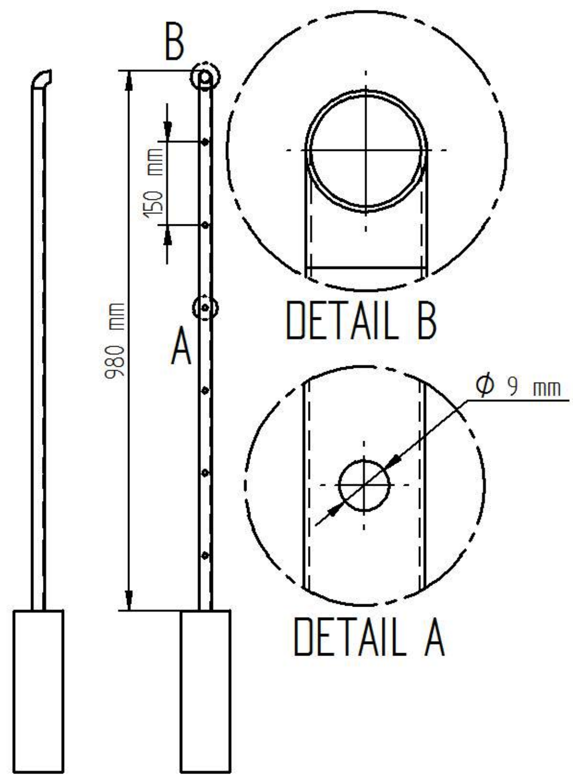


Figure 2. Manifold #2

III. METHODOLOGY

To test the performance of the manifolds, the experimental set-up shown in Figure 3 was designed and constructed. An insulated acrylic tank of square cross-section with a volume of 370 liters (0.5 m x 0.5 m x 1.48 m) was used in the experiments. Temperature, pressure and flow rate data collected by the data acquisition system were recorded at three-minute intervals on a dedicated computer as described in detail in Alsagheer [11]. Seven thermocouples were installed inside the manifold from the bottom to the top and in front of each opening to measure the heated water temperature. An additional twenty-two thermocouples were installed in two probes (one probe with 12 and the second with 10 thermocouples) located in two corners of the tank to measure the temperature in 12 layers from the top to the bottom as shown in Figure 4.

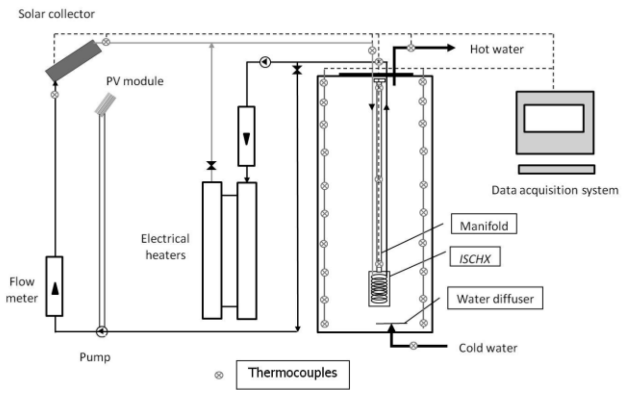


Figure 3. Schematic diagram of the experimental set-up

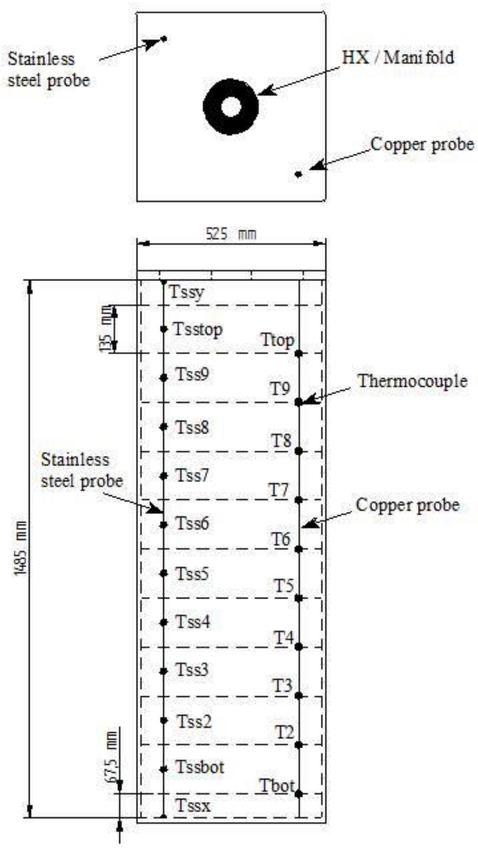


Figure 4. Locations of thermocouples on the two probes.

The thermal performance was evaluated in terms of tank exergy and entropy, maximum tank temperature, and thermal stratification, and the results from the different manifold designs were compared to determine the most effective manifold.

All four manifolds were tested under three conditions, which simulated a fixed heat input to the tank (20 MJ of electrical energy over two hours), a sunny day and a cloudy day in Nova Scotia, Canada. To simulate the operation of an actual SDHW storage tank, three initial tank conditions were used, i.e. cold tank, hot tank and mixed tank leading to nine tests for each manifold. The initial tank conditions are defined as follows:

Cold tank condition: the tank was drained before the start of the test and filled with the water from the cold water mains. Cold water temperature was in the range of 10 – 21°C depending on the time of the year that the test was conducted, while the temperature difference between the top and the bottom of the tank was in the range of 1 – 2°C.
Hot tank condition: the water in the tank was heated in the previous day and the energy in the storage tank was carried to the day of the test. The water temperature in the tank at the beginning of the tests was in the range of 18 – 51°C, while the temperature difference between the top and the bottom of the tank was as high as 22°C.

Mixed tank condition: the tank was filled with water the day before the test so that through heat loss (or gain) the temperature of the water after a full day approached room temperature. The water temperature in the tank at the beginning of the tests was in the range of 16 – 26°C depending on the time of the year that the test was conducted, while the temperature difference between the top and the bottom of the tank was in the range of 1 – 2°C.

The evaluation of the performance of the manifolds is based on a comparison of the exergy and the entropy of the actual tank achieved at the end of each test with the exergy and the entropy of a “perfectly stratified tank” and a “fully mixed tank”, both idealized tanks representing two extreme conditions.

A “perfectly stratified tank” contains two distinct temperature zones. The temperature of the top zone is equal to the temperature at the top of the actual tank at the end of the test, while the temperature of the bottom zone is equal to T0. The mass of water in each zone is calculated such that the energy content of the perfectly stratified tank is the same as the energy content of the actual tank at the end of the test.

A “fully mixed tank” is at a uniform temperature, which is equal to the average temperature of the actual tank at the end of the test. Thus, the energy contents of the perfectly stratified and the fully mixed tanks is the same as the energy content of the actual tank at the end of a test.

The thermal performance of the manifolds is evaluated using exergy (A) and entropy (S) ratios as defined in equations 1 and 2:

$$A_{Ratio} = \frac{A_{Actual}}{A_{PerStr}} \quad (1)$$

$$S_{Ratio} = \frac{S_{PerStr}}{S_{Actual}} \quad (2)$$

where,
A_{Actual} = Exergy of the water in the actual tank at the end of the test

$A_{PerfStr}$ = Exergy of the water in the perfectly stratified tank

S_{Actual} = Entropy of the water in the actual tank at the end of the test

$S_{PerfStr}$ = Entropy of the water in the perfectly stratified tank

The exergy and entropy of the water in the tank is determined based on the temperature of the tank measured by the 12 thermocouples mentioned above:

$$A_{Tank} = m_{Tank}\left(\sum_{i=1}^{12}[(h_i - h_o) - T_0(s_i - s_o)]\right) \quad (3)$$

$$S_{Tank} = m_{Tank}\left(\sum_{i=1}^{12} S_i\right) \quad (4)$$

where:

m_{Tank} = Mass of the tank

i = Layer number, the temperature of each layer of water is measured by a thermocouple

h_i, s_i = Specific enthalpy and specific entropy of the water of layer i evaluated at the measured temperature

h_0, s_0 = Specific enthalpy and specific entropy of the water at reference environment temperature

T_0 = Reference environment temperature

Thus, the best performing manifold is the one that results in exergy and entropy values that are closest to the exergy and entropy of the perfectly stratified tank; i.e. the best performing manifold results in the highest exergy and entropy ratios.

Approximately five days were required to set up and conduct each one of the 36 tests. Thus, close to five months were required to complete the experimental protocol. During this period, both the ambient and the cold water mains temperatures varied substantially. For example, cold water temperatures from the mains on May 19 and August 21, 2009 were 10°C and 21°C, respectively. Due to the variation of temperature during the test period, the selection of T_0 is not a trivial task, with no obviously “right” or “wrong” choice. Therefore, several values of T_0 were tested to identify the most suitable choice in the calculation of exergy. As discussed in detail in Alsagheer [11], the average temperature of the water in the tank at the beginning of each test was found to be the most appropriate choice of T_0 for this work. Thus, for each test, a different T_0 was used. However, since the exergy and entropy ratios were calculated separately for each test, using a different T_0 for each test was feasible. Furthermore, using the average temperature of the water in the tank as T_0 results in a zero exergy condition in the beginning of each test regardless of the type or conditions of the test conducted, which is a desirable feature.

IV. RESULTS AND DISCUSSION

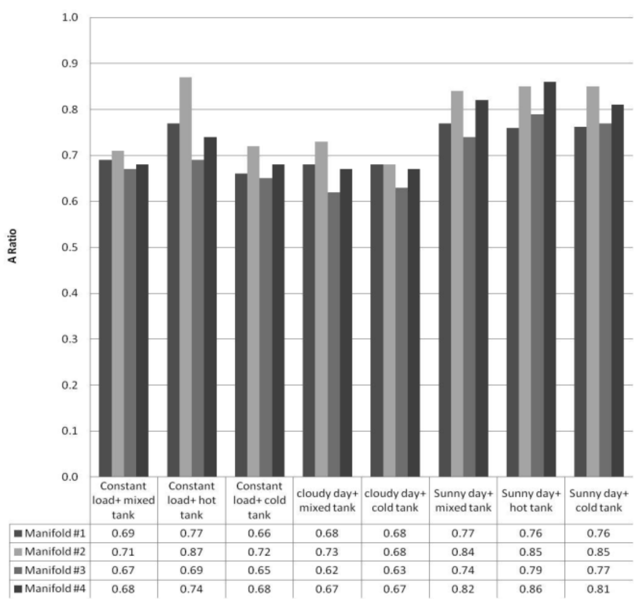
The exergy ratios and entropy ratios for each manifold under all experimental conditions are plotted in Figures 5 and 6. As it seen from these figures, the most effective manifold is Manifold #2, which consistently produced the highest exergy and entropy ratios. The stratification performance of Manifold #2 in terms of tank temperature distribution is shown in Figures 7-9. The temperature distributions achieved with other manifolds are given in Alsagheer [11].

With the cold tank condition, as shown in Figure 7, as soon as the heat addition started, the tank temperature started increasing. In the test simulating a sunny day condition, the temperature throughout the tank was 16ºC at the beginning of the test. When heat addition from the hot glycol started at 9:30, the temperature at the top of the tank increased sharply, while the temperature at the bottom of the tank did not start to rise until 10:30. As more heat was transferred to the tank, the temperatures at the lower zones began to increase gradually after 11:00, and twelve distinct thermal zones could be distinguished from the bottom to the top of the tank, with a difference between them of about 1.5ºC. The temperature increased to 37ºC at 17:30 and at that time heat addition stopped. Similar behavior of the temperature distribution is seen with cloudy day and constant load tests. The tank starts heating from the top, and as more energy is transferred, the hot water flow through the holes at lower points in the manifold promotes stratification.

With a hot tank on a cloudy day, the water temperature inside the storage tank was higher than the glycol temperature most of the day as seen in Figure 8. There was no differential temperature controller in the experimental set-up, which would have stopped the solar pump from circulating the glycol through the solar collector. Therefore the storage tank was heating the glycol in the beginning. Since this operation is contrary to the purpose of a solar collector, the results for cloudy day with hot tank condition are not useful. However, under sunny day and constant load conditions, it is seen that the perforated manifold promoted stratification as soon as the tests started, and delivered the heated water to all levels at the appropriate temperature.

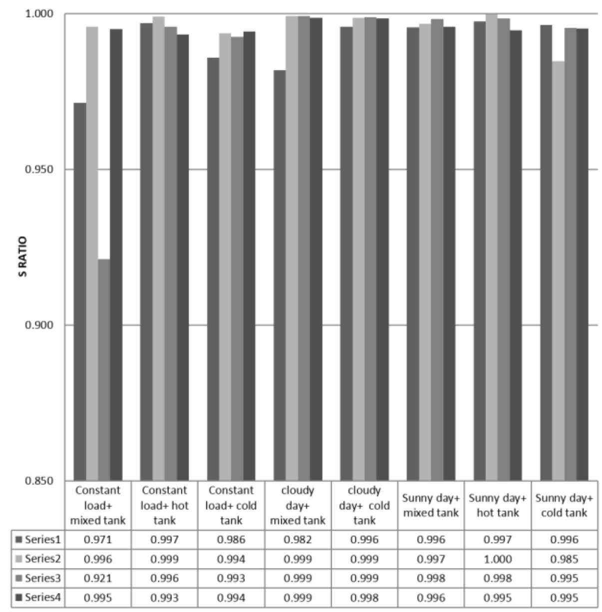
With a mixed tank, the heating process was similar to that with a cold tank as seen in Figure 9. As soon as the tests started the temperature at the top of the tank increased, and in time the temperature at the bottom of the tank started increasing as the perforated manifold delivered the water heated by the heat exchanger to different levels inside the storage tank resulting in a stratified temperature distribution with clearly defined thermal zones from the bottom to the top of the tank. The temperature difference between the zones varied from 1ºC to 3ºC.

The variation of exergy under sunny day conditions with initial cold, hot and mixed tank conditions with Manifold #2 is given in Figure 10. As to be expected, the availability of the actual tank remains between that of the perfectly stratified and fully mixed tanks. The availability and entropy variations for all tests with the other manifolds are given in Alsagheer [11].



	Constant load+ mixed tank	Constant load+ hot tank	Constant load+ cold tank	cloudy day+ mixed tank	cloudy day+ cold tank	Sunny day+ mixed tank	Sunny day+ hot tank	Sunny day+ cold tank
Manifold #1	0.69	0.77	0.66	0.68	0.68	0.77	0.76	0.76
Manifold #2	0.71	0.87	0.72	0.73	0.68	0.84	0.85	0.85
Manifold #3	0.67	0.69	0.65	0.62	0.63	0.74	0.79	0.77
Manifold #4	0.68	0.74	0.68	0.67	0.67	0.82	0.86	0.81

Figure 5. Exergy ratios for all manifolds under all test conditions



	Constant load+ mixed tank	Constant load+ hot tank	Constant load+ cold tank	cloudy day+ mixed tank	cloudy day+ cold tank	Sunny day+ mixed tank	Sunny day+ hot tank	Sunny day+ cold tank
Series1	0.971	0.997	0.986	0.982	0.996	0.996	0.997	0.996
Series2	0.996	0.999	0.994	0.999	0.999	0.997	1.000	0.985
Series3	0.921	0.996	0.993	0.999	0.999	0.998	0.998	0.995
Series4	0.995	0.993	0.994	0.999	0.998	0.996	0.995	0.995

Figure 6. Entropy ratios for all manifolds under all test conditions

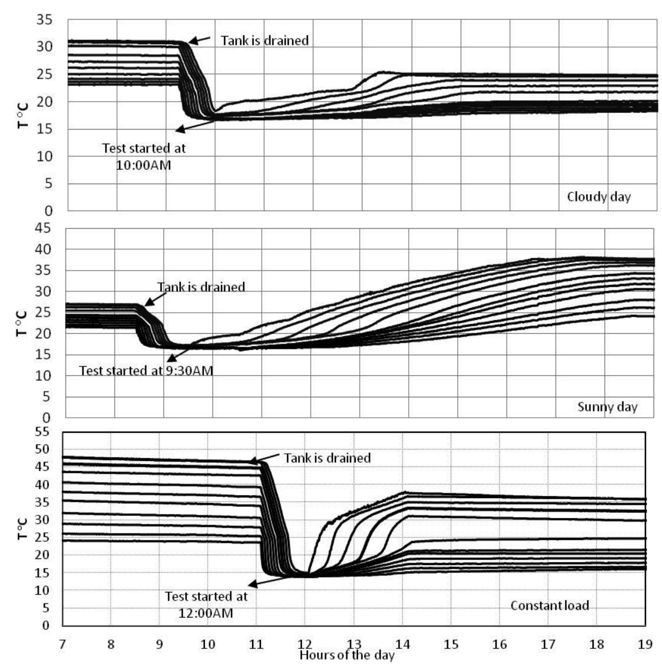
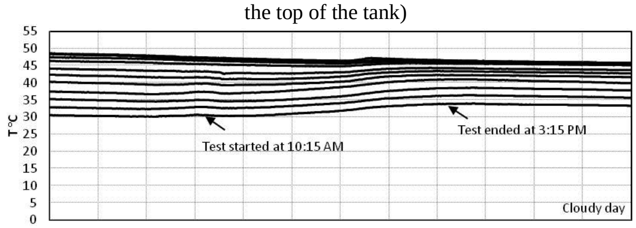


Figure 7. Stratification performance of Manifold #2 under cold tank condition (the constant temperature lines from the bottom to the top in the figure correspond to the temperature readings obtained from the bottom to the top of the tank)



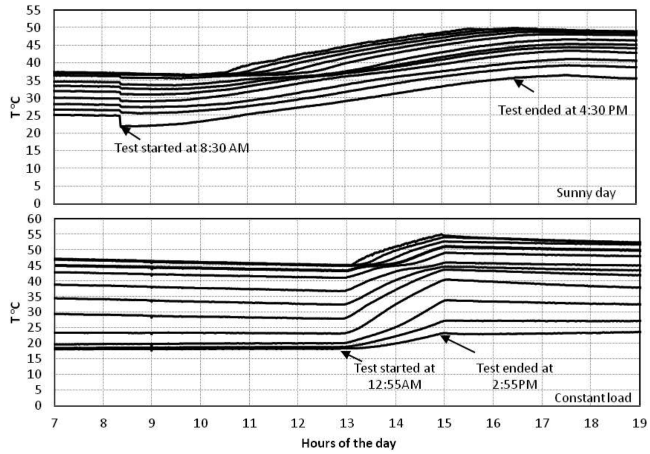


Figure 8. Stratification performance of Manifold #2 under hot tank condition (the constant temperature lines from the bottom to the top in the figure correspond to the temperature readings obtained from the bottom to the top of the tank)

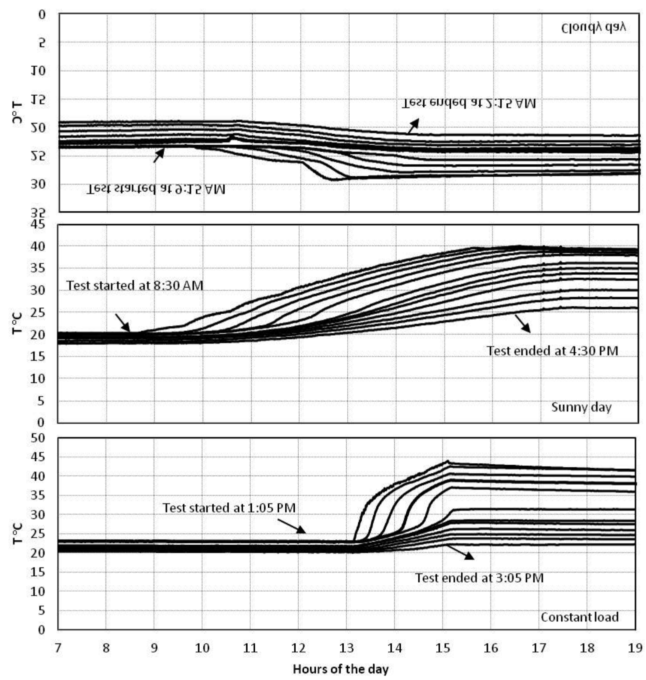
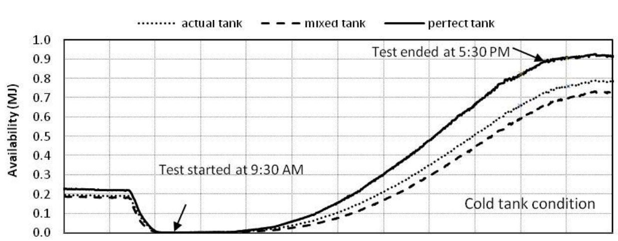


Figure 9. Stratification performance of Manifold #2 under mixed tank condition (the constant temperature lines from the bottom to the top in the figure correspond to the temperature readings obtained from the bottom to the top of the tank)



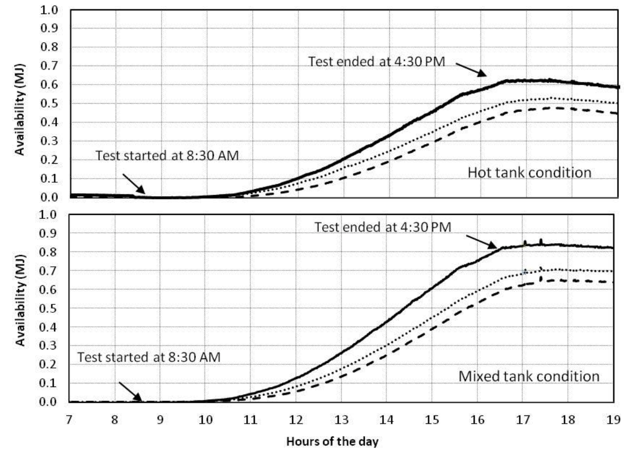


Figure 10. Availability ratio for sunny day condition with Manifold 2.

V. CONCLUSION

The experimental study of three perforated manifolds and their performance in achieving thermal stratification in a SDHW tank presented here indicates that stratification can be achieved by using a perforated manifold under most operating conditions. In this work, it was found that the perforated manifold that had six holes each 9 mm in diameter performed better than the other two designs tested. While generalizations cannot be made from the results of this limited experimental work, it is clear that use of perforated manifolds present an opportunity to enhance stratification in SDHW tanks, which in turn results in improved system performance. Further work, especially using CFD tools will help in identifying favorable perforated manifold designs.

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