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The effect of manifold in liquid storage tank applied to solar combisystem[†]

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Abstract

There exists a return piping in solar combi-system for heating and hot water supply. When the temperature of water returning from the load is mixed with the lower side cold water of the storage tank, useful energy is reduced. This paper describes a diffuser and manifold for preventing this mixing and maintaining temperature stratification. Results from experiments show that manifold holes are optimum at 8.5 mm in diameter with a total of 96 in number of holes at a flow rate of 0.3 lpm.

Keywords: Solar combisystem; Stratification; Thermal energy storage; Manifold; Diffuser

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1. Introduction

Solar thermal systems converts incident solar irradiation into thermal energy in the form of heated water, which are considered as one of the most competitive systems in the renewable energy field due to the high economic feasibility and availability [1]. Scientific and engineering efforts have continued to identify refinements that can increase the total system efficiency by improved collector performance, control system enhancements, and increased thermal stratification in the hot water storage tank. Previous experimental and theoretical studies showed that stratification enhancement leverages higher collection efficiency; thereby leading to higher overall system efficiency with lower thermal exergy loss [2, 3]. Physically, several mechanisms work to erode stratification including fluidic mixing in the inlet region, energy loss through the tank wall due to the poor insulation, heat transfer in the metallic wall itself and thermal diffusion inside the tank [4-7]. Out of those effects, the inlet mixing is among the most influential on establishing stratification; consequently, techniques to develop and maintain stratification during operation are of interest.

Two stratification enhancing mechanisms were previously used in the solar water storage tank. The direct circulation system, schematically shown in Fig. 1(a), usually adopts a diffuser (horizontal spraying bar or disc in the upper side of storage tank in Fig. 1(a)) or a manifold (long tube with many holes on the surface, longitudinally centered inside the storage tank of Fig. 2) [8-12]. Remarkably, the manifold studied by Hong and Kim [9] was shown to build up an almost perfect stratification when the high temperature water returning from the collector during charging is exactly distributed into the same temperature region of storage tank, which already have a stratified temperature profile. However, the simplicity of direct circulation system and the advantage stemming from stratification effect is no more applicable in the area such as Korea due to freezing risks (freeze and burst) during the winter season. Usually, an external heat exchanger system as shown in Fig. 1(b), is used to prevent collector freezing risks. In this system, an antifreeze solution is circulated in the closed loop between the collector and heat exchanger. In order to increase the total efficiency, a higher circulation rate is essential for the fluid flowing in the collector loop. High fluid velocity on the tank-side of a solar thermal system can enable high heat exchanger performance [13, 14] but intense mixing caused by the high velocity does not admit the employment of diffuser and manifold; especially, manifold is not almost used.

By utilizing forced fluid circulation, solar heating systems have evolved from water-only heating to heating and air-conditioning combined system for all-weather purposes. Fig. 1(c) illustrates a combined system which includes an additional heating source (auxiliary heater). In this system, it is essential for higher collector efficiency and more useful energy that the water with moderately high temperature, returning from the heating load is distributed into the region of the storage with an equivalent temperature. As a drastic case, the mixing of cold city water and hot water returning from the load should be avoided when the city water is supplied to the tank's lower side. In this situation, the diffuser itself will not

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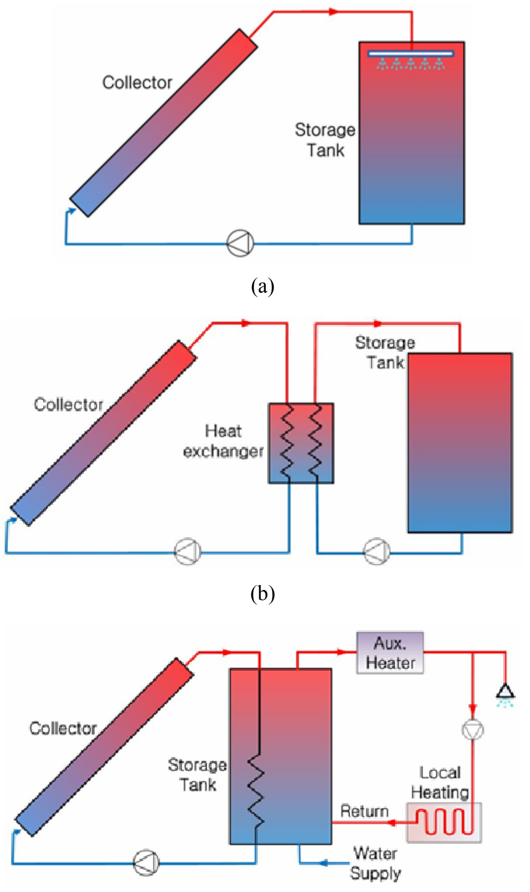


Fig. 1. Active solar thermal systems: (a) direct circulation system; (b) external heat exchanger system; (c) combisystem.

be useful for maintaining stratification; rather, hot water returning from the load should be delivered to the tank at exactly same temperature region inside the storage tank for higher stratification enhancement.

In research related to the manifold, heated working fluid from the collector is injected to the upper part of storage tank through the manifold to enhance the stratification [8-11]. In the present work, however, lower temperature water returning from the load is supplied to lower part of storage to maintain the stratification by preventing from mixing with cold water. In this study, a manifold that provides higher stratification performance than diffuser for the combisystem as shown in Fig. 1(c) is proposed. Furthermore, a statistical experimental design technique is used to optimize the manifold diameter and number of holes. Results for studied how the performance of proposed manifold varies according to the flow rate are presented.

2. Experiment

2.1 Experiment setup

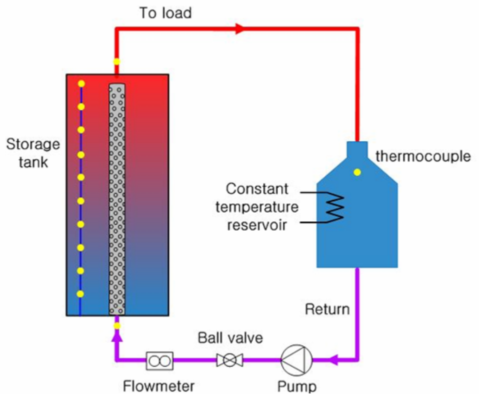
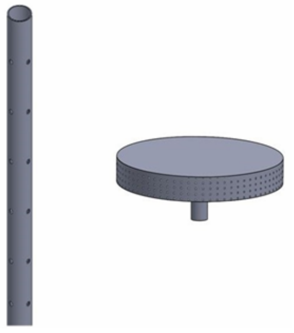


Fig. 2. Schematic of experiment system.



(a) (b)

Fig. 3. Manifold (a); and diffuser (b) used in experiment.

Fig. 2 shows the experimental setup which is comprised of a water reservoir (b), where the temperature is maintained constant and a storage tank with a manifold (a). This simplified system represents the auxiliary heater loop used in the combisystem (see Fig. 1(c)) while allowing a quantitative evaluation of the manifold's contribution to tank stratification performance. The flow rate is adjusted using the ball valve and measured by the flow meter installed downstream. The reservoir is maintained at 55°C by controlling the electric heater immersed in the reservoir. The reservoir temperature selected corresponds to the temperature generally used in commercial hot water mattress systems. The storage tank itself is 300 mm in diameter and 1500 mm in height. The tank is made of transparent acrylic (thickness 5 mm) so that the internal flow can be visualized using a black dye. The inside water temperature of the storage tank is measured using K-type thermocouples installed at elevation intervals of 15 mm. The diffuser shown in the right of Fig. 3 is 80 mm in diameter and 10 mm high. The manifold shown in the left-side of Fig. 3 is made of urethane pipe with an overall height of 1500 mm. The inner diameter (D) of the manifold and the number (n) of surface holes (diameter 3 mm) are parameters in the design for experiments analysis conducted.

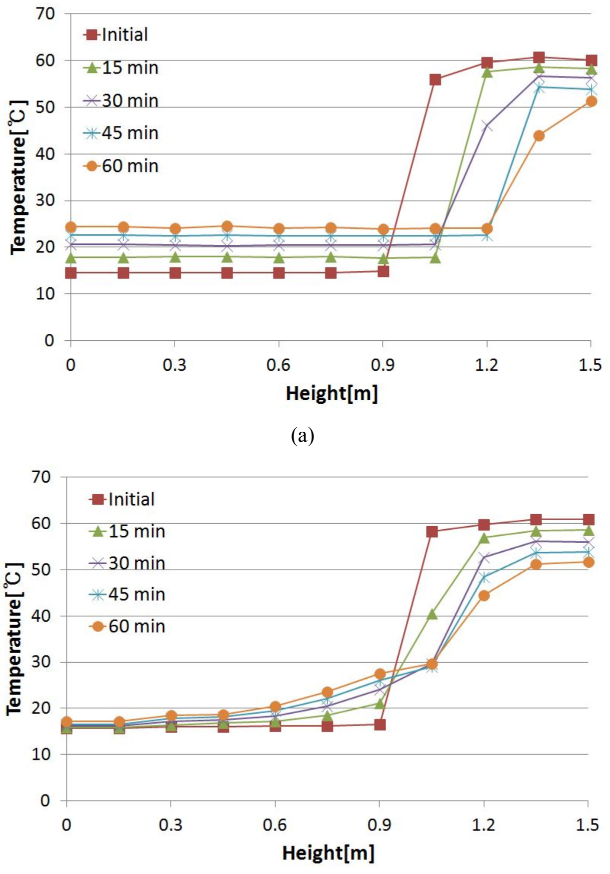
2.2 Experiment method

At first, the lower 60% of tank volume (y = 0 to 0.9 m, y: distance from the bottom) is filled with the cold water at a

Table 1. Degree of thermal stratification R_{TS} by mean square deviation method.

Inner diameter, *D* [mm]	Number of holes *n* (ratio of hole area)		
	30 (0.59%)	90 (1.76%)	160 (3.13%)
6	0.33	0.38	0.33
	0.31	0.36	0.35
8	0.39	0.41	0.42
	0.40	0.41	0.34
12	0.32	0.31	0.26
	0.26	0.26	0.31

temperature of 16°C while the upper 40% of the tank volume (y = 0.9 to 1.5 m) is filled with hot water at a temperature of 60°C. Then water at a temperature of 55°C is supplied through diffuser or manifold at the flow rate of 0.3 lpm to simulate typical flow rates associated with commercial hot water mattress systems. Water temperatures inside the tank are measured at 10 sec intervals for a period of 60 minutes. The above procedure is repeated two times for nine conditions (three manifold diameters: 6, 8, 12 mm, three alternative number-of-holes in the manifold: 30, 90, 160) as summarized in Table 1. The results from this set of experiments are used to identify the optimal manifold configuration. Next, the water flow rate was changed to identify a flow rate range that allows stable stratification.



(a)

(b)

Fig. 4. Temperature profile variations for diffuser (a); and manifold (b).

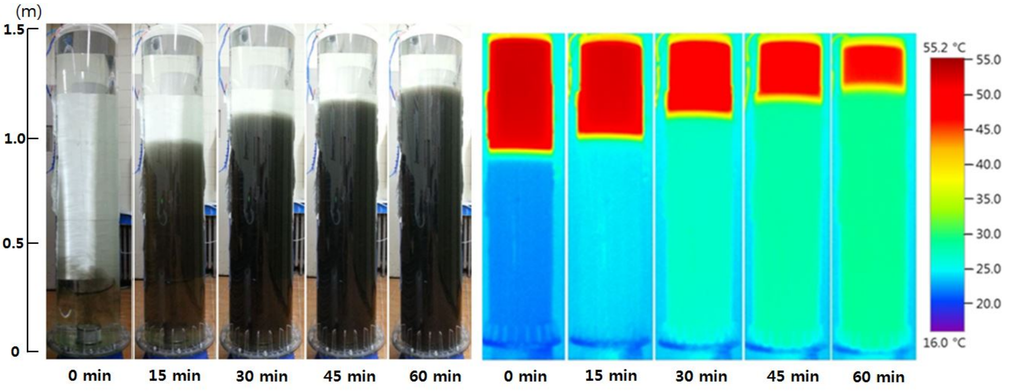
3. Results and analysis

3.1 Comparison between diffuser and manifold

Figs. 4(a) and (b) show temperature profile variations for both the diffuser and manifold (configured with 30 holes 8 mm in diameter) at five time steps of t = 0, 15, 30, 45, 60 minutes using a flow rate of 0.3 lpm. In order to visually understand the stratification phenomena, the photos of flow progress were simultaneously taken by adding a black dye to the supplied water, and also the instantaneous temperature distributions using an infrared thermal camera. For the diffuser corresponding to Fig. 4(a), the left five photos of Fig. 5 illustrates how the dyed flow progresses as time passes, whereas the right five photos correspondingly reveals the temperature images. For the manifold corresponding to Fig. 4(b), Fig. 6 illustrates dyed flow progresses and temperature images, respectively.

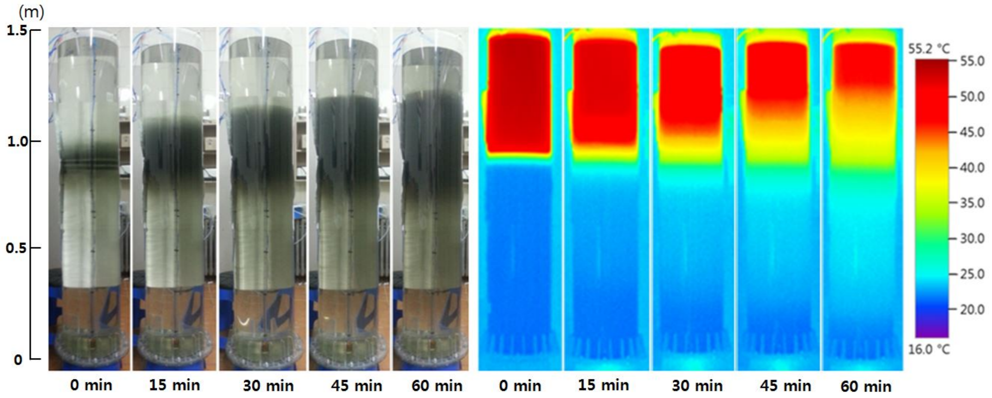
For the diffuser, the initial profile of Fig. 4(a) clearly shows a temperature jump at y = 0.9 m. On the other hand, the 60 min profile manifests that the temperature increases by 10K up to y = 0.9 m. This result can be explained using the left dye photos of Fig. 5 as follows. Supplied hot water almost perfectly mixes with the cold inside water to increase the temperature (this temperature rise can be reconfirmed by the right thermal images), and the mixed region slowly proceeds upward. Interestingly, the thermal images show that there is a steep temperature jump (lower yellow lines in Fig. 5) on the lower boundary of the hot water region (red colored region in Fig. 5). These steep boundaries suggest that there is almost no mixing on the boundary and the overall fluid dynamic situation can be characterized as "piston flow." However, the flow due to the manifold shows a quite different flow pattern. Although manifold's profile of 0 min (see Fig. 4(b)) shows the same steep temperature gradient nearly identical to the diffuser at y = 0.9 m, the ensuing pattern is quite different from diffuser. The lower temperature profile maintained at 16°C does not significantly rise (see 15 to 60 min profiles of Fig. 4(b) for y = 0 to 0.9 m). This moderate temperature rise can be reconfirmed by the thermal images shown on the right temperature images presented in Fig. 6. However, the left dye photos explain the physical stratifying process. Apparently, a thin black dye cloud focused on y = 0.9 m (see dye photo of 0 min) slowly expands in an upward direction (see 0 through 60 min). This expansion is mainly due to the mass conservation; a water supply into the tank at y = 0.9 is balanced by the same amount removed through the upper pipe.

The fading black color on both lower and boundaries (left five dye photos, Fig. 6) corresponds to the temperature gradients shown in Fig. 4(b) (y = 0.9 to 1.2 m), which are clarified



(a) (b)

Fig. 5. Visualized diffuser's stratification performance: photos of flow progress (a); and instantaneous temperature distribution (b).



(a) (b)

Fig. 6. Visualized manifold's stratification performance: photos of flow progress (a); and instantaneous temperature distribution (b).

by the smearing yellow regions in the right thermal images at the later times. The comparatively lower temperature gradients provide evidence of turbulence from injected flow which is disrupting stratification within the tank.

The degree of stratification can be expressed in various ways. In this study, the manifold's stratification performance is quantified using following equations for the stratification coefficient, ST, and stratification ratio, R_{TS}, originally proposed by Wu and Bannerrot based on mean square deviation method [15].

$$ST = \frac{1}{m_{total}} \sum_{i=1}^{N} m_i \left(T_i - T_{avg}\right)^2 \tag{1}$$

$$R_{TS} = \frac{ST_t}{ST_0} \tag{2}$$

where m_{total}: total water mass inside the tank, N: number of horizontally sliced sections, i: identifies each section, T_{avg}: mass averaged tank temperature. ST_0 and ST_t are stratification coefficient at time 0 and t, respectively. As the extreme cases, $R_{TS} = 1$ and $R_{TS} = 0$ mean perfect stratification and perfect mixing, respectively.

Fig. 7 shows how R_{TS} degenerates during 60 minutes for no stratification device(×), diffuser (■) and manifold (▲). Diffuser's R_{TS} decreases faster than manifold's R_{TS} which suggests that manifold is more effective for stratification enhancement compared to the diffuser; 0.22 for diffuser, 0.38 for manifold at the 60 min time period. It is notable that there is almost no difference between operation without a stratification device and the diffuser, which means the diffuser has little effect to enhance the stratification in this particular experimental setup.

3.2 Effects of manifold's inner diameter D and number of surface holes n

In order to find the range of manifold diameters, D, where the manifold functions properly, a series of preliminary experiments were conducted at a constant flow rate of 0.3 lpm. The left photo of Fig. 8(a) reveals the injected flow pattern for too small D (4 mm); injecting holes widely ranges over and under the expected injection point ($y = 0.9$ m) for too small D. The static pressure inside the manifold is supposed to higher than the outside. On the other hand, the right photo reveals the injected pattern for too large D (28 mm); main injection occur-

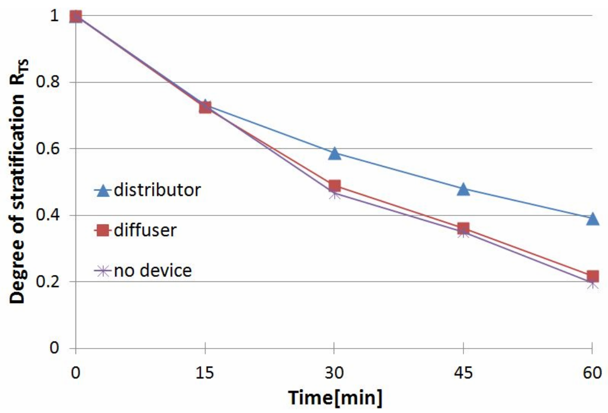
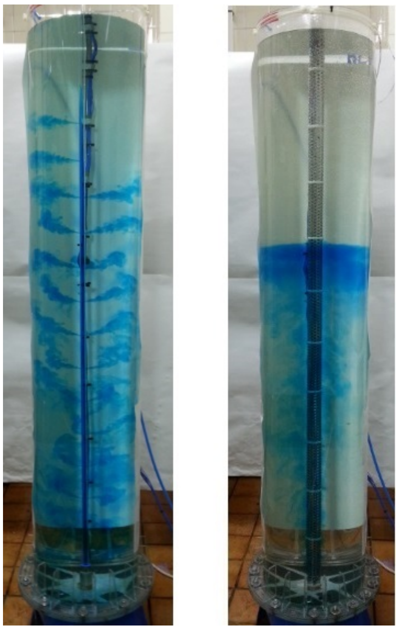


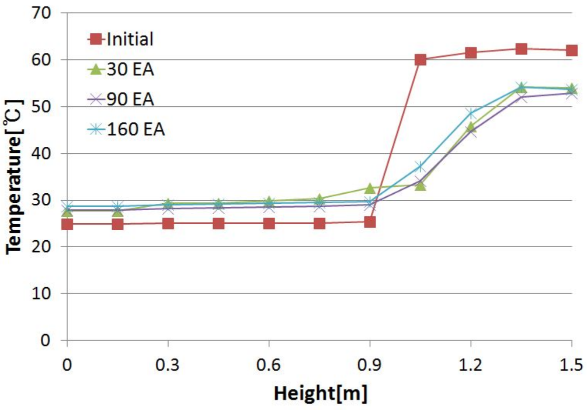
Fig. 7. Comparison of RTS between no device, manifold and diffuser.



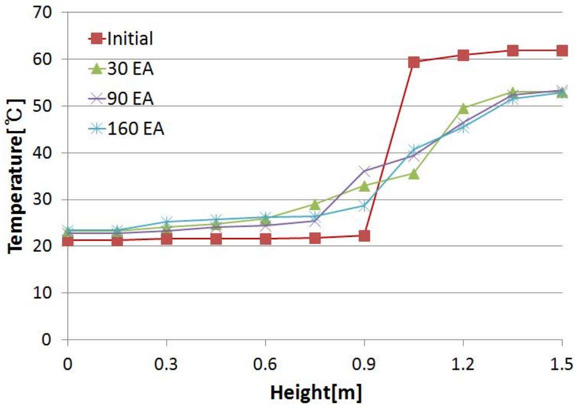
(a) Too small (b) Too large

Fig. 8. Injected flow patterns for too small and large manifold's diameter.

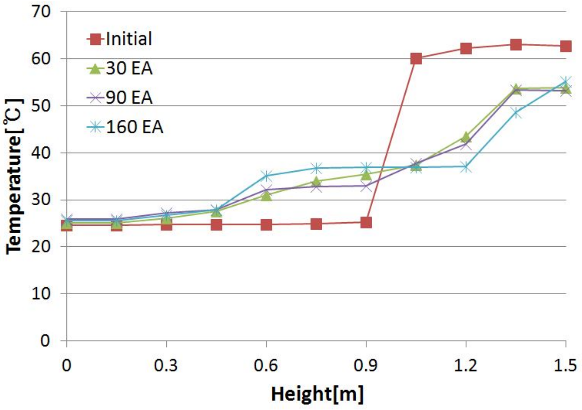
ring at $y = 0.9$ m and widely ranged injecting holes below $y = 0.9$ m. As the physical mechanism, it is supposed that cold water (16°C) penetrates into the manifold, and consequently, manifold's inside temperature quickly decreases down to the surrounding tank water to lose the buoyancy. Additional experiments suggests the proper D to be about 8 mm. In this context, we designed the previously mentioned experiments based on statistical two-way layout (see Table 1).



(a)



(b)



(c)

Fig. 9. Temperature profile variations according to D and n variations: (a) $D = 6$ mm; (b) $D = 8$ mm; (c) $D = 12$ mm.

Figs. 9(a)-(c) manifest how three number-of-hole n variations (30, 90, 160) changes the temperature profiles for three D's (6, 8, 12 mm) at the 60 min interval with initial state $t = 0$ min. The roughly overlapping graphs for varied range of n values considered indicate that n does not substantially affect the stratification. Higher temperatures at the 60 min period below $y = 0.9$ m is attributable to the foregoing buoyancy loss. The stratification ratio R_{TS} is calculated in order to estimate the D and n's quantitative effects on the stratification performance (see Table 1). $D = 8$ mm shows higher average R_{TS} of 0.40 compared to $D = 6$ mm (0.34) and $D = 12$ mm (0.29). However, n's effect is not recognizable for all the nine cases. Statistical analysis of variance interprets the above results such as D is significant and n is not significant (significance level = 0.05). The optimal condition is calculated to be hole diameter of $D = 8.6$ mm and number-of-holes $n = 96$, which is very

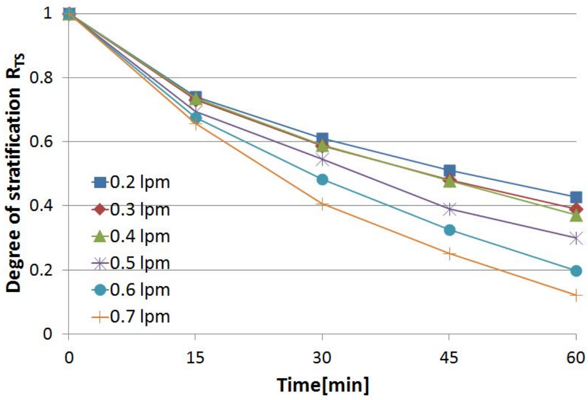


Fig. 10. Changes of RTS with flow rate variations.

close to the experimental D = 8 mm and n = 90. Of course, extremely high and low n are supposed to affect the stratification results.

3.3 Effect of flow rate

The flow rate was varied from 0.2 to 0.7 lpm to identify the best condition for the D = 8 mm and n = 90 diffuser design. Fig. 10 shows time-dependent R_{TS} variations. Three R_{TS} graphs of 0.2, 0.3, 0.4 lpm shows a close agreement whereas 0.5, 0.6, 0.7 lpm show recognizable R_{TS} degradations. Those degradations are attributable to the previously discussed widely ranging injecting holes (see Fig. 8(a)).

4. Conclusions

A lab-scale experimental study was performed to understand manifold's stratification performance in the solar water storage tank. The use of a manifold was shown to be more effective than diffuser to maintain tank stratification. The manifold's three key parameters; inner diameter, number of holes on the surface, and flow rate were evaluated to determine an optimal diffuser design. The optimal diffuser design is based on a statistical approach and quantitative analyses with the stratification coefficient as the response. The results showed that inner diameter of manifold and flow rate are influential on the stratification ratio. The statistical analysis resulted in the optimal condition of 8.6 mm of inner diameter and 96 surface holes under the flow rate of 0.3 lpm and temperature range between 16°C and 60°C. The results demonstrate that statistical experiments design can be a useful approach for the manifold design in an actual water storage tank.

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