Basics of

Thermal Stratification

In Solar thermal systems

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EYECULAR
Innovating Thermal Stratification

1. Introduction

Up through the 60ies and the 70ies, several scientific articles were written about the (at the time) newly discovered concept of low flow systems, with optimal flow rate of 0,2 $l/min/m^2$ solar collector. These systems could, as something new, efficiently build and maintain thermal stratification in solar thermal hot water tanks.

This was an alternative to the traditional systems of having high flow coil heat exchangers with a typical flow rate of 1,0 $l/min/m^2$ solar collector. These systems where and are still known for creating mixing of the thermal layers in tanks during the charging process.

It became apparent that thermal stratification can lead to longer operation hours and thus a significantly larger utilization of solar collectors, and thereby a reduction in the use and cost of auxiliary energy (Lavan & Thomsen, 1977), (Van Koppen et al., 1979).

Andersen and Furbo states that "the heat store of small solar heating systems is the most important component of the system, both from an economy point of view and from a thermal performance point of view" (Andersen & Furbo, 2008b).

This claim is supported by Shuklar et al. who state "The storage tank is an important component of the SWH system which plays a major role in dictating the system performance" (Shuklar et al., 2013).

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2. Thermal stratification

2.1 Due to heat loss

If not disturbed a hot water tank can over time become thermally stratified. Water close to thermal bridges such as tank walls, inlet and outlet connections, will lose heat to the surroundings and become cooler. Thermal dynamics due to density differences between hot and cold water, will establish thermal stratification throughout the storage tank (Fan and Furbo, 2012).

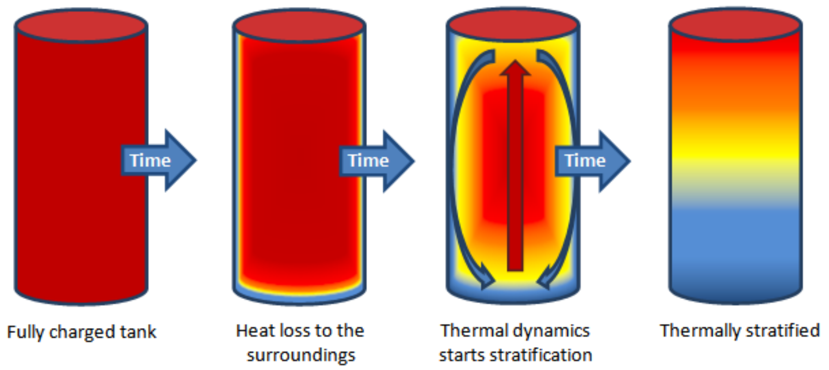

Figure 1: Hot water tanks can become stratified over time if not disturbed

2.2 During charging

When using conventional heating (oil, gas, district heating etc.), the water in the tank (top) is never warmer than the water coming from the heat source.

This may seem obvious, but it is an important statement, when comparing this to e.g. solar heating.

The stratification can be kept intact during heating by applying the heated water to the top of the tank, and drawing off the cold water (which is to be heated) from the bottom of the tank.

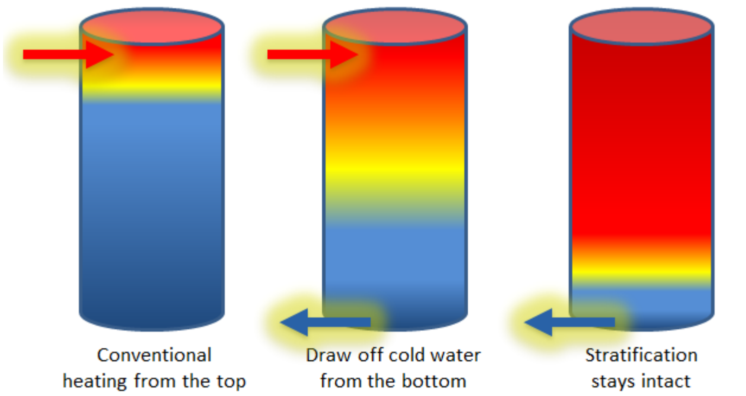

Figure 2: Stratification is kept intact by heating from the top

2.3 During discharging

When a tank is stratified, the water is always warmest at the top of the tank. Therefore, when discharging hot water for domestic use or space heating, the draw off is always done from the top part of the tank. Refilling will occur at the bottom of the tank to avoid thermal mixing.

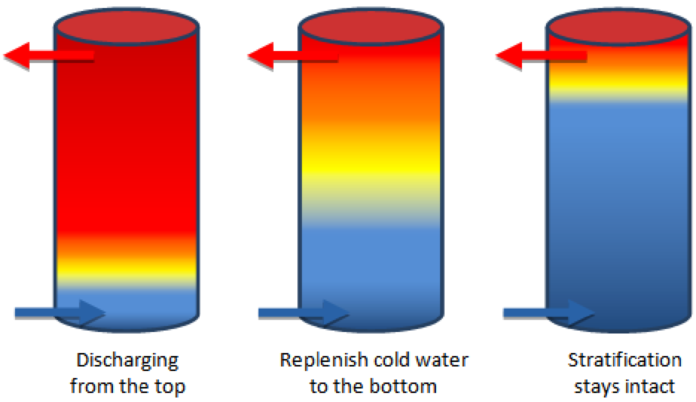

Figure 3: Stratification is kept intact during discharge

3. Solar thermal systems

A solar thermal system consists of three main components: Solar collector, storage tank and circulation pump as seen in figure 4.

When the temperature in the collector exceeds the temperature at the bottom of the tank, the pump starts to circulate the heat transfer fluid.

This way of controlling the pump was suggested and recommended by Close (1967) and is the prevailing method today.

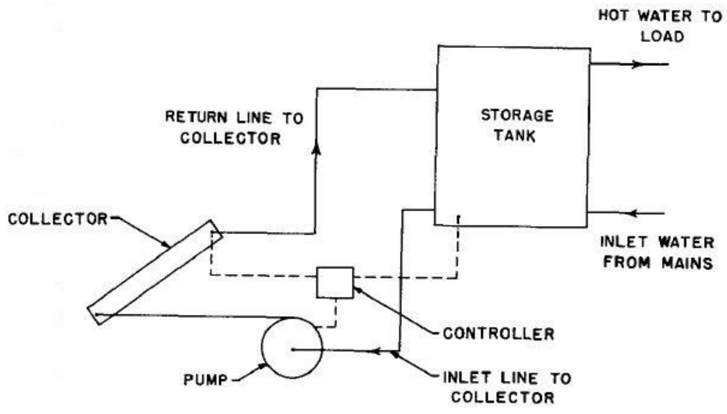

Figure 4: Solar thermal system (Close, 1967)

On the other hand, Close's suggestion of supplying the heated water to the top of the tank as seen for conventional heating in Figure 2, is outdated when working with solar energy. The most usual heat transfer method today is to supply the heated water to the bottom part of the tank, either in a coil heat exchanger, or a stratification device.

4. Advantages

There are several advantages by building and maintaining thermal stratification in hot water tanks. Here, five of the most significant ones for solar thermal systems, will be described:

1. Increased utilization of collectors
2. Reduced heat loss from equipment
3. Less lime scaling
4. Smaller tanks needed
5. More often comfort temperature

4.1 Increased utilization of collectors

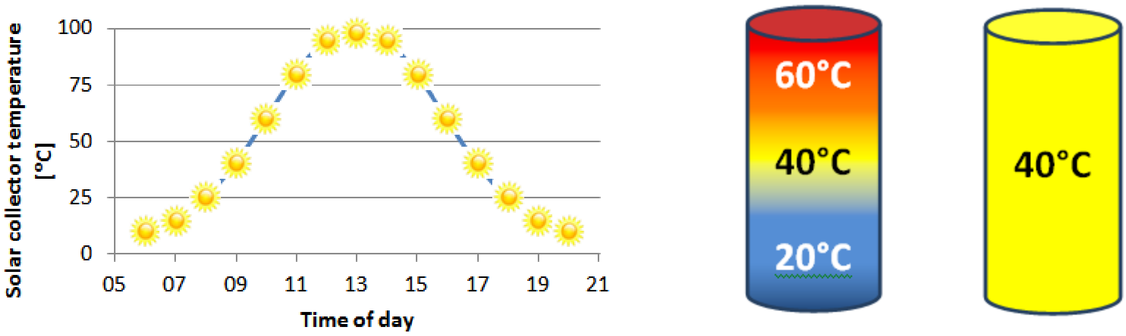

Figure 5: A mixed tank will start to be charged later in the day than a stratified tank

As explained earlier a solar collector starts to charge a solar tank when the temperature in the solar collector is higher than the temperature at the bottom of the tank. Above, a comparison between two tanks with the same quantity of energy is shown.

In the example the mixed tank will not be charged until the time of day when the solar collector temperature is higher than 40°C. The thermally stratified tank will start already when the collector has exceeded 20°C.

The solar thermal system will start to store energy earlier in the morning, and continue until later in the afternoon, when the storage tank is stratified rather than mixed. Consequently, the utilization of the solar system increases when the tank is stratified, and the use and cost of auxiliary energy drops accordingly.

4.2 Reduced heat loss from equipment

The water from the solar thermal tank is circulated through several meters of piping, both to and from the solar collector outside the building. The lower the temperature of the circulated water is, the lower the heat loss from the system will be.

The temperature at the bottom of a thermally stratified tank is significantly lower than the bottom temperature in a comparable mixed tank. Consequently, a stratified tank results in a lower average circulation temperature, and thereby results in a lower heat loss from the system than as seen for a mixed tank.

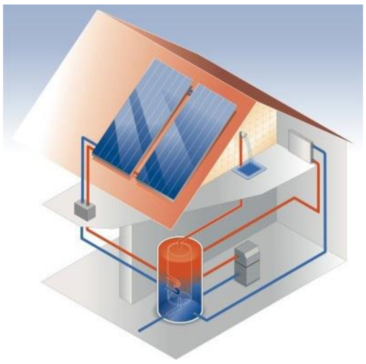

Figure 6: Solar thermal system (selaenergy, 2013)

When having a significant cold side of the circulation system, it is possible to install poorly isolated equipment such as expansion tanks, valves etc. on the cold side, and further reduce the overall heat loss.

Additionally, circulation pipes with smaller diameters can be applied in a low flow system, compared to conventional high flow systems. This also reduces the collective heat loss from the system (alongside the cost of piping).

All reductions of heat loss decreases the use and cost of auxiliary energy.

4.3 More often comfort temperature

Domestic hot water is obtained by mixing hot water from the top of a tank, and cold water from the water supplier.

If the temperature at the top of the tank is not high enough to provide the needed comfort temperature, the auxiliary heat has to turn on and supply heat to the top part of the tank.

The average temperature at the top of a stratified tank is generally higher than in a comparable mixed tank. Thus, the comfort temperature is more often available in a stratified tank.

Therefore, the use and cost of auxiliary heat will be less for a stratified tank, when compared to a mixed tank.

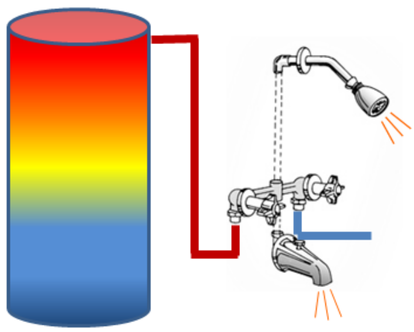

Figure 7: Hot and cold water is mixed to comfort temperatures

4.4 Less lime scaling

In the lifetime of a hot water tank, the water consumption and following the volume of circulated through a thermally stratified tank - is less - compared to a mixed tank. The reason is that the temperature in the top part of a stratified tank as well as the outlet from the tank is higher, and therefore less volume of hot water is needed in order to supply a certain comfort temperature.

The additional consumption of water from a mixed domestic hot water tank, and following the additional refilling of lime containing fresh water, will increase the lime scaling in the tank. Scientific studies indicates that the lime scaling in a low flow system can be 2,5 times less, than in a comparable mixed tank (Furbo, 2004).

4.5 Smaller tanks are needed

As argued above, the higher the temperature is in the top part of the tank, the less volume of hot water is needed in order to supply a certain temperature.

Therefore, smaller (and cheaper) tanks can be applied to a certain system offering the some comfort, when the tank is thermally stratified, compared to a mixed.

Furthermore, the reduced volume of circulated water in a thermally stratified tank, will cause less disturbance of the thermal layers, and therefore further enhance the stratification of the tank.

5. Quantification

There are many factors influencing both the efficiency of a solar thermal system, and the quantitative advantages from obtaining thermal stratification. Below are some of these factors:

- Height/ diameter ratio of tank
- Thermal bridges in the top part of the tank
- Tank insulation
- Tank design
- Flow rates
- Stratification enhancers
- Solar fraction of the system

Figure 8 gives an example of the correlation between the performance ratio and the solar fraction.

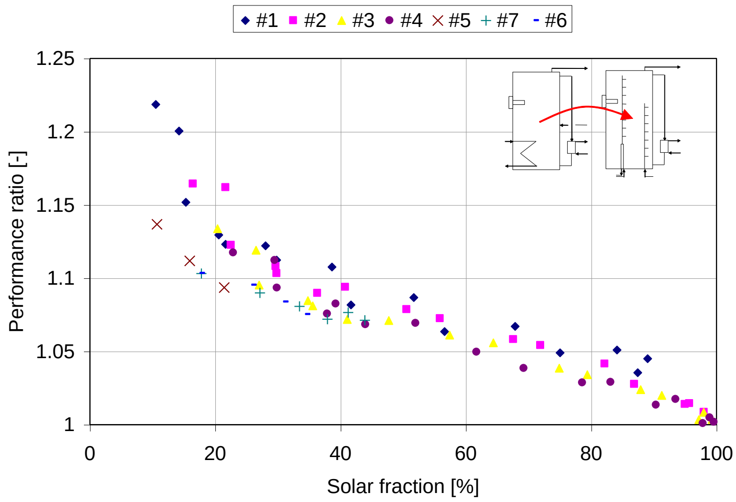

Figure 8: Performance ratio as a function of solar fraction (Andersen and Furbo, 2008a)

It becomes obvious that the improved performance through stratification is closely connected to e.g. the solar fraction, and it can be misleading to give an exact percentage of performance improvement, without detailing the solar fraction also. Consequently, performance improvement is often indicated in intervals.

A brief overview of previous studies on performance improvement as a result of thermal stratification in solar applications can be seen below:

- Duffie & Beckman 1974 9 % (Sharp & Loehrke, 1979)
- Davis & Bartera 1975 10 % (Zurigat & Ghajar, 2002)
- Van Koppen et al. 1979 5 % – 10 %
- Sharp & Loehrke 1979 5 % – 15 %
- Veltkamp 1981 10 % – 20 %
- Cole & Bellinger 1982 5 % – 20 %
- Wuestling et al. 1985 12 % – 15 %
- Hollands & Lightstone 1989 38 %
- Furbo 2014 10 % – 25 % (PhD course, 2014)

Improvements are calculated in relation to the percentage of the heating demand covered by solar thermal energy, with and without thermal stratification in the storage tank (Sharp & Loehrke, 1979).

6. Disturbance

There can be great challenges in building and maintaining thermal stratification in a solar thermal system. Three topics are of most relevance to this paper:

1. Variable inlet temperatures
2. Variable height of a specific thermal layer
3. Heating from the bottom of the tank

6.1 Variable temperatures

The temperature of water from a solar collector, and thus the inlet temperature into a solar storage tank, range from 20°C – 100°C as indicated in Figure 9.

If water at 20°C enters a stratified tank at the top part, this cooler water will push its way downwards towards the bottom of the tank, and the thermal stratification will be disturbed.

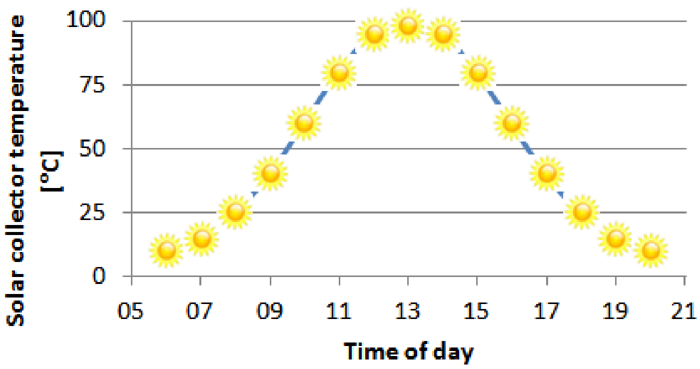

Figure 9: Example of solar collector temperature as a function of the time of day.

If 100°C hot water enters a stratified tank at the bottom part, the water will be pushed upwards towards the top the tank, and the thermal stratification will also be disturbed.

The challenge is that the thermal layer, appropriate to the inlet water, differs according to the variable inlet temperature as well as the temperature profile inside the tank.

6.2 Variable height

Water in space heating loops can be circulated back to a solar thermal storage tank. In larger systems, the domestic hot water is also circulated and returned to the storage tank.

The temperature of the water in these return inlets does not necessarily vary a great deal. However, the temperature profile inside the tank can vary a lot, which results in the appropriate thermal layer for the returning water being at different heights. E.g., the return water may be rather stable between 40ºC - 50ºC but the equivalent thermal layer inside the tank can be close to the bottom or close to the top, depending on how much and how well the energy is stored in the tank, as seen in Figure 10.

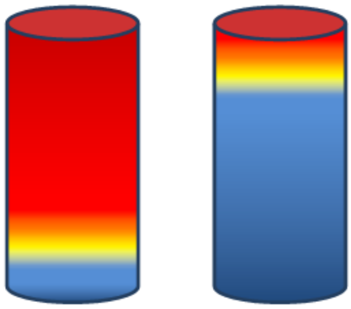

Figure 10: Thermal layers in different heights

If the returning water enters the tank in a thermal layer with a temperature different to that of the returning water, the thermal stratification will be disturbed.

6.3 Heating from bottom

Many solar storage tanks has a coil heat exchanger installed in the lower part of the tank as seen in Figure 11.

When this type of technology heats up a stratified tank, the heated water will be pushed up towards the top the tank, and the thermal stratification will can be disturbed.

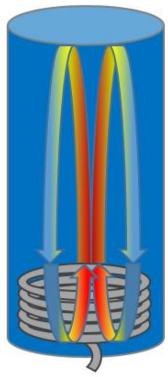

Figure 11: Tank heated from the bottom

7. Discussion

The qualitative impact on performance improvement due to thermal stratification seems to be well documented through numerous scientific researches. The quantitative determinations for the solar thermal area, however, are not aligned in absolute numbers.

The development in perceptions appears to entail an increase of the possible performance improvements due to thermal stratification. In the 70ies, the general perception was 5 – 10 % while in the 80ies it had become 10 - 20 % (leaving Hollands & Lightstone (1989) out of the account).

The most recent assessment of performance improvements indicates a potential of up to 10 – 25 % (PhD course, 2014).

A 10 – 25 % performance therefore appears to be a reliable interval when discussing the possible performance improvements associated with establishing thermal stratification. The large potential does indeed justify the application of stratification enhancers in commercial hot water storage tanks.

8. References

Abu-Hamdan, M. G. ; Zurigat, Y. H. & Ghajar, A. J. (1992). An experimental study of a stratified thermal storage under variable inlet temperatures for different inlet designs. *Int. J. Heat Mass Transfer. Volume 35, Issue 8, pp. 1927-1934.*

Adams, D. E. ; Davidson, J. D. (1993). Tank stratification with a flexible manifold. *Proceedings of Solar '93, the 1993 American Solar Energy Society Annual Conference.*

Andersen, E & Furbo, S. (2008a). Inlet stratification device, proof-of-concept report.

Andersen, E. & Furbo, S. (2008b). Heat storage for solar heating systems - now and in the future. *Proceedings of Conference on Thermal Storage, Prague, Czech Republic.*

Andersen, E. (2007). Solar combi systems. *DTU Civil Engineering, DTU Tryk*

Andersen, E. ; Furbo, S. & Fan, J (2007). Multilayer fabric stratification pipes for solar tanks. *Journal of Solar Energy, Volume 81, Issue 10, pp. 1219-1226*

Castell, A. ; Medrano, M. ; Solé, C. & Cabeza, L. F. (2010). Dimensionless numbers used to characterize stratification in water tanks for discharging at low flow rates. *Renewable energy, Volume 35, Issue 10, pp. 2192-2199*

Close, D. J. (1967). A design approach for solar processes. *Solar Energy, Volume 11, Issue 2, pp. 112-122*

Cole, R. L. & Bellinger, F. O. (1982). Thermally stratified tanks. *ASHRAE Transactions, Volume 88, pt 2, pp. 1005-1017*

Davidson, H.H. ; Adams, D. A. & Miller, J. A. (1994). A coefficient to characterize mixing in solar water storage tanks. *Journal of solar energy engineering - transactions of the ASME, Volume 116, Issue 2, pp. 94-99*

Davidson, J. H. & Adams, D. A. (1994). Fabric stratification manifolds for solar water heating. *Transactions of the ASME. Journal of Solar Energy Engineering, Volume 116, Issue 3, pp. 130-136*

Fan, J. & Furbo, S. (2012). Thermal Stratification in a hot water tank established by heat loss from the tank. *Solar energy, Volume 86, Issue 11, pp. 3460-3469*

Fanney, A. H. & Klein, S. A. (1988). Thermal performance comparisons for solar hot water systems subjected to various collector and heat exchanger flow rates. *Proceedings of the Ninth Biennial Congress of the International Solar Energy Society, Volume 1, pp. 538-543*

Furbo, S. (2004). Low flow solar heating systems. *Educational note: Byg DTU U-067 (ISSN 1396-4046)*

Gari, H. N. & Loehrke, R. I. (1982). A controlled buoyant jet for enhancing stratification in a liquid storage tank. *Journal of fluids engineering - transactions of the ASME, Volume 104, Issue 4, pp. 475-481*

Haller, M. Y. ; Cruickshank, C. A. ; Streicher, W. ; Harrison, S. J. (2009). Methods to determine stratification efficiency of thermal energy storage processes – Review and theoretical comparison. *Solar Energy, Volume 84, Issue 6, pp. 997-1007*

Haller, M. Y. ; Yazdanshenas, E ; Andersen, E ; Bales, C. ; Streicher, W. and Furbo, S. (2010). A method to determine stratification efficiency of thermal energy storage processes independently from storage heat losses. *Solar Energy, Volume 84, Issue 6, pp. 997-1007*

Han, Y. M. ; Wang, R. Z. & Dai, Y. (2009). Thermal stratification within the water tank. *Renewable and sustainable energy reviews, Volume 13, Issue 5, pp. 1014-1026*

Hollands, K. G. T. & Lightstone, M. F. (1989). A review of low-flow, stratified-tank solar water heating systems. *Solar Energy, Volume 43, Issue 2, pp. 97-105*

Kline (1985), Promising control alternatives for solar water heating systems. *Journal of solar energy engineering - transactions of the ASME, Volume 107, Issue 3, pp. 215-221*

Lavan, Z. & Thomsen, J. (1977). Experimental study of thermally stratified hot water storage tanks. *Solar energy, Volume 19, Issue 5, pp. 519-524*

Loehrke, R. I. ; Holzer, J. C. ; Gari, H. N. & Sharp, M. K. (1979). Stratification enhancement in liquid thermal storage tank. *Journal of energy, Volume 3, Issue 3, pp. 129-130*

Panthalookaran, V. ; Heidemann, W. & Mueller-Steinhagen, H. (2007). A new method of characterization for stratified thermal energy stores. *Solar energy, Volume 81, Issue 8, pp. 1043-1054*

PhD course (2014). Heat storage for solar heating systems. Lyngby: *Department of Civil Engineering, Technical University of Denmark.*

Selaenergy (2013). Retrieved 2013.16.011 from *Selaenergy.com*

Sharp, M. K. & Loehrke, R. I. (1979). Stratified thermal storage in residential solar energy applications. *Journal of energy, Volume 3, Issue 2, pp. 106-113*

Sheridan, N. R. ; Bullock, K. J. & Duffie, J. A. (1967). Study of solar processes by analog computer. *Solar Energy, Volume 11, Issue 2, pp. 69-77*

Shuklar, R. ; Sumathy, K. ; Erickson, P. & Gong, J. (2013). Recent advances in the solar water heating systems: A review. *Renewable and Sustainable Energy Reviews, Volume 19, pp. 173-190*

Van Koppen (1979). Patent application. Retrieved 2014.08.02 from *http://www.google.com.ar/patents/US4420032*

Van Koppen, C. W. J. ; Simon Thomas, J. P. & Veltkamp, W. B. (1979). The actual benefits of thermally stratified storage in a small and a medium size solar system. *Electric Power Research Institute (Report) EPRI EA, pp. 576-580*

Veltkamp, W. B. (1981). Thermal stratification in heat storages. *Thermal Storage of Solar Energy: Proceedings of an International TNO-Symposium, pp. 47-59*

Wang, S. & Davidson, J. D. 2014). Performance of rigid porous stratification manifolds. *Journal of Solar Energy Engineering - Transactions of the ASME, Volume 136, Issue 2, pp. 021021-1 - 021021-7*

Wuestling, M.D. ; Klein, S. A. & Duffie, J. A. (1985). Promising control alternatives for solar water heating systems. *Journal of solar energy engineering - transactions of the ASME, Volume 107, Issue 3, pp. 215-221*

Yee, C. K. ; Lai, F. C. (2001). Effects of a porous manifold on thermal stratification in a liquid storage tank. *Solar energy, Volume 71, Issue 4, pp. 241-254*

Zurigat, Y. H. & Ghajar, A. J. (2002). Chapter 6: Heat transfer and stratification in sensible heat storage. In: Dincer, I. & Rosen, M. (eds.), Thermal energy storage - Systems and applications. New York: *John Wiley & Sons, pp. 264 270.*