Literature study

How is the thermal performance of solar heating systems influenced by thermal stratification in the heat storage

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1 Introduction

1.1 Aim

The aim is to study the influence of stratification on thermal performances in solar water heating systems incorporating sensible heat storage tanks.

1.2 Objectives

The objectives are to undertake a literature review in order to:

- Give an overview of the studies that have been carried out so far on thermal stratification in sensible heat storage;
- Introduce to different methods of stratification in thermal storage;
- Show how stratification may affect the performances of the overall system.

These objectives lead to the following research questions, which form the structural basis for this paper:

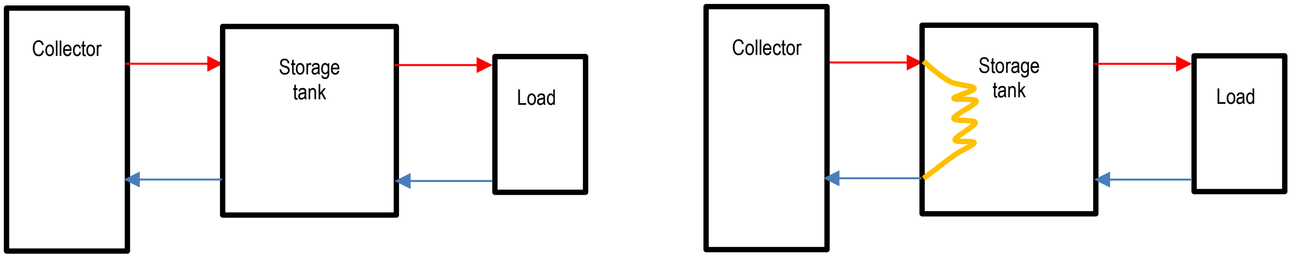
1. Why is thermal stratification important to solar water heater performance?
2. How is thermal stratification quantified?
3. How is solar water heater overall system performance quantified?
4. How is thermal stratification achieved and maximised?
5. What factors cause destratification and how can they be minimized?
6. How do the performances of stratified and non-stratified solar water heater system compare?

1.3 Solar water heating systems overview

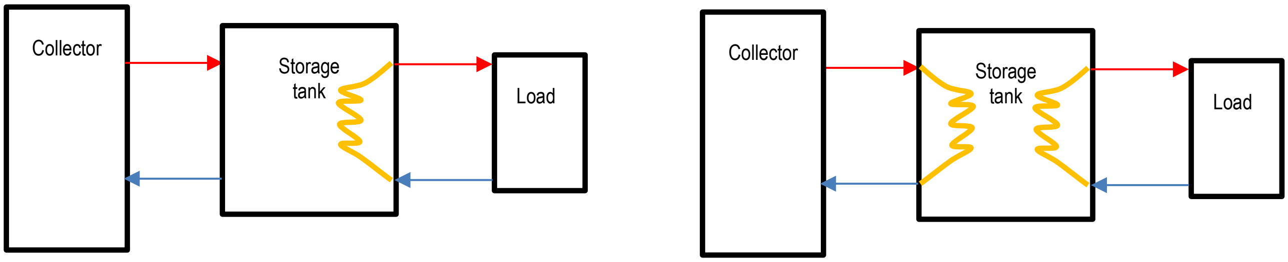
There are many different types of solar water heating systems (SWH). All systems consist of a collector (or an array of collectors) and a load such as a domestic hot water system, a space heating system, or an industrial process. Solar energy is only available during daytime and its intensity is variable dependent upon time of day, time of year and cloud cover. Hot water loads are also variable and demand is usually temporally mismatched with solar energy availability. For this reason, SWH systems usually include a thermal storage tank.

1.3.1 Tank and heat exchanger arrangements

Hot water storage tank arrangements can be broadly classified (see Kalogirou, 2009) as being either direct (open loop) systems or (indirect) closed loop systems. Direct systems involve the same water being heated within the collector, stored in the tank, and delivered to the load. In indirect systems the working fluid passing through the solar collector is separated from the potable hot water by means of one or more heat exchangers. Figure 1.1 shows the four main possibilities for SWH system configurations.



a) Open loop – open loop b) Closed loop – open loop



c) Open loop – closed loop d) Closed loop – closed loop

Figure 1.1: Solar hot water system configurations

Closed loop systems tend to involve increased capital cost for heat exchangers but offer benefits in respect of sanitary requirements (eg controlling risk of bacterial growth in the storage tank which could contaminate the potable water) and prevention of damage to collectors in cold climates (eg by using antifreeze chemicals in the collector loop).

Auxiliary heating such as electrical resistance heaters, combustion boilers (gas, oil or biomass), or heat pumps are typically incorporated into SWH systems to provide heat when the available solar energy is insufficient to meet demand.

1.3.2 Passive and active systems

Each of the SWH system types shown in Figure 1.1 can be either passive, active or a hybrid. The terms passive and active distinguish the systems in the context of the method of achieving fluid flow circulation in the system (Kalogirou, 2009).

Active systems utilised mechanical pumps to circulate water through the collector loop and to deliver hot water to the load.

Passive systems utilise natural thermosiphonic (natural convection) effects in order to induce flow around the solar collector loop. The flow rates are determined by the temperature difference in the system and are typically quite low. Passive systems often incorporate a raised cold water tank in order to use gravity to supply hot water to the load. Integrated-collector-storage (ICS) systems are a special type of passive system whereby the solar collector is incorporated into wall of the storage tank, thus removing the need for a separate collector pipework loop.

This study focuses primarily on active SWH systems for small scale applications such as domestic hot water and space heating in dwellings. Passive systems have not been examined in detail although the importance of stratification in these systems is briefly discussed. Solar air heating systems have not been examined.

1.4 Definition of thermal stratification

Thermal stratification is defined as the state when the local store temperature is a function of the vertical store height, with the temperature decreasing from top to bottom (prEN 12977-3:2008).

1.5 Sanitary considerations

There are a number of references in the literature concerning possible sanitary and public health issues associated with stratified tanks owing to the occurrence of relatively stagnant zones of water being stored at temperatures conducive to the rapid growth of bacteria such as Legionella. Consideration of sanitary risks is beyond the scope of the present study, but the reader is referred to Armstrong (2014) which gives an overview of some of the issues.

2 The importance of stratified heat storage

This section aims to answer the first research question: Why is thermal stratification important to solar water heater performance?

In solar thermal stores, the cold water from the lower temperature section circulates through the collectors, heated by solar radiation and returns to the storage tank. If the hot water is allowed to mix with the cold water in the tank, the supplied temperature to the load is lowered and the useful quality of energy is degraded. Mixing results also in an increased temperature in the lower part of the tank, so that the efficiency of solar collector decreases and heat losses from the bottom of the tank increase.

The decay of performance that occurs in non-stratified tanks was investigated by Andersen and Furbo (1999). They looked at the mixing effect that occurs in hot water tank during draw-off. Figure 2.1 shows that circa 51% of the lower part of the store has a temperature below 30°C. However, authors remark that the extension of the mixing zone depends on the flow rate during draw-offs.

Stratified thermal storage can minimise both installation and running costs. In fact, due to better temperature stratification in the tank, heat losses to the environment are reduced, and so too are the insulation costs. Furthermore, the auxiliary energy consumption can be reduced by the lower running time of the auxiliary heater. In low flow pumped systems, low flow rates permit higher temperature at the collector outlet, and if the tank is stratified, higher temperature differences across the solar loop can be achieved. The advantages of these systems are quite significant compared to systems with mixed tanks, as reported in Van Koppen et al., (1979) Wuestling et al., (1985) and Hollands and Lightstone, (1989). The latter authors remark that the degree of improvement depends on load pattern and the real degree of stratification.

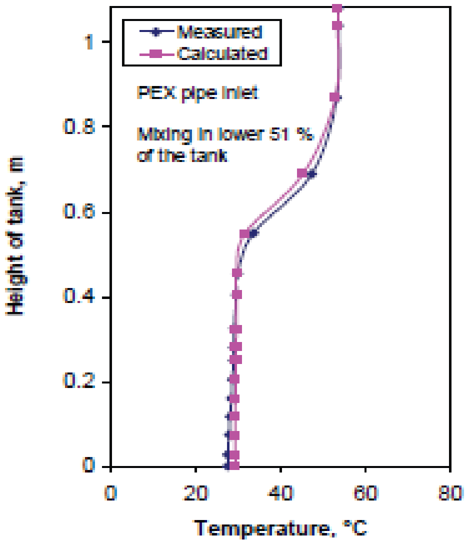


Figure 2.1: Andersen and Furbo, (1999) measured and calculated temperature profiles after 20 L draw-offs with volume flow rates of 20 L/min

Hollands and Lightstone (1989) give a simple example illustrating the influence which hot water draw-off has upon the performance of heat storage in stratified tanks versus fully mixed tanks:

> *"Suppose the total night time draw-off is equal to one tank volume and that it occurs in two separate, equal draw-offs. The tank is… uniformly heated to a high temperature TH during daylight hours. After the first draw-off the bottom half will be at TL and the top at TH. In the fully mixed model these will be mixed to produce a tank uniformly at (TH+TL)/2. This process repeats after the second draw-off… the tank will be uniformly at (TH+3TL)/4, which is hotter that the stratified tank, now uniformly at TL, the thermal front having now reached the top… At the start of the next day… the well-mixed system will be sending water at a higher temperature to the collectors, and, since collector efficiency falls off with increasing temperature, the mixed tank system will deliver less energy".*

In conclusion, the importance of stratification is linked to:

- reduction of mixing effect during draw-offs;
- increase of the efficiency of collectors;
- reduction of the auxiliary consumption;
- limitation of storage heat losses;
- reduction of installation and running costs (especially for low flow systems).

3 Quantification of stratification and destratification

This section aims to answer the second research question: How is thermal stratification quantified? To answer this question, many performance parameters (or indices) have been encountered in during the literature review. Some of them are listed below.

The ***Stratification number*** evaluates the thermal stratification of the water inside the tank. In Fernández-Seara et. al. (2007) the authors define the stratification number as the ratio of the mean of the temperature gradients at any time to the maximum mean temperature gradient for the discharging/charging process. A similar definition (referred to as stratification index) was also used Gnafakis and Manno (1989). This was later also used by Smyth, Eames and Norton (1999).

The ***decay rate of stratification*** was defined by Shyu et al., (1989) as the ratio of temperature gradient at a given time to that of zero time in the initially stratified region. Gnafakis and Manno (1989) used a similar dimensionless time measure defined as the time taken for the stratification index to decrease to $0.37e^{-1}$ of its initial value.

In Phillips and Dave, (1982) the ***stratification coefficient*** is defined as the ratio of the actual useful energy gain to the energy gain that would be achieved in a fully mixed tank. The stratification coefficient is equal to 1 for a completed mixed tank. An inverted version of this parameter referred to as heat extraction efficiency (whereby a value of 1 corresponds to an ideal stratified tank) was used by Lavan and Thompson (1977).

The ***MIX*** number is defined in both Davidson et. al.(1994) and Andersen and Furbo (1999). The difference between them is the time which the reference condition refers to. Davidson et. al. (1994) refers to the initial condition whether Andersen and Furbo (1999) refer to the previous time step. The MIX number is based on the energy distribution level in the tank (reader is referred to Davidson et. al.(1994) and Andersen and Furbo (1999)).The MIX number is equal to 1 for fully mixed tanks. Garcia-Mari et. al. (2013) used an inverted version of the MIX number whereby a value of 1 corresponds to an ideal stratified tank.

Fernández-Seara and Sieres (2007) and Rosen et. al. (2004) showed the importance of using exergy efficiency to evaluate performances of thermal storage. Indeed, the temperature at which the energy is stored in the tank is highly relevant for system comparisons. Other performance parameters have been used by authors Haller et. al. (2009) and Dincer and Rosen, (2002).

Despite many definitions being available in the literature, the most common way to quantify stratification is plot temperature and/or temperature gradient along the tank. In Rosen et. al. (2004) for example, authors use the ***three-zone temperature-distribution model*** which represents the temperature distributions in vertically stratified thermal storage zones. The temperature varies linearly within each zone, and continuously across each zone. Figure 3.1 summaries both general and basic model; the second one is given for engineering purposes.

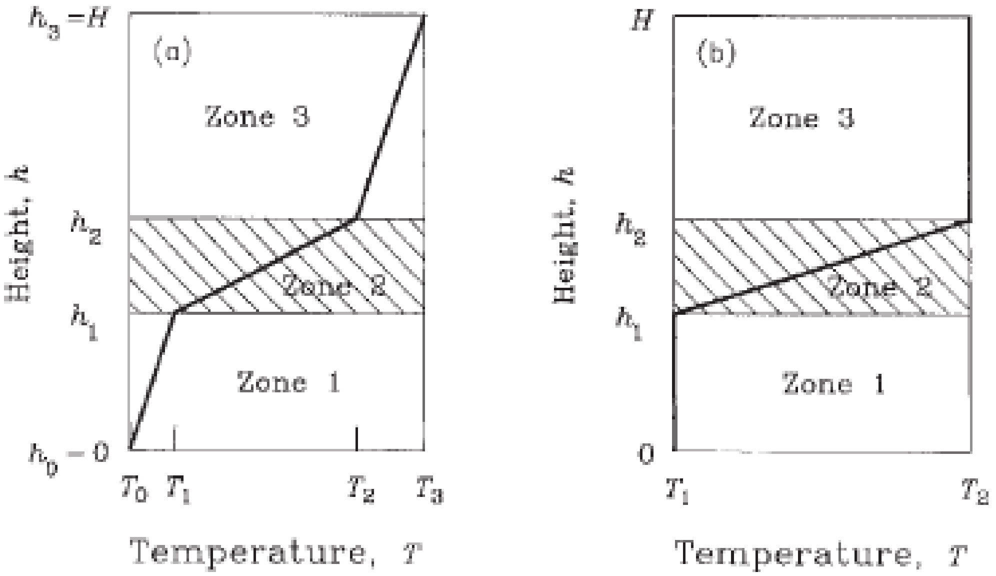


Figure 3.1 Rosen et al. (2004) – Three zone temperature distribution model

Andersen and Furbo (1999) describe stratification using dimensionless temperature distributions. This way of presenting the temperature profiles eliminates small differences in the temperature profiles at the start of the draw-offs and in the cold-water temperatures from one test to another when comparing results of tests on tanks operating over different temperature ranges. Likewise, the use of dimensionless tank height, dimensionless flow rates and dimensionless time allow similar comparisons between dissimilar test conditions.

In conclusion, the quantification of stratification can be achieved by using a variety of different performances parameters. However, the most common way to quantify stratification is by plotting temperature and/or temperature gradient along the tank.

4 Quantification of system performance

This section aims to answer the third research question: How is solar water heater overall system performance quantified?

Many studies available in literature use the definition of fractional savings to quantify and compare the performance of systems. ***Fractional savings***, according to prEN 12977, compares the gross energy demand of the auxiliary heater of the solar heating system to the gross auxiliary energy demand of a conventional heating system.

Jordan and Vajen (2001) investigated the influence of domestic hot water (DHW) flow rate on fractional energy savings. The authors included in the definition of fractional savings the contribution of electric energy of pumps (both for collector and DHW loops) since this can be affected significantly by flow rate.

An overview of other definitions and performance indices is listed in Table 4.1. Haller, M. (2012) defines seasonal performance factor for solar combisystems as per Equation 4.2, where $Pel,_{SHP}$ represent the annual energy (kWh) consumption of the whole system.

$$Pel,SHP = Pel,HP + Pel,SC + Pel,EH + Pel,PU + Pel,Ctr \qquad \textit{(Equation 4.1)}$$

$$SPF_{SHP} = \frac{\int (Q\dot{}_{SH} + Q\dot{}_{DHW}).dt}{\int P_{el,SHP}.dt} \qquad \textit{(Equation 4.2)}$$

Reference	***Parameter***	***Definition***
Andersen and Furbo (1999)	***Net utilized solar energy***	The tapped energy minus the energy supplied from the auxiliary energy supply system.
Andersen and Furbo (1999)	***Performance ratio***	The ratio between the net utilized solar energy for the system with the inlet and volume flow rate in question, divided by the net utilized solar energy for the system used as the reference for comparison.
Jordan and Furbo (2005)	***Performance reduction***	It is defined as the difference of auxiliary energy supply of the investigated SDHW system, compared to the auxiliary energy supply of a reference system (system with inlet height equal to zero).

Bales and Persson (2003)	***Auxiliary energy corrected***	$Q_{\mathrm{aux,corr}} = Q_{\mathrm{aux}} \cdot \left(1 - \frac{Q_{\mathrm{load}} - Q_{\mathrm{load,nom}}}{Q_{\mathrm{load,nom}}}\right)$

5 Design of stratified storage tanks

5.1 Main factors affecting stratification performance

The development and maintenance of thermal stratification in sensible heat storage tanks is affected by the following factors, each of which is discussed in more detail below with reference to the literature:

- Tank shape, in particular the aspect ratio.
- Thermal conductance of tank walls in the vertical direction (heat transfer between strata).
- Thermal conductance of the tank walls in the horizontal direction (heat loss to ambient environment).
- Heat inputs and outputs, namely fluid inlets and outlets for open loop systems, or heat exchangers for closed loop systems:
    - Location;
    - Temperature;
    - Fluid velocities and associated convection flow patterns.
- Baffles and obstacles located within the tank.

5.2 Storage vessel size and shape

The majority of studies encountered in the literature consider cylindrical tanks, but some have also investigated rectangular tanks, such as Gnafakis and Manno, (1989) Andersen, Furbo and Fan (2007). None of the studies encountered in the present review make direct comparisons between cylindrical and rectangular tanks. However, there is a broad consensus in the literature that the aspect ratio of the tank is a key parameter affecting the quality of stratification.

In cylindrical tanks the aspect ratio is defined as the ratio of tank height (H) to diameter (D) is of particular importance. Lavan and Thompson (1977) examined the relationship between aspect ratio and heat extraction efficiency (η) as shown in Figure 5.2. Lavan and Thompson developed an expression (Equation 5.1) for predicting extraction efficiency based on aspect ratio along with the Reynolds number of the inlet (Re) and the Grashof number (Gr) based on tank diameter.

$\eta = 1 - e^{-0.067 Re^{-0.55} Gr^{0.35} (H/D)^{0.58}}$ *(Equation 5.1)*

Heat extraction efficiency (η) in this case takes the usual form of "energy out divided by energy available" where the former is represented by the product of tank volume and the inlet/outlet temperature difference at the beginning of a draw-off, and the latter is represented by the draw-off volume and the inlet/outlet temperature difference at the end of the draw-off. This definition of heat extraction efficiency is intrinsically related to the degree of stratification in the tank.

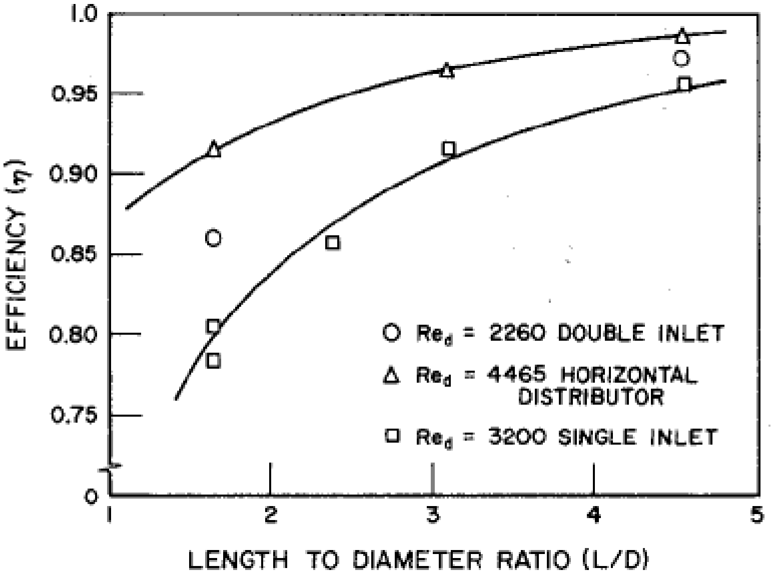


Figure 5.1: Relationship between heat extraction efficiency and tank aspect ratio, courtesy of Lavan and Thompson (1977).

Figure 5.1 suggests that a reasonable degree of stratification is achievable with an aspect ratio of 3 to 4, and that there is diminishing benefit to be gained from increasing aspect ratio beyond 5. Visual observations using coloured dye during Lavan and Thompson's experiments showed that significant mixing occurred within the bottom part of the tank up to a height equal to one tank diameter.

5.3 Storage vessel wall material and insulation

Murthy, Nelson and Rao (1992) examined stratification in three identical sized tanks constructed of different metals (1mm aluminium, 2.4mm mild steel, and 1mm mild steel) characterised by Biot numbers (3.7h, 5.9h and 14.1h respectively), according to Equation 5.2 where k (W/mK) and h (W/m^{2}K) are the thermal conductance and conductivity respectively, d is the tank wall thickness, and H is the tank height.

$$Biot\ number = \frac{hH^2}{kd} \qquad \text{(Equation 5.2)}$$

Murthy, Nelson and Rao's experimental results demonstrate that tanks with high Biot numbers result in the highest degree of achievable stratification and maintain this stratification for a longer time. The low Biot number tanks allow heat transfer between the strata (high thermal conductance in the vertical direction) which leads to destratification.

In addition to the vertical direction wall conduction effects, convection currents originating at the tank walls also cause destratification. These convection currents are generated by buoyancy effects, typically:

- Water in a lower strata being heated and becoming less dense (causing it to rise) due to vertical transfer of heat through the wall from an upper strata.
- Water in an upper strata being cooled and becoming more dense (causing it to sink) due to vertical transfer of heat through the wall into a lower strata.
- Water in an upper strata being cooled and becoming more dense (causing it to sink) due to heat lost through the wall to the ambient environment. The importance of this effect has been highlighted by several other authors. Gnafakis and Manno (1989) showed that heating the side walls in the upper region of the tank helped to stabilize the stratification.

Based on the above, it can be concluded that, in order to maximise thermal stratification, the walls of the storage vessels should have a low thermal conductance. The best way to achieve this is by constructing the tank from a material of low thermal conductivity, such as a polymer (see Rhee et. al. 2010), and by making them as thin as possible. However, the mechanical and structural requirements for large volume tanks typically favour metal which has a high conductivity which can be compensated for by insulating the tank:

- on the inside (eg using a polymeric liner) to minimise transfer of heat between the temperature strata, and;
- on the outside (eg using a foam or fibre insulation material) to minimize heat losses to the ambient environment.

5.4 Inlet/outlet and heat exchanger arrangements

5.4.1 Incoming fluid velocities

Hollands and Lightstone (1989) highlight that the importance of low flow rates (~2 g/s/m^2 of collector area) in active open-loop stratified-tank SHW systems had been identified by previous authors as early as 1965. Prior to this, systems were typically designed to have high flow rates (~15 g/s/m^2) in order to maximise solar collector heat transfer coefficients, and typically used non-stratified storage tanks. The primary reason for reducing flow rates was a recognition that high flow rates in open loop systems cause mixing which disrupts tank strata.

Hollands and Lightstone (1989) identified that the destratification associated with high flow rates related to the momentum of the fluid jet entering the tank and explain that the effect can be assessed by considering the Richardson number, as per Equation 5.3, where g is gravitational acceleration, β is the thermal expansion coefficient of water, and v is the velocity of the incoming fluid. The term ΔT is the difference between the incoming water temperature and the temperature of the tank strata at which the water enters.

$Richardson\,number = \frac{g\beta\Delta TH}{v^2}$ *(Equation 5.3)*

Equation 5.3 shows that buoyancy and inertia forces play an important role in the flow evolution in the tank. This concept is also expressed by the ***Peclet*** number (Pe) which is the product of the Reynolds and Prandtl numbers, and the ***Froude*** number (Fr) which is expressed by Equation 5.4 as the ratio of the inertia and gravity forces. Han et. al. (2009) used these parameters, but referring to different quantities: inlet Reynolds number and the tank Reynolds number.

$Fr = \frac{u}{\sqrt{gl}}$ *(Equation 5.4)*

Figure 5.2 shows the relationship between the Richardson number and the dimensionless height of the mixing zone. It is clear that low Richardson numbers (which would result from high fluid velocity) correspond to large mixing zones and thus the greatest degree of destratification. It should be noted that this relationship appears to be unreliable for Richardson numbers higher than those shown on the figure when the flow is turbulent.

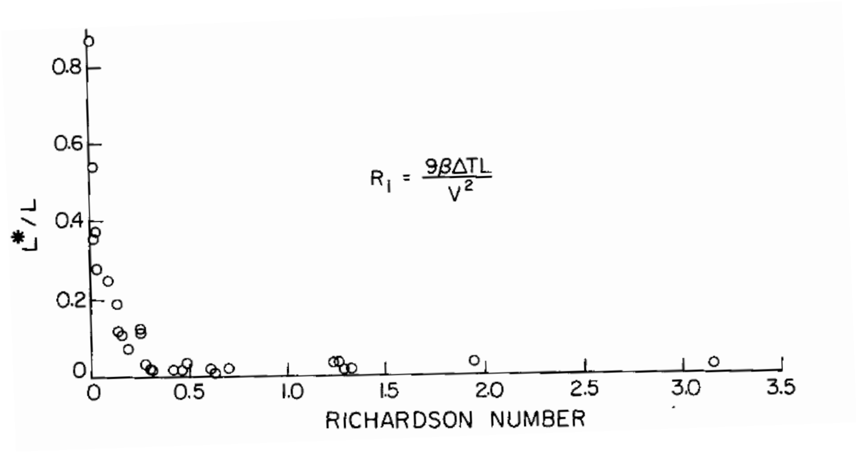


Figure 5.2: Relationship between Richardson number and degree of stratification, courtesy of Hollands and Lightstone (1989)

The velocity of the fluid entering the tank can be reduce in order to avoid destratification effects by either:

- Using a large diameter inlet pipe, or multiple inlet pipes.
- Using an inlet diffuser (eg perforated plate) or obstacle to break up the jet
- Adding a bend to direct the flow towards the tank base
- Change the open loop system to a closed loop system so that the open inlet is replaced by a heat exchanger.

There are numerous examples of all of these approaches in the literature. Lavan and Thompson (1977) compared the use of single, double and multiple horizontally distributed inlets. As can be seen from the results on Figure 5.1, the latter design performed considerably better than the single and double inlets, mainly because the mixing zone was reduced.

Jordan and Furbo (2005) used experiments and simulations to examine the impact of the cold water inlet device on the thermal stratification in two marketed tanks. One tank incorporated a concave hemispherical cup type diffuser (diameter equal to inlet pipe) and the other tank used a circular flat plate diffuser (diameter five times the inlet pipe). Whilst the two tanks differed in several ways (eg volume, heat exchanger arrangements) the numerical simulations were able to demonstrate that the larger inlet diffuser reduced mixing and resulted in better utilisation of the solar energy (lower consumption of auxiliary energy).

García-María et. al. (2013) investigated use of sintered bronze conical inlet diffusers and found that it favoured the development and maintenance of stratification much more effectively than a simple elbow inlet, at both high and low flow rates.

The principle of reducing inlet flows to minimise mixing also applies to tank outlets, but there appears to be a dearth of literature examining this.

5.4.2 Locations of inlets, outlets and heat exchangers

According to Equation 5.3, high Richardson numbers (corresponding to good stratification and minimal mixing) can also be achieved by minimising the temperature difference (ΔT) between the incoming fluid and the fluid in the tank near the inlet. In order to achieve this, tanks inlet need to be located at an appropriate height in the tank. For example, a cold water inlet should be located at the base of the tank adjacent to the coldest strata and the supply from the solar collector should be located adjacent to warmer strata near the top of the tank.

As highlighted by Hollands and Lightstone (1989), when fluid inlets or heat exchangers are located at the wrong strata height, buoyant plumes develop in the tank. These plumes entrain additional fluid and cause extensive mixing which destratifies the tank and leads to exergy destruction.

Whilst it is relatively simple to locate the cold water inlet at the base of the tank, it is much more difficult to ensure that the supply from the solar collector is delivered to the “right” height temperature strata in the tank. Temporal variations occur in both the solar collector output temperature (eg due to sun position and cloud cover) and in the locations and vertical extents of the tank temperature strata. The solution to this problem is to use either a mantle tank arrangement or inlet stratifier devices, such as:

- Floating inlet devices (Van Koppen et al 1979)
- Vertical fabric tubes stratifiers (Andersen, Furbo and Fan, 2007)
- Porous mantle devices (Smyth, Eames and Norton, 1999)
- Mantle tank heat exchangers (Knudsen and Furbo, 2004)

5.5 Baffle partitions and other storage vessel design features

Gnafakis and Manno (1989) investigated the effect of partial partitioning to separate the hot upper region from the lower cold region in a rectangular tank of air. They found that the baffles resulted in much steeper vertical stratification during the heating phase than the unbaffled case, due to mixing suppression effects. However, they also observed evidence that the baffles caused increased mixing (and hence faster destratification) when the tank was left to stagnate.

A similar study be Rhee et. al. (2010) suggests that toroidal baffle devices fitted with a special chimney arrangement achieved a three-fold improvement in stratification. Their tests involved a 2 hour heating period via a coil placed at the bottom of the tank followed by a 1 hour cool-down period. Whilst the improvement yielded by the toroidal chimney baffle appears to be very substantial, the overall quality of stratification achieved was quite poor owing to the non-ideal location of the heat exchanger at the bottom of the tank.

Aluntop et. al. (2005) undertook numerical simulations to investigate the effect of baffles in stratified cylindrical hot water tanks during hot water discharge. They also found that baffles improved the development of stratification. They found that baffle arrangements forming a gap in the centre of the tank (ie toroidal shape) appeared to be more effective than those forming gaps near the tank walls. Unfortunately, Aluntrop et. al. did not examine the effect of the baffles upon the rate of destratification during stagnant periods, so the overall benefit of such devices is somewhat uncertain.

6 Comparison of stratified and mixed tank systems

In passive systems (thermosyphons) circulation is guaranteed by the density difference of hot and cold fluid across the collector. Thus, the effect of stratification is highly evident. Morrison and Braun (1985) studied the influence of vertical and horizontal storage. Figure 6.1 shows the improvement in solar fraction for a solution that employs vertical storage compared to one which employs horizontal storage. It is clear that the solar fraction for the vertical storage (in which better stratification would be expected) is better than for horizontal storage.

Smyth, Eames and Norton (1999) examined the effect of stratification in several designs of passive ICS systems. A basic vessel design with no convection suppression was tested and was found to have a low stratification index and a rapid destratification time due to convection currents associated with top-of-tank heat losses. An optimised vessel which featured a perforated low conductivity inner sleeve achieved a much better stratification index and longer destratification time. The optimised vessel was found to perform 20% better than the basic vessel (30% better for the upper 1/3 volume) when tested for heat retention efficiency during a 16 hour cool-down period. A subsequent study Smyth, Eames and Norton (2003) found that the optimised tank had a 2% better collection efficiency than the basic tank when used in conjunction with a concentrating reflector. The optimised stratification design would therefore be expected to achieve a higher solar fraction than the basic vessel design.

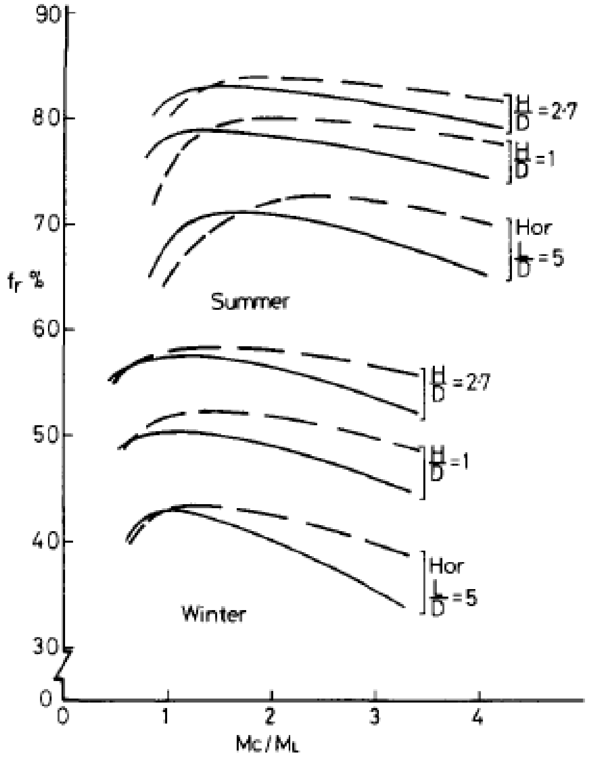


Figure 6.1: Solar fraction as a function of collector to load flow ratio, courtesy of Morrison and Braun (1985)

In their discussion of the benefits of low-flow stratified-tank systems compared to high-flow mixed-tank, Hollands and Lightstone (1989) presented Figure 6.1a below. Similar results were found in a more recent study by Cristofari et. al. (2002) which combine numerical simulation (see Figure 6.1b) and also experimental validation of a SWH system utilising polymeric collectors:

- Increasing collector flow rate from a stagnation condition up to ~1 g/s/m^2 allows a similar degree of increase in SWH system performance for both mixed tank and stratified systems, owing to improved heat transfer (due to reduced boundary layer thicknesses) within the collectors.
- Increasing collector flow rate between 1 and 6 g/s/m^2 causes a pronounced increase in performance for the stratified tank system but a more limited increase for the mixed tank system. Whilst both benefit from the resulting increased heat transfer in the collectors, the higher performance achieved by the former appears to be related to the stratification phenomena.

- At collector flow rates beyond 6 g/s/m^2 the stratified tank system continues to perform better than the mixed tank system, but the difference is less pronounced. This can be explained by the fact that high flow rates tend to cause destratification.
- At Point B on Figure 6.1a the stratified tank system achieves a solar fraction which is 37% higher than that achieved by the mixed tank system. The corresponding maxima point of Figure 6.1b shows a more modest improvement (around 5%).

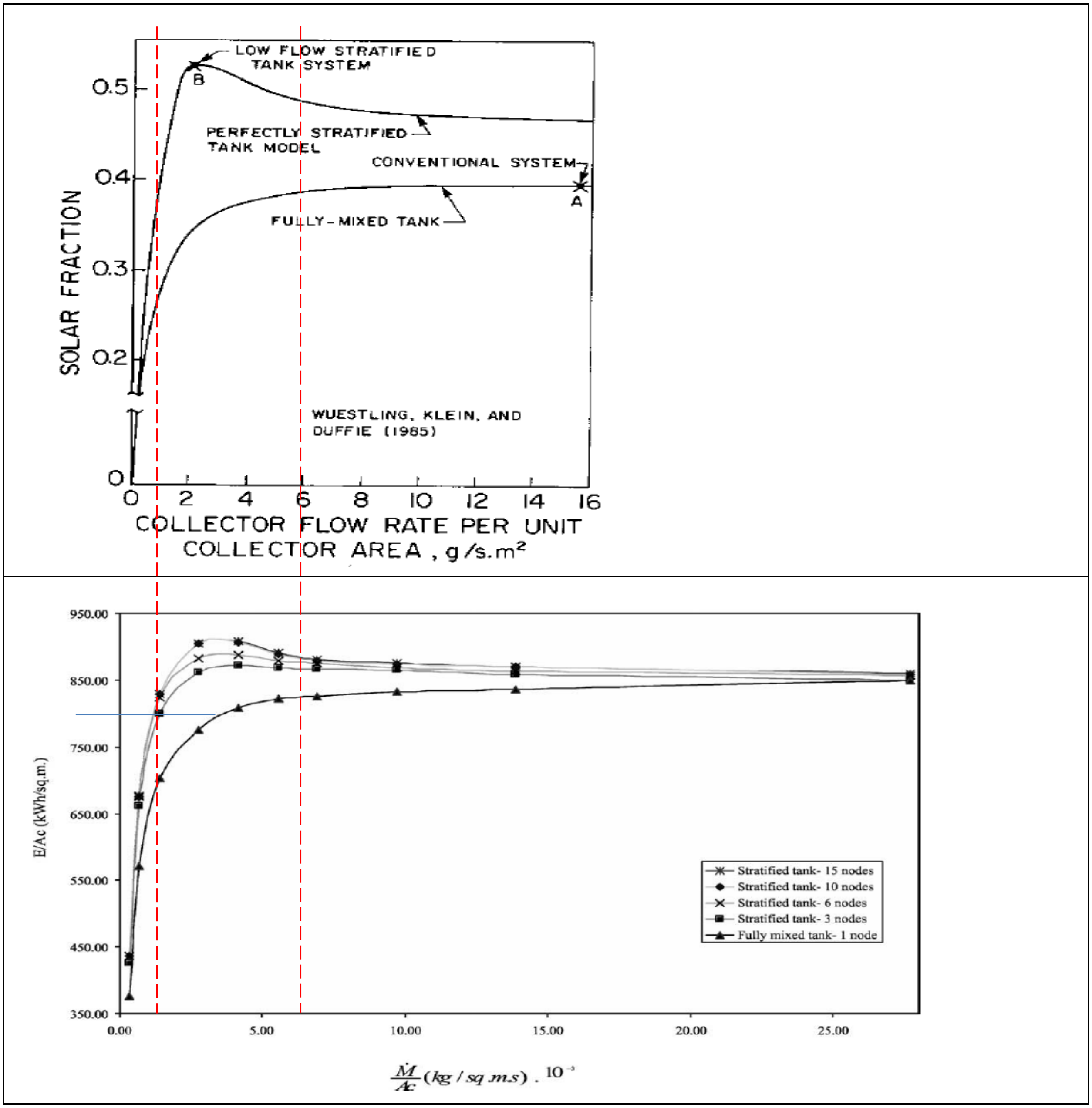


Figure 6.1: Relationship between collector flow rate, stratification and solar fraction, courtesy of Hollands and Lightstone, 1989 (Fig. a) and Cristofari et. al., 2002 (Fig. b)

Jordan and Furbo (2005) carried out numerical simulations (validated by experiments) of the annual performance of a mantle tank SWH system. They found that with an inlet delivering cold water into a relative storage height of 0.3 compared to a permanent inlet at the bottom of the tank lead to a 7% decrease of the solar fraction. This was attributed to increased mixing in the lower part of the tank caused by low density cold water down-flow. The effect was found to decrease at lower flow rates.

In practice, the benefit to be gained from using a stratified tank will depend upon the quality of the stratification achieved and the degree to which this can be maintained. Stratification quality and longevity are both dependent upon the tank design and operating conditions. The collector flow rate corresponding to maximum overall SWH system performance will depend upon the tank design (collector loop inlet/outlet or heat exchanger) and also the performance characteristics of the collector (relationship between flow rate and heat transfer). Cristofari et. al. (2002) found that the optimum collector flow rate corresponded to around 12% of the tank volume per hour.

7 Conclusion

Literature survey on the influence of stratification on thermal performances in sensible heat storage systems have been carried out.

The main conclusions are:

1) the importance of stratification is linked to:

- the increase of the efficiency of collectors;
- the reduction of the auxiliary consumption;
- the limitation of storage heat losses ;
- the reduction of mixing effect during draw-offs;
- the reduction of installation and running costs (especially for low flow systems);
- the increase of system's efficiency of thermosyphons (especially with vertical tank)

2) the quantification of stratification is defined by defining performances parameters. However, the most common way to quantify stratification is given by plotting temperature and/or temperature gradient along the tank;

3) fractional savings is mostly used to quantify and compare the performance of systems. For solar combisystem the definition of seasonal performance factor (SPF) can be used instead;

4) The development and maintenance of fluid stratification in sensible heat storage tanks is affected by:

- Tank shape, in particular the aspect ratio.
- Inlet and outlet fluid velocities, which can be minimized by:
    - Using large diameter inlet pipes, or multiple inlet pipes.
    - Using inlet diffusers such as perforations or spreader plates.
    - Changing an open loop system to a closed loop system so that high flow rate open inlets are replaced by heat exchangers.
- Suppression of convection currents by minimizing thermal conductance of tank walls in the:
    - vertical direction (heat transfer between strata).
    - horizontal direction (heat loss to ambient environment).
- Suppression of convection currents caused by inlet water flows by delivering incoming water to the correct height temperature strata by using:
    - Floating inlet devices.
    - Vertical fabric tubes stratifiers.
    - Porous mantle devices.
    - Mantle tank heat exchangers.
- Adding baffles within the tank to form a partition between the lower cold fluid strata and the uppermost hot fluid strata.

5) Increases in overall performance of SWH systems of perhaps 30% may be achievable in some cases when a fully mixed tank is replaced by a well stratified tank. In practice, however, the benefit to be gained will depend upon the quality of the stratification achieved and the degree to which this can be maintained. Stratification quality and longevity are both dependent upon tank design and operating conditions. The collector flow rate corresponding to maximum overall SWH system performance will depend upon the tank design (collector loop inlet/outlet or heat exchanger) and also the collector performance characteristics (relationship between flow rate and heat transfer). Several studies have demonstrated readily achievable performance improvements of around 5 to 10%.

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