COMPARARATIVE ANALYSIS OF THERMAL ENERGY STORAGE STRATIFICATION EFFICIENCY – A NEW METHOD COMBINES ADVANTAGES OF PREVIOUS APPROACHES

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ABSTRACT

In solar thermal heating systems, optimal stratification within the storage tank results in lower return temperatures of the collector and reduces auxiliary heating demand. Despite the extensive research in the field of tank stratification, a widely accepted parameter that can be used to quantify the stratification efficiency of a thermal storage has not emerged yet. In this contribution, existing methods to determine stratification efficiency are analyzed from a theoretical point of view, and a new method is shown that combines advantages of the existing approaches. It is claimed that the new method, if applied to any storage process, determines its stratification efficiency alone, eliminating as much as possible the bias of storage heat losses that has sometimes been included in previous approaches. A theoretical example illustrates the effectiveness of the new method presented.

1. BACKGROUND

A key parameter for high solar fractions in solar thermal heating systems is the stratification efficiency of the thermal energy storage (TES) (e.g. Lavan & Thompson 1977; Hollands & Lightstone 1989; Andersen & Furbo 2007). Stratification leads to lower collector inlet temperatures and avoids "unnecessary" auxiliary heating by reaching set temperatures for comfort faster and maintaining them longer. Both effects lead to increased savings of conventional fuels such as oil, natural gas or electricity that are typically used to maintain the required temperature level in the upper parts of the TES.

For the development and testing of TES, and in particular of components that enhance stratification, it is desirable to have an "index" or "measure" to determine the ability of a TES to promote stratification during charging and discharging as well as to maintain stratification during "standby". Several indices have been proposed and used in the past for this purpose, but none of them has been widely accepted until today (Zurigat & Ghajar 2001; Panthalookaran et al. 2007). Haller et al. (2008) have compared different approaches that can be found in literature to define a stratification efficiency that spans from 0% for a fully mixed store to 100% for a perfectly stratified store under the light of hypothetical cases of charging, discharging and storing heat. The conclusion of this work was that only one of the investigated methods was in good qualitative agreement with the entropy generation (or exergy loss) caused by mixing (or destratification), even if heat losses to the ambient were assumed to be negligible. The influence of heat losses to the ambient on this parameter however has not been addressed yet.

In this work the theoretical fundament of the proposed methods is discussed in order to show advantages and disadvantages of these methods. Based on this analysis, a new method that combines the advantages of the existing methods is proposed. The new method is applied to a theoretical case of charging, storing and discharging in order to verify its capability to eliminate as much as possible the bias of storage heat losses on the determined stratification efficiency.

2. GENERAL ANALYSIS OF STRATIFICATION EFFICIENCY INDICATORS

Stratification in TES is a natural phenomenon encountered in liquid storage systems such as water tanks above a temperature of 4 °C. Due to buoyancy forces, hot water tends to accumulate at the top of a TES, whereas colder water will always be forced to move downwards. Therefore, a TES based on water will always show a certain amount of stratification. However, different factors tend to destroy the stratification in a TES:

- Mixing of water due to natural convection caused by buoyancy of hotter fluid that is surrounded by colder fluid (e.g. if the fluid inlet is hotter than the temperature at the position of the inlet or if a TES is charged with an immersed heat exchanger).
- Inlet jet mixing (or plume entrainment) caused by the kinetic energy of the water entering the TES.
- Thermal conduction and diffusion within the fluid itself, within the TES wall and TES components immersed in the fluid.

A completely unstratified TES can always be seen as a fully mixed TES. The ability to promote stratification during charging and discharging is not only dependent on the construction of a TES and its stratification enhancing devices, but also on the inlet mass flows and temperatures (Lavan & Thompson 1977; Carlsson 1993; Andersen et al. 2007). Therefore, the boundary conditions of the charging and discharging processes play a crucial role for the determination of any stratification efficiency.

Methods for the evaluation and comparison of stratification efficiencies proposed in literature can be classified as follows (Panthalookaran et al. 2007; Haller et al. 2008):

- Graphical presentations of temperature curves (not further discussed here)
- Methods based on the thermocline gradient or the thickness of the thermocline region after a particular experiment.
- Methods based on the first law of thermodynamics (considering e.g. the "useful" energy that can be discharged after a TES has been charged).
- Methods based on second law of thermodynamics (exergy or entropy balances or comparison of the exergy or entropy content of the TES after a particular experiment).
- Other methods such as the MIX-number (Davidson et al. 1994; Andersen et al. 2007).

THERMOCLINE GRADIENT, THERMOCLINE THICKNESS AND FIRST LAW EFFICIENCIES

Methods based on the thermocline gradient at its center region have been successfully used e.g. by Sliwinsky et al. (1978) and (Shyu & Hsieh (1987). Also the fraction of the height of the TES occupied by the thermocline region, or its opposite, has been used for the evaluation of stratification efficiencies (Kandari 1990; Bahnfleth & Song 2005). For the calculation of these numbers, only a snapshot of the temperature distribution within the TES at the end of an experiment is needed. However, it has to be kept in mind that these methods pose certain requirements on the experiment conducted before the snapshot is taken, these are in general:

- a uniform initial temperature
- a constant inlet temperature during the charging / discharging process
- a time of charging / discharging that is small enough that the thermocline does not start to leave the TES

A change in inlet temperature during charging might lead to more than one thermocline in the TES. Thus, a variable temperature of charging as it usually occurs in a solar heating circuit cannot be used for the determination of a stratification efficiency with these methods.

Other authors have used first law efficiencies for the definition of a stratification efficiency (Abdoly & Rapp 1982; Chan et al. 1981; Tran et al. 1989). Generally spoken, these methods determine a fraction of useful heat (or cold) that can be recovered after charging / discharging. An arbitrary temperature limit determines whether the recovered heat (or cold) is considered to be useful or not. Thus, the recoverable fraction decreases as mixing or destratification increases. These methods also pose the requirements of uniform initial temperature and constant inlet temperature on the experiment conducted. Thus, they are also restricted in their application and not well suited for the evaluation of an experiment with variable inlet temperatures.

Another shortcoming of the thermocline gradient and first law methods is that they do not consider the entire temperature profile at the end of the experiment, but only certain key points of the temperature profile, such as the section of highest temperature gradient, or the position of the temperature curve where a certain limit temperature is reached. Outside of these key points, differences in the temperature curve will not result in a different value for the determined stratification efficiency.

MIX NUMBERS AND SECOND LAW EFFICIENCIES

The MIX number (Davidson et al. 1994) and second law efficiencies (Rosen 1992; van Berkel 1997; Shah & Furbo 2003; Panthalookaran et al. 2007; Huhn 2007) have been defined in order to consider the whole temperature curve and to overcome the shortcomings of the above mentioned methods that use thermocline gradient, thermocline thickness or first law approaches.

The mix number (MIX) has been used by Davidson et al. (1994) for the investigation of storage charging processes in solar heating applications. In this method, a "momentum of energy" (M_E) has been defined that is basically the height-weighted average TES energy content (E). Height (y) being the vertical distance of each water volume from the bottom of the tank:

Eq. 1 $$M_E = \sum_{i=1}^{N} y_i \cdot E_i$$

Values ranging from 0% for a fully mixed TES to 100% for a fully stratified TES can be obtained by comparing the MIX number of an experimental TES (exp) with the MIX numbers of a fully mixed reference TES (mix) and a perfectly stratified reference TES (str):

Eq. 2 $$MIX = \frac{M_E^{str} - M_E^{\exp}}{M_E^{str} - M_E^{mix}}$$

It has to be noted however that the use of the MIX number defined by Davidson et al. (1994) is based on the assumption that $M_E^{str} \geq M_E^{exp} \geq M_E^{mix}$. This assumption seems to be true for the processes of charging and storing heat in a TES, but it may be violated in the case of discharging heat from a TES (Haller et al. 2008).

Second law efficiencies are based on the second law of thermodynamics and the definitions of entropy and/or exergy that are associated with this law. Looking at an adiabatic system composed of two volumes of water that are at different temperatures, mixing the two volumes will not change the overall energy content of the system, but it will increase the entropy of the system and at the same time decrease the exergy of the system. Unlike energy, entropy and exergy are not conserved in a closed system. In a TES process however, the conservation of entropy and exergy is wanted. The ideal case of any storage process (charging, storing or discharging) is thus the isentropic process.

Therefore, one way of comparing the amount of mixing that is taking place in a storage process is to show the absolute values of entropy generation or exergy losses of the storage tank. Although this is a useful method, the result does not tell us how far from the ideal case of perfect stratification or the worst case of full mixing the investigated process is.

For this purpose, several authors have defined stratification efficiencies η_{st} that range from 0% to 100% using values based on entropy and/or exergy. Similar to the definition of the MIX number, these methods are based on the entropy change ΔS or exergy change $\Delta \Xi$ of the experimental process (exp), compared to the reference cases of the ideally stratified process (str) and the fully mixed process (mix):

Eq. 3 $$\eta_{st,S} = \frac{\Delta S^{mix} - \Delta S^{\exp}}{\Delta S^{mix} - \Delta S^{str}}$$

Eq. 4 $$\eta_{st,\Xi} = \frac{\Delta \Xi^{mix} - \Delta \Xi^{\exp}}{\Delta \Xi^{mix} - \Delta \Xi^{str}}$$

Unfortunately, different authors use different definitions for the fully stratified TES as well as for the fully mixed TES, and even different definitions for the entropy change ΔS or the exergy change $\Delta \Xi$ of a storage process.

One way to obtain a fully mixed reference TES from an experimental TES is to mix the experimental TES at any time of the experiment (Figure 1a). Also a perfectly stratified reference TES can be obtained by rearranging the energy content of the experimental TES at any time of the experiment in a way that only two different temperatures can be found in the perfectly stratified TES. One temperature being the highest temperature involved in the experiment (or encounterd in the TES), the other one being the lowest temperature involved in the experiment (or encountered in the TES). This method has been used by Andersen et al. (2007) for the calculation of a MIX number and by Panthalookaran et al. (2007) for the calculation of an entropy generation ratio. Under certain boundary conditions, these methods may deliver useful results. However, there are some critical aspects that must be pointed out:

- In the case of variable inlet temperatures the question arises if the separation of the perfectly stratified TES into two layers of different temperature is a good representation for a perfectly stratifying TES.
- If the experimental TES has reached a uniform temperature, the method of calculation may become undefined (division by zero). Thus, this method can not distinguish the case of a well stratifying experimental TES that has a uniform temperature because it has been charged long enough with a constant temperature, from an experimental TES that has been charged for a short time with a higher temperature but has reached the same uniform temperature because it is fully mixed.
- for experiments where a thermocline is starting to leave the TES the significance of values obtained by these methods is not clear and not in qualitative agreement with the rate of internal entropy production (Haller et al. 2008).

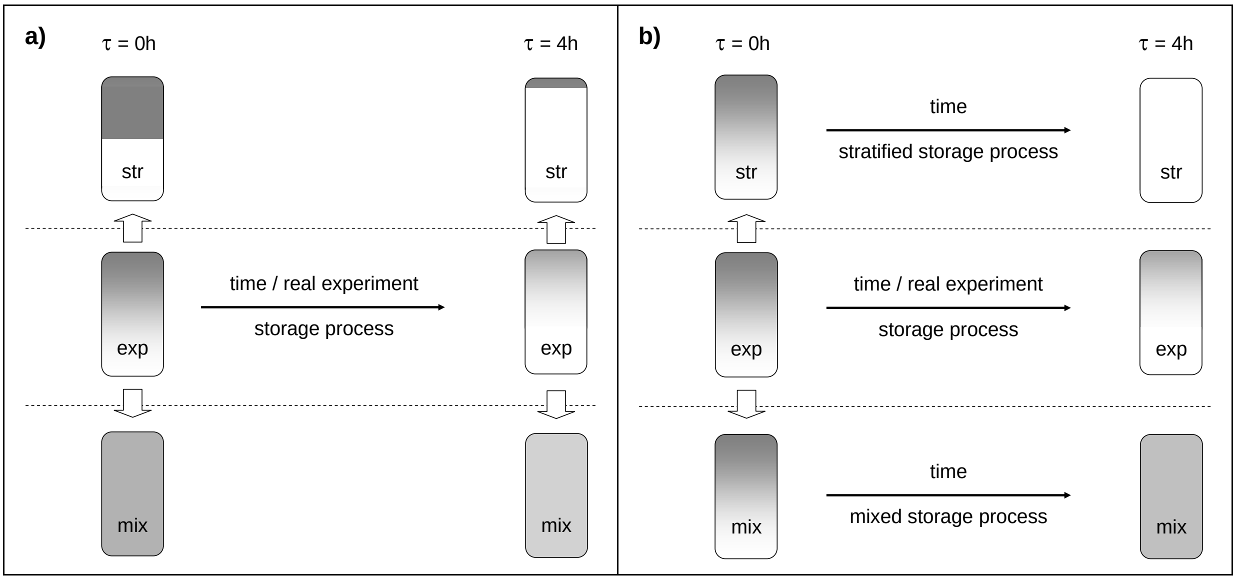

Figure 1: Different ways of defining a fully mixed and a perfectly stratified TES for a discharge test (dark: hot water, light: cold water). a) Mixing or stratifying the experimental store at any time (τ) of the experiment. b) Calculating the mixed and the stratified TES processes from the same starting point ($\tau = 0h$) as the experimental TES, with inlet mass flows and temperatures equal to the ones in the experiment. In the example shown, at $\tau = 4h$ the entire volume of the tank has been replaced (plug flow) for the stratified storage process (b).

These problems can be avoided by defining a fully mixed or a fully stratified reference TES starting from the experimental TES at the beginning of the experiment, and then applying the same inlet mass flows and temperatures to the reference TES as are applied to the experimental TES (Figure 1b). This method has been proposed by Adams and Davidson (1993) for the calculation of MIX numbers, and it has been used for second law efficiencies by van Berkel (1997), Shah & Furbo (2003) and Huhn (2007). van Berkel (1997) assumed that also a fully stratified TES can not avoid thermal diffusion caused by Brownian motion of the water particles inside the TES. Thus, the fully stratified TES processes are anisentropic. Other authors however assumed that the storage processes are isentropic for the perfectly stratified TES (Shah & Furbo 2003; Huhn 2007). This has the advantages that the fully stratified TES does not depend on the fluid it contains, and it also simplifies computation. Adams & Davidson (1993) assumed that the perfectly stratifying TES has the same heat loss coefficients as the experimental TES, thus distinguishing between heat losses and mixing effects.

Yet another difference in the various methods concerns the definition of entropy change ΔS or exergy change $\Delta \Xi$. Shah & Furbo (2003) as well as Panthalookaran et al. (2007) define ΔS and $\Delta \Xi$ as the entropy / exergy change of the TES alone, not accounting for the entropy / exergy changes associated with mass flows in and out of the TES. On the other hand, Huhn (2007) does account for these entropy / exergy changes. Haller et al. (2008) applied these different approaches to hypothetical cases of charging, storage and discharging of a TES with negligible heat losses. In their study, a good agreement with the rate of entropy production by mixing could only be obtained if the entropy / exergy change associated with the mass flows in and out of the TES were considered in the calculation.

3. COMBINING ADVANTAGES OF PREVIOUS APPROACHES

From the theoretical analysis of the existing methods and based on the results of Haller et al. (2008), the method of Huhn (2007) shows the best potential to be applicable to a wide range of experiments. There is no indication for a restriction to a very specific testing procedure (e.g. a uniform starting temperature and constant charging or discharging temperature of limited time). It is most likely also applicable to experiments with variable inlet temperatures and mass flows and long term experiments or simulations. A remaining question concerning this method is how to deal with entropy / exergy changes due to heat losses to the ambient. This question has not been addressed so far. Combining the ideas of van Berkel (1997), Huhn (2007) and Adams & Davidson (1993), the following solution for this problem is proposed: The irreversible entropy production caused by processes inside the TES such as mixing or destratification (int) $\Delta S_{irr,int}$ is calculated by subtracting the entropy change associated with mass transfer ΔS_{flow} and heat losses $\Delta S_{hl,store}$ from the entropy change of the TES itself ΔS_{store}. Exergy losses caused by processes inside the TES $\Delta \Xi_{L,int}$ are calculated likewise.

Eq. 5 $\Delta S_{irr,int} = \Delta S_{store} - \Delta S_{flow} - \Delta S_{hl,store}$

Eq. 6 $\Delta \Xi_{L,int} = -\Delta \Xi_{int} = \Delta \Xi_{flow} + \Delta \Xi_{hl,store} - \Delta \Xi_{store} \geq 0$

Assuming no thermal diffusion for the case of perfect stratification, the values of $\Delta S_{irr,int}^{str}$ and $\Delta \Xi_{L,int}^{str}$ must be zero for the case of a perfectly stratifying TES, and therefore Eq. 3 and Eq. 4 simplify to:

Eq. 7 $\eta_{st,S} = 1 - \frac{\Delta S_{irr,int}^{exp}}{\Delta S_{irr,int}^{mix,hl}}$

Eq. 8 $\eta_{st,\Xi} = 1 - \frac{\Delta \Xi_{L,int}^{exp}}{\Delta \Xi_{L,int}^{mix,hl}}$

With these definitions, stratification efficiencies based on exergy losses by mixing and based on entropy production by mixing are the same:

Eq. 9 $\eta_{st,S} = \eta_{st,\Xi}$

It has to be noted that in contrast to the method of Huhn (2007), the fully mixed reference TES is here calculated including heat losses (hl), by applying the measured heat loss coefficients of the experimental store. Another difference is that entropy/exergy changes caused by heat losses are calculated separately and not included in the values for entropy/exergy change that represent the effects of mixing. A simpler definition of a stratification efficiency $\eta_{\Xi,simple}$ that does not account for heat losses of the TES is given with Eq. 10 and Eq. 11. With this simpler definition, all exergy losses are attributed to destratification, although part of it is in reality lost to the ambient:

Eq. 10 $$\eta_{\Xi,simple} = \frac{\Delta\Xi_L^{exp}}{\Delta\Xi_L^{mix}}$$

Eq. 11 $$\Delta\Xi_L = -\Delta\Xi = \Delta\Xi_{flow} - \Delta\Xi_{store} \geq 0$$

To illustrate the difference between $\eta_{st,\Xi}$ and $\eta_{\Xi,simple}$, the following hypothetical experiment has been simulated:

A 1000 l water TES whose inlets at the top (charging) and at the bottom (discharging) are each causing some mixing in the topmost (charging) and the bottommost (discharging) layers. The TES is initially at 20 °C. Charging takes place from time 0 to 2.5 h with 400 l/h and an inlet temperature of 60 °C. After a standby time of 5 h, a discharge takes place from time 7.5 to 10 h with a flow rate of 400 l/h and an inlet temperature of 20 °C. No thermal diffusion is simulated in the calculation model. The thermodynamic equilibrium temperature has been set to 20 °C for exergy calculations. Figure 2 shows that heat losses to the ambient considerably affect the result obtained by calculating the stratification efficiency based on Eq. 10, whereas no effect is visible on the result obtained with Eq. 8.

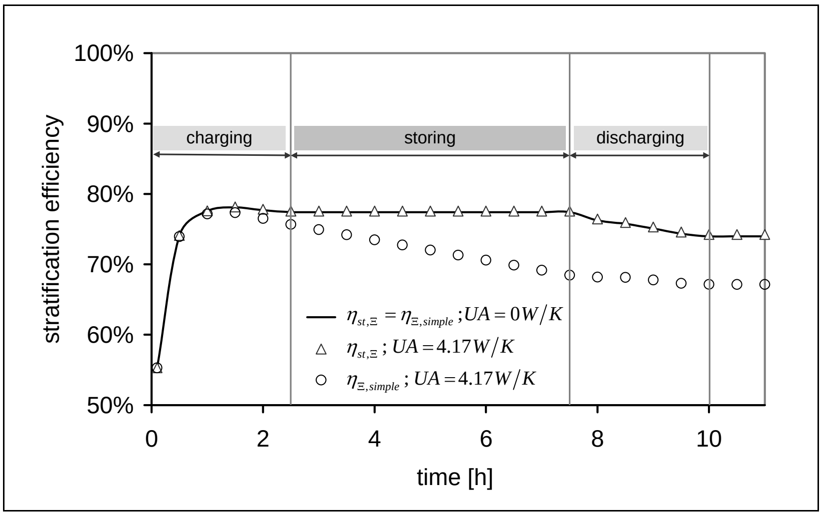

Figure 2: Stratification efficiencies calculated for a hypothetical heat storage process without heat losses and with heat losses.

4. CONCLUSIONS

A theoretical analysis of methods for the comparison of stratification efficiencies of TES processes revealed that most methods found in literature are not suited for an application to experiments that include variable inlet temperatures of charging and discharging as they occur in solar heating applications. The one method that showed a real potential for the use with realistic temperature profiles of charging and discharging inlets however is biased by heat losses of the storage tank. This may be unproblematic if only e.g. different inlet geometries are compared within the same TES. It may be a problem however, if different TES are compared with each other, since the obtained efficiency value may be an indicator for the storage heat losses rather than for the goodness of stratification. The new method introduced in this work combines the advantages of previous methods. It is expected to be applicable to experiments with variable inlet temperatures and mass flows, and a simulated case of charging, storing and discharging of two TES with different heat loss coefficients showed that the method has the potential of eliminating the bias of heat losses effectively.

Acknowledgement

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- Plume entrainment occurs when a plume of water develops caused by buoyancy of hotter fluid that is surrounded by colder fluid (e.g. if the fluid inlet is hotter than the temperature at the position of the inlet or if a TES is charged with an immersed heat exchanger). In this case, a plume can be observed that entrains surrounding water and mixes with it.
- Inlet jet mixing caused by the kinetic energy of the water entering the TES.

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Eq. 1 $\eta_{\Xi,simple} = 1 - \frac{\Delta\Xi_L^{exp}}{\Delta\Xi_L^{mix}}$

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