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Dimensionless numbers used to characterize stratification in water tanks for discharging at low flow rates

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ABSTRACT

The efficiency of thermal energy storage and solar collector systems is improved if the water tank is stratified. There are many parameters to characterize stratification but no work compares their suitability. This paper identifies the most used dimensionless numbers to characterize stratification in water tanks and studies their suitability. Experiments with different flow rates were done and the dimensionless numbers were determined. Richardson is the best number to define stratification in a water tank, while Mix number presents some problems and a bad behaviour. The other numbers do not clearly characterize stratification but can be useful combined with Richardson.

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1. Introduction

Sensible heat storage for solar heating systems is required in order to accommodate the intermittent nature of solar radiation and other variable energy resources. Thermal Energy Storage (TES) systems are used for liquids with low-to-medium temperature ranges. Solar thermal systems can be used in buildings to supply Domestic Hot Water (DSW) and/or space heating needs.

It is well known and proven that the efficiency of TES and solar collector systems is improved dramatically if the water in the storage tank is stratified. Stratification of the water in tanks is created by the difference in density between hot and cold water. Cold water remains at the bottom of the tank, while hot water flows to the top. The intermediate region is called the thermocline. The larger the temperature difference (ΔT) between the top and the bottom of the tank is the greater the efficiency is. Many techniques are used for this purpose, such as directing the water stream to the correct height of the tank by varying the design and location of the inlets.

The formation of the thermocline is determined by the geometry of the tank, the inlet, the hydrodynamics and thermal characteristics of the water flow in the tank. Water flows are a function of charging when hot water enters the tank and discharging when hot water is drawn out of the tank to service a load.

Stratified thermal storage tanks have been studied for a long time. During the early 1970s a significant amount of experimental and theoretical work was done. Brumleve [1] demonstrated the possibility of separating hot and cold water inside of a water tank using a natural thermocline. A similar situation exists naturally, for example in deep cold lakes and other bodies of salt water.

Studies have been performed to characterize stratification in storage tanks and many parameters, both dimension and dimensionless, have been defined to characterize the level or probability of stratification. The selection of the parameter to be used in each case presents some problems, since little work compares their suitability or performance. Haller et al. [2] studied the behaviour of some parameters in different theoretical cases.

The aim of the work is to study and compare different numbers with several experimental results using different flow rates and determine the influence of the most important variables for each one (flow rate, water temperature of the tank, inlet and outlet temperature, thermal properties). Comparing the real temperature profile inside the tank with the stratification parameters, one can determine the most suitable number to characterize thermal stratification for different working conditions. Some numbers can be very dependent and sensible to some variables resulting in wrong interpretations and contradicting results.

2. Theoretical methodology

Several dimensionless numbers found in the literature can be used to characterize stratification in water tanks. From all the

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numbers found only the following will be calculated and compared in this paper. The remaining ones are not suitable for the experiments done [2] or they are seldom used. The exergetic analysis is not presented since it was done in a previous work by the authors [3].

2.1. MIX number

MIX number was defined by Davidson et al. [4]. It is based on the energy and temperature distribution level in the tank and it is determined by the first moment of energy. This methodology was modified by Andersen et al. [5], considering the energy stored in the tank for each time step, and therefore overcoming the problems presented in the analysis of discharging processes. In these cases the energy drop during the discharging for a perfectly stratified tank is higher than for a fully-mixed tank. Therefore the MIX number as defined by Davidson gives few information of the process [2]. For this reason, in this work the MIX number modified by Andersen has been used.

$$\mathrm{MIX} = \frac{\left(M_{E,\mathrm{stratified}} - M_{E,\mathrm{actual}}\right)}{\left(M_{E,\mathrm{stratified}} - M_{E,\mathrm{fully-mixed}}\right)} \qquad \text{(eq. 1)}$$

where:

$$M_E = \sum_{i=1}^{n} y_i \cdot E_i \qquad \text{(eq. 2)}$$

$$E_i \quad E_i = \rho \cdot V_i \cdot C_p \cdot T_i \qquad \text{(eq. 3)}$$

The MIX number ranges from 0 to 1, with MIX = 0 representing a perfectly stratified tank and MIX = 1 when there is a fully-mixed tank.

2.2. Richardson number

The Richardson Number is extensively used to describe stratification. It is a measure of the ratio of buoyancy forces to mixing forces, which is expressed by:

$$Ri = \frac{g \cdot \beta \cdot H \cdot (T_{\mathrm{top}} - T_{\mathrm{bottom}})}{v_s^2} \qquad \text{(eq. 4)}$$

where:

$$v_s = \frac{Q}{\pi \cdot r_{\mathrm{stratifier}}^2} \qquad \text{(eq. 5)}$$

a small Richardson number means a mixed storage tank, while a larger Richardson number indicates a stratified storage tank. Several researchers worked on this parameter ([6–16]).

2.3. Ratio H/D

The simplest of the stratification parameters is the Height to Diameter ratio (H/D). Many studies demonstrated that a taller tank maintains better stratification than a short one, but a taller tank suffers more heat losses to the surrounding environment. The ratio between the height and the diameter can help to determine the stratification level of the tank. The larger the ratio, the more stratified the tank is.

Analytical studies found that for a height to diameter ratio greater than 3.3 ([14,17,18]) the improvement in thermal performance was negligible. Lavan and Thompson [19] studied the effect of the H/D ratio on the stratification of a storage tank, and concluded that a value between 3 and 4 appears to be a reasonable compromise between performance and cost.

2.4. Discharging efficiency ratio

The discharging efficiency is a ratio that compares the amount of useful heat (cumulative over time) that can be discharged from a tank with the total heat recoverable (thermodynamic maximum) [20,21].

The ratio helps to evaluate the thermal stratification during a discharging process. Ideally, the ratio should be one, which would mean there was no heat transfer between the inlet and outlet fluid streams. In reality it is always less than 1 because of the combined heat transfer and mixing processes occurring within the tank.

$$\eta_d = \frac{Q_d}{Q_o} \qquad \text{(eq. 6)}$$

where:

$$Q_o = M_t \cdot C_p \cdot (T_{\mathrm{start}} - \overline{T}_{\mathrm{in}}) \qquad \text{(eq. 7)}$$

$$Q_d = \sum \dot{m}_d \cdot C_p \cdot (T_{\mathrm{out}} - T_{\mathrm{in}}) \cdot \Delta t \quad \text{while } \{T_{\mathrm{out}} \geq 45^\circ\mathrm{C} \qquad \text{(eq. 8)}$$

2.5. Peclet number

The Peclet number provides a relationship between bulk heat transfer and conductive heat transfer. It is typically used with the Richardson number to define stratification in storage tanks ([6,14,22]).

$$Pe = \frac{v \cdot H}{\alpha} \qquad \text{(eq. 9)}$$

where:

$$v = \frac{Q}{\pi \cdot r_{\mathrm{tank}}^2} \qquad \text{(eq. 10)}$$

2.6. Reynolds number

The Reynolds number is a comparison between inertial and viscous forces given by:

$$\mathrm{Re} = \frac{\rho v_s \cdot D_{\mathrm{stratifier}}}{\mu} \qquad \text{(eq. 11)}$$

where:

v_s is the average velocity (m/s) calculated as showed in eq. (5)

The flow is laminar for *Re* numbers up to 2100–2300, transitional up to 4000, and typically turbulent over 4000. Reynolds number is used with other dimensionless numbers to define stratification in storage tanks [19].

3. Experimental methodology

3.1. Description of the experimental set-up

The tank studied is 1560 mm high with a diameter of 500 mm and a capacity of 287 L. It was for vertical floor installation with a heating coil in the lower part. The relation H/D was 3.12, in the recommended range for a good stratification (3–4). Several data were registered:

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