ASSESSING STRATIFICATION EFFICIENCY DURING CHARGING AND DISCHARGING PROCESSES OF THERMAL STORAGE TANK USING MODIFIED INLET DIFFUSERS

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Abstract

To satisfy the needs of space heating and domestic hot water, the use of renewable energies and particularly solar energy stands out for its technical feasibility and competitiveness. However, in order to mitigate the variations on the availability of the resource and fully meet the thermal loads, storage systems are commonly used. In those systems, water is usually used as heat transfer fluid, due to its low cost and thermophysical parameters that facilitate the stratification. Aiming to further this phenomenon, different geometries of inlet diffuser were proposed and assessed through computational simulations of the charging and discharging process. CFD simulations were carried out using ANSYS Fluent, aiming to compare the temperature profiles , and considering the stratification efficiency as a figure of merit. The results of the CFD simulations show that the use of the diffusers and the inlet flow through the upper zone of the tank generate the best stratification efficiencies, reducing unexpected mixing in the storage tank.

Keywords: CFD simulation, Thermal energy storage, thermal stratification, stratification efficiency.

1. Introduction

Fossil fuels are widely used to meet the needs of space heating (SH) and domestic hot water (DHW), however, it presents significant issues regarding its availability and environmental pollution. In this context, solar energy offers outstanding potential as a substitute for fossil fuel for domestic applications. However, it still presents technological challenges that hinder its widespread application. As a solution for the offset the domestic loads presents, regarding the availability of solar radiation, solar thermal systems are commonly coupled to thermal energy storage (TES) systems. For instance, in the domiciliary applications, the use of TES allows achieving high efficiencies and simple operation, constituting the sensible heat storage using water as a working fluid, as the best option (Tian et al., 2013).

Depending on their geometry, storage tanks facilitate the occurrence of thermal stratification. This phenomenon is explained by the variation on the fluid's temperature inducing a variation on its density, which results in the emergence of buoyancy forces, which causes that the tank's upper zone remains at higher temperatures than the lower zone. Thermal stratification in storage tanks have been widely studied, where the benefits of having a thermally stratified tank have been assessed both for SH and DHW (Sharp et al., 1979), as well as the possibility of coupling storage tanks with heat pumps systems as it's shown by Haller et al. (Haller et al., 2014). In this study, experimental and numerical analyses were carried out and allowed to identify that the thermal stratification efficiency is crucial in the performance of the storage tanks, being even more important than the size of the tank's insulation. The thermal stratification efficiency is based on the second law of thermodynamics (Haller et al., 2010), which considers the entropy generation in the tank, due to internal irreversibilities, allowing to compare its operation under different conditions. Taking into consideration such a numerical simulation framework that allows assessing the fluid dynamic behavior in the tank, and the impact of variations in the flow structure during charging and discharging processes, as well as the potential benefits of introducing innovative geometries for diffusers. is both a guideline and a template for preparing your manuscript for the joint conference proceedings.

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2. System Description

The system analyzed herein consists of the modeled storage tank and its internal fluid dynamics and heat transfer phenomena. The control volume is delimited by the tank; and its relationship with the environment as flow inlet and outlets, and thermal losses with the environment. Two innovative diffuser geometries were considered. These geometries are inspired in those proposed in other investigations, such as a T type diffuser (Gwerder et al., 2016), and an elbow type diffuser (Moncho-Esteve et al., 2017). Both geometries are illustrated in Fig 1.

The charging and discharging processes last between 5 and 10 minutes, depending on the flow used. For charging, the outflow is through the lower area of the tank, and for the discharge, the outflow is through the upper zone. The used tank is shown in Fig 2 has a volume of 83 [lt] a height of 0.75 [m] and a diameter of 0.395 [m]. The inlet and outlet channels had a 32 [mm] diameter.

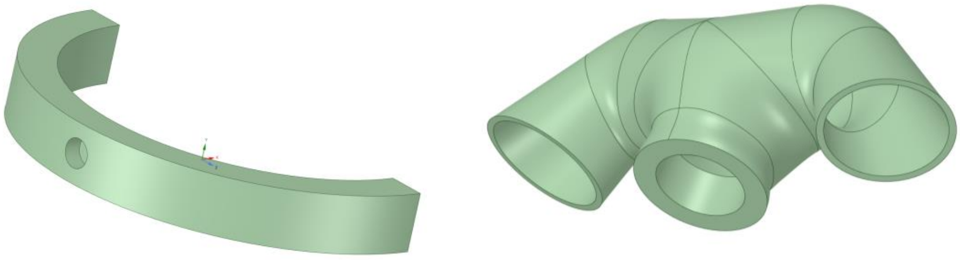

Fig. 1: Diffuser Geometries, T tipe diffuser (left) and elbow type diffuser (right)

3. Methodology

The performance analysis of storage tanks proposed herein is conducted by a CFD simulation framework, which is validated in an experimental setup.

3.1. Experimental setups

Aiming to validate the simulations, a dedicated test bench was implemented, considering the same conditions used in the simulations. Therefore, a set of numerical/ experimental experiments were carried out, allowing to assess the accuracy of such simulation runs. This experimental setup it's shown in fig 3, and it can be seen that the operating conditions considered constant flow rates and constant inlet temperature.

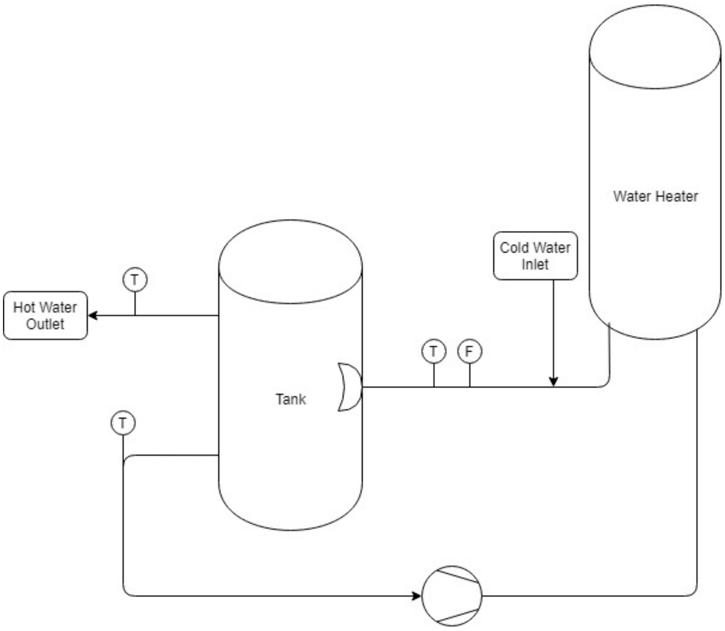

Fig. 2: Test bench for validation

Then the temperature distribution in the storage tank is measured in 6 points, as well as at the inlet and outlet conditions. The ambient conditions were also considered since it correlates the thermal losses of the storage tank. The diffuser geometries are complex to manufacture and therefore were 3D printed, as it's shown in Fig 4

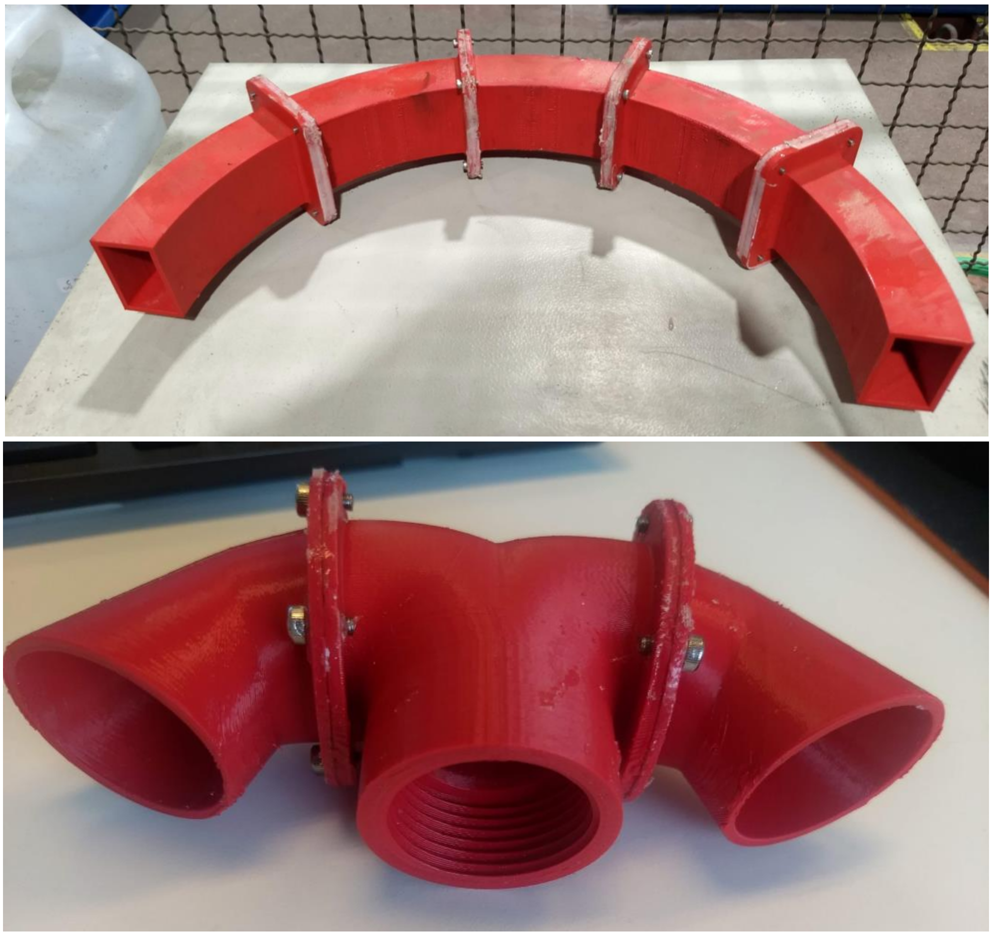

Fig. 3: 3D printed diffusers

3.2 Computational simulations

The transient simulations are carried out in ANSYS Fluent 18.2, while the post-processing procedure for computing the stratification efficiency is carried out using MATLAB R2015a.

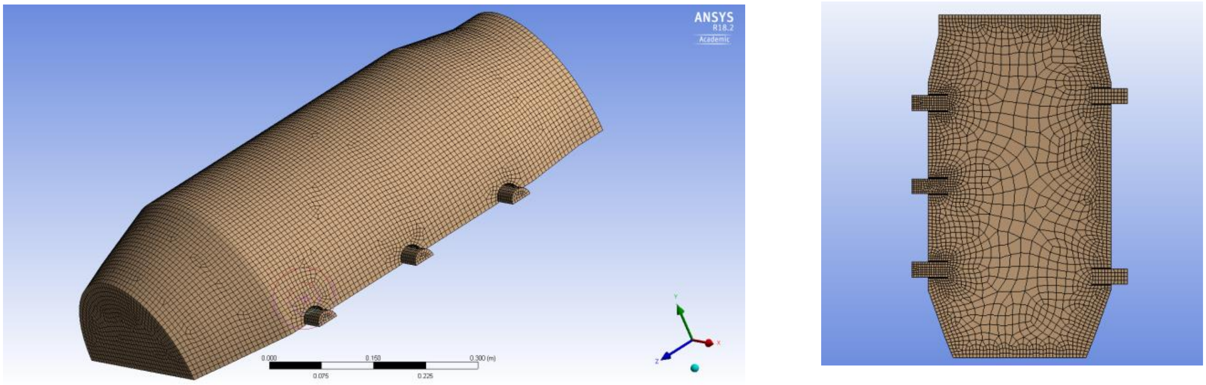

Fig. 4: Mesh used

For these simulations, the following considerations are taken, described below. Since the problem has a plane of symmetry, only half of the tank is simulated, imposing a symmetry border condition on the plane mentioned. The tank is simulated considering a heat flow, taking into account the conductive resistance of the tank wall, the external convective resistance and an ambient temperature of 20 [C]. It is considered a 3-mm thick HDPE tank. The input flows are simulated as a constant velocity profile on the face of the input, with a constant temperature in time equal to 70 [C] for the charging process, and 19 [C] for the discharging process. A flow rate Q1 of 3 [lt/min] and a flow rate Q2 of 7 [lt/min] are used. A turbulent intensity of 5% is considered, following the configuration of Gwerder (Gwerder et al., 2016). The outlet is imposed as constant pressure, equal to the ambient pressure. Taking into account the turbulence present in the model, it is considered appropriate to use a turbulence model of two equations such as the k-ω SST model. The buoyant forces are simulated using the Bousinessq model. For spatial discretization of the domain, a hexahedral mesh is used, which is convenient due to the low number of elements obtained. The mesh is shown in figure 4.

4. Results

4.1 Thermal behavior

The results of the validations shows a resemblance between the simulations and experiments, which can be seen in Figures 5 and 6. A result that is worth analyzing is the fact that the results of the mesh 1, for almost every simulation, presents a lower error than mesh 2. This makes sense in a first analysis, since experience indicates that a greater refinement usually brings results closer to reality, contrary to the ones presented in this study. This phenomenon could be explained by an implicit compensation of the internal errors, generated by the worst quality mesh. With this, mesh 1 is selected, which has an RMSE between 1.5 and 3.4 [K].

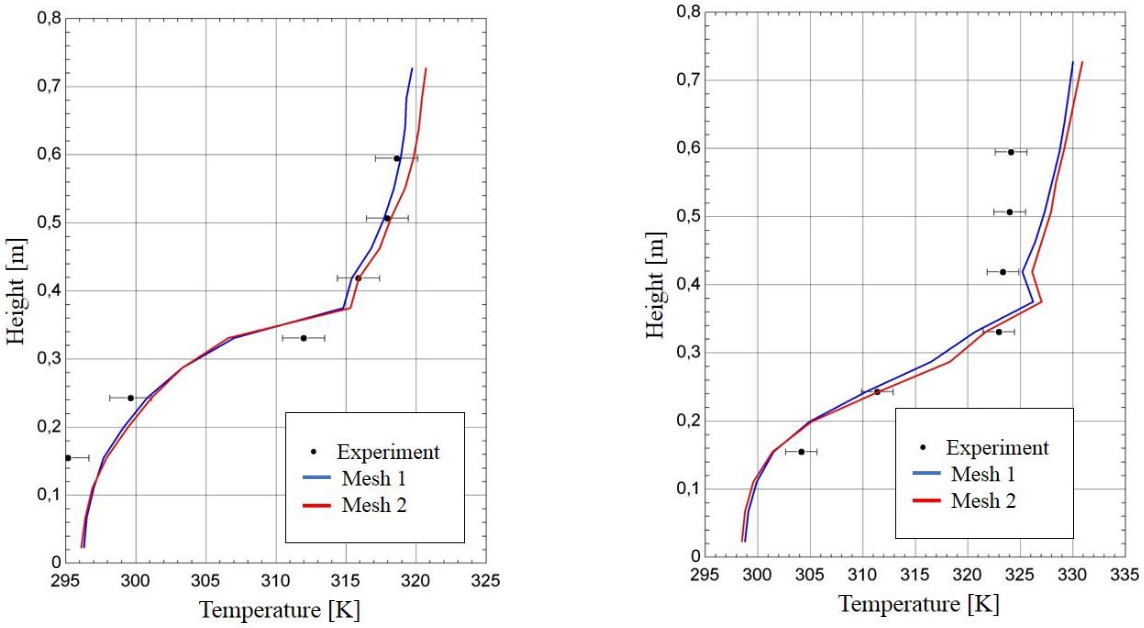

Fig. 5: Validation results, T diffuser, flow 3 [lt/min] (left) and flow 7 [lt/min] (right)

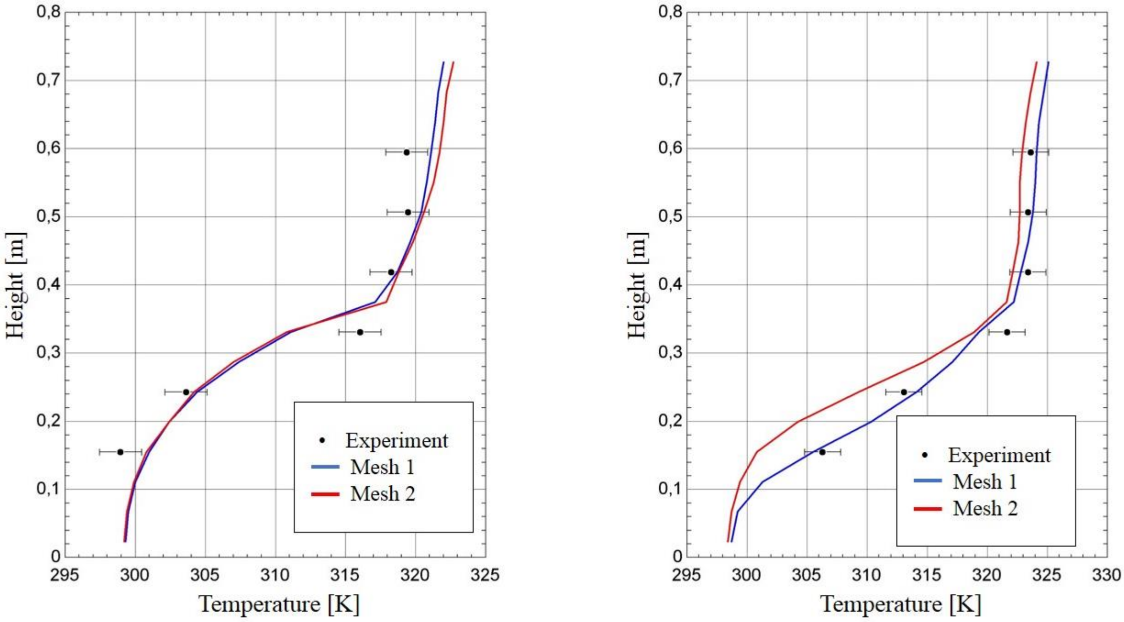

Fig. 6: Validation results, elbow diffuser, flow 3 [lt/min] (left) and flow 7 [lt/min] (right)

Results points out that the variable with the highest impact on the thermal stratification is the location (height) of the inlet diffuser, showing that the stratification is accentuated as higher the inlet is located. Both of the innovative geometries showed a more pronounced stratification than the base case, where the highest stratification was developed by the T diffuser. This diffuser shows a wide thermal range and an accentuated thermal stratification. The elbow type diffuser also presents better results than the base case, but in some of the experiments its improvement is negligible in terms of thermal stratification. The inlet region of the flow is easily recognized by inspecting the discontinuities in the temperature profiles, and these are more pronounced for high flow rates, when using the T type diffuser, because it has a higher cross-section surface of the tank.

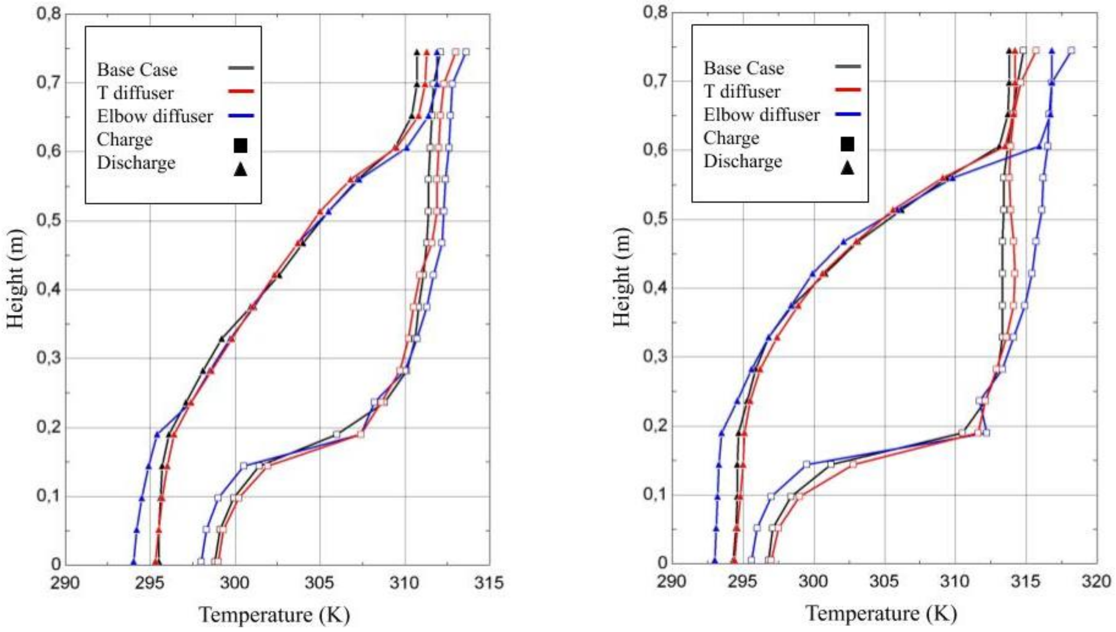

Fig. 7: Temperature profile, low inlet. Flow 3 [lt/min] (left) and flow 7 [lt/min] (right)

The difference between the results of the low and high flow rates is considerable since it denotes that for higher inlet flows, wider thermal ranges can be achieved, such as demonstrating that the diffusers are more effective for these conditions. The latter may be explained by the fact that the diffusers help to decrease the effect of the incoming flow on the thermocline, which increases along with the level of turbulence. It was also analyzed the variations in the outlet temperature of the tank for the different configurations since it has high impact in terms of the potential applications of the tank. Figure 10 to 13 shows the temperatures of the outlet flow of the tank, where a discontinuity is observed when charging and discharging processes are activated.

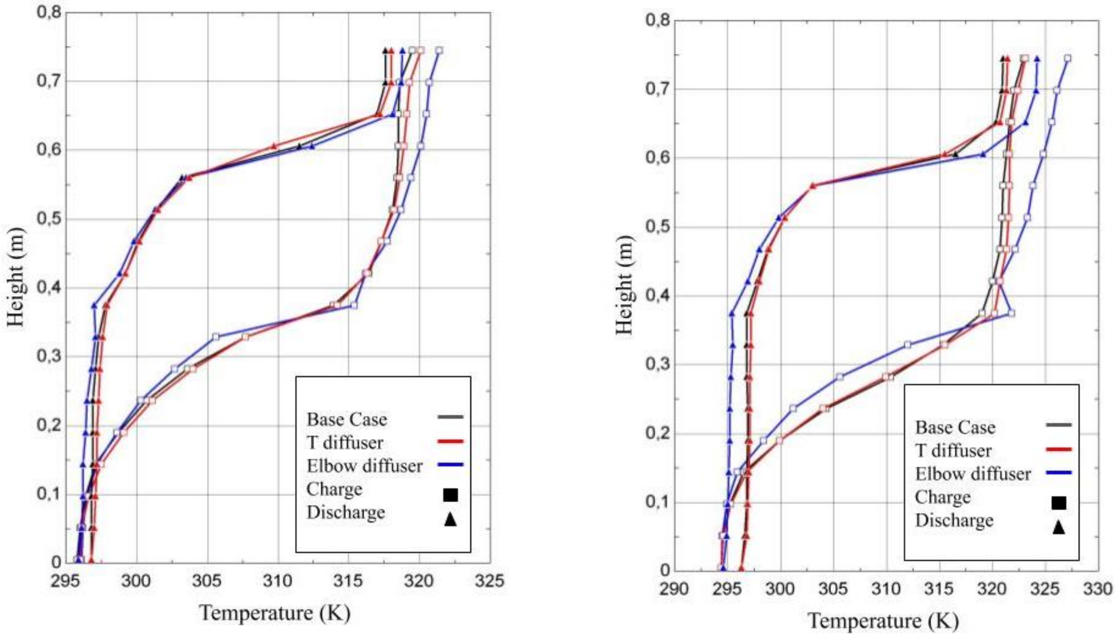

Fig. 8: Temperature profile, middle inlet. Flow 3 [lt/min] (left) and flow 7 [lt/min] (right)

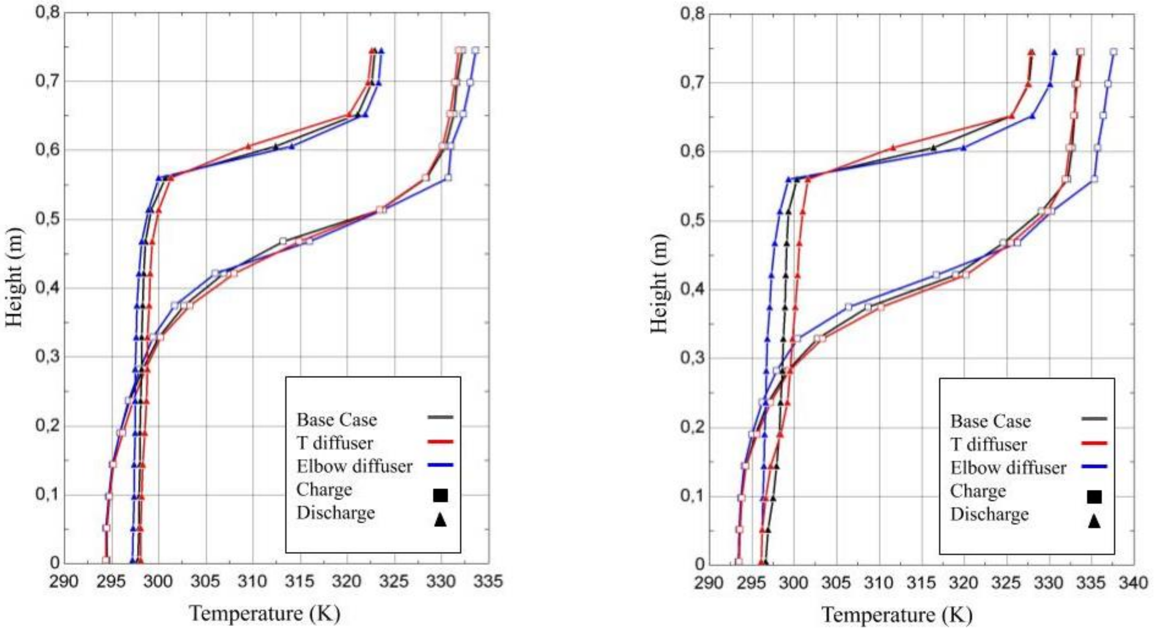

Fig. 9: Temperature profile, high inlet. Flow 3 [lt/min] (left) and flow 7 [lt/min] (right)

4.2 Stratification Efficiency

Important differences were observed in terms of the stratification efficiency, for each of the analyzed configurations where the T type diffuser presented the best results. The effect of the different flows shows a considerable improvement for almost all the cases, allowing to observe stratification efficiency values ranging from 55% to 94.5%.

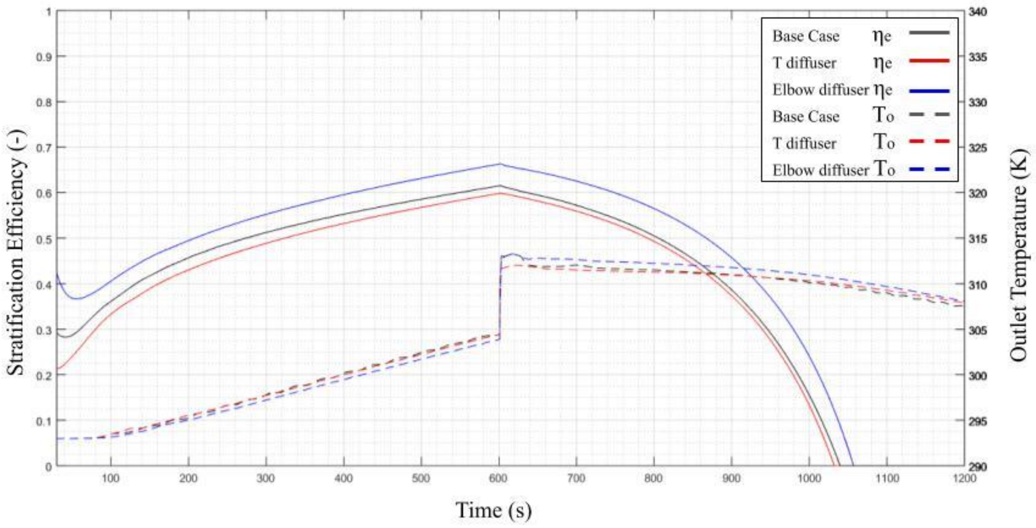

Fig. 10: Stratification efficiency and outlet temperature. Flow 3 [lt/min] and low inlet location.

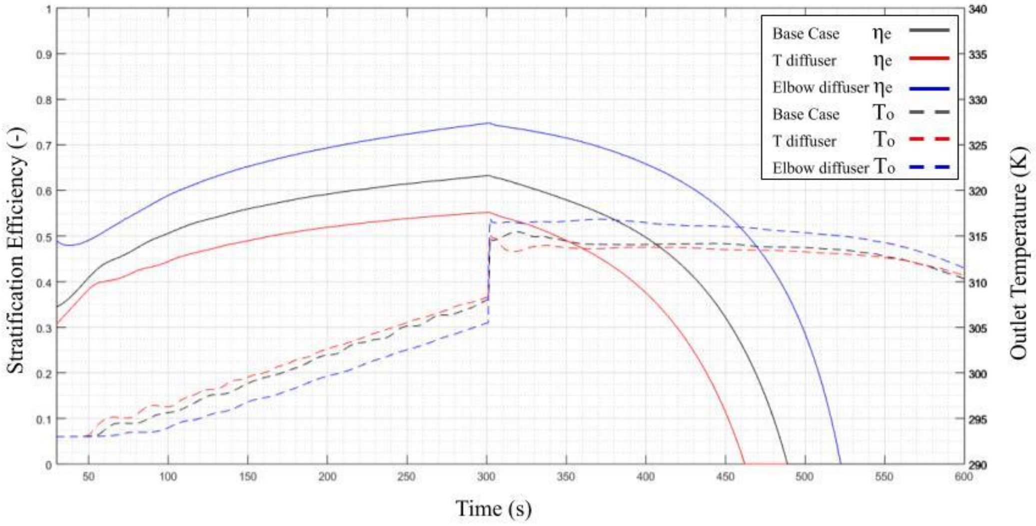

Fig. 11: Stratification efficiency and outlet temperature. Flow 7 [lt/min] and low inlet location.

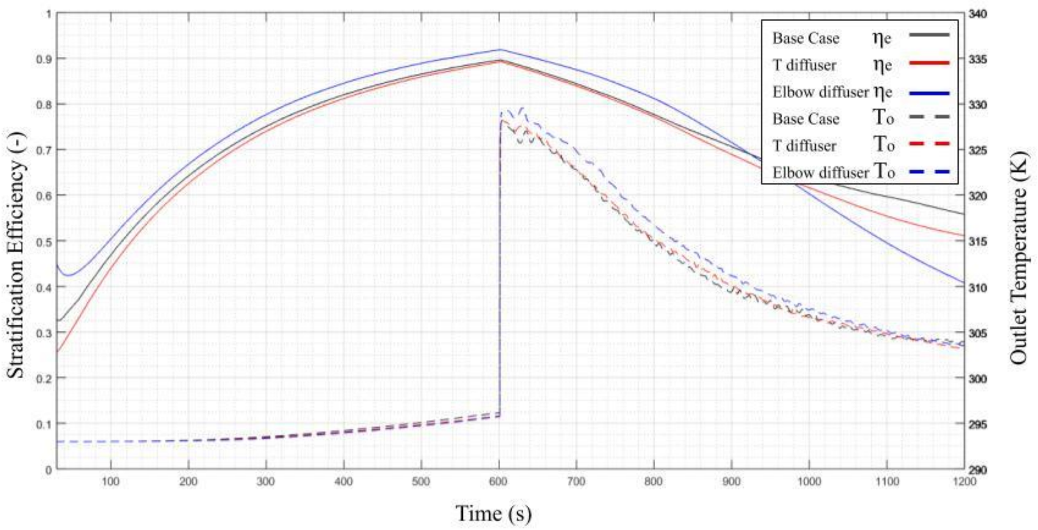

Fig 12: Stratification efficiency and outlet temperature. Flow 3 [lt/min] and high inlet location.

The effect of the different flows, shows an improvement for the stratification efficiency up to 9%, for the elbow diffuser in the low height, shown in figure. The only case that shows a decrease in this parameter is for the base case and height 1, where it decreases by 5%. The maximum stratification efficiency is achieved in all cases by the end of the loading phase, which leads to consider that the tanks can further increase their efficiencies by increasing the charging period. The stratification efficiency values range from 55% for the case without diffuser and with the flow rate Q2, to 94.5% for the diffuser in T with the flow rate Q2. It can be seen how the efficiency curves do not start from 0, which is due to the addition of the heat loss factor through the walls, where this term forces the initialization of the calculation data of efficiency should start from the same point. With the outlet temperature, the analysis of the impact of the diffusers can be extended, where it is observed that for inlet heights through the lower zone they generate a more constant temperature output, which makes sense since the pond meets a lower thermal range, ie less stratified. By improving stratification, you can see how the outlet temperatures increase in the tank. For charging heights 2 and 3, the outlet temperature is no longer as constant, but higher values are achieved. A trend is seen between greater stratification efficiency, and generating a peak output temperature at the start of the discharge.

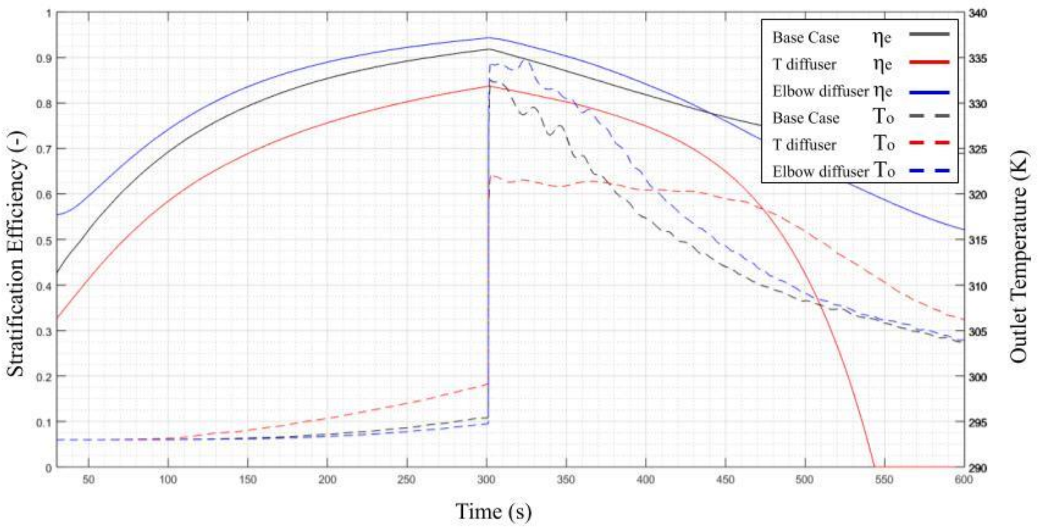

Fig. 13: Stratification efficiency and outlet temperature. Flow 3 [lt/min] and high inlet location.

5. Conclusions

In the present investigation, charging and discharging configurations of a thermal storage tank with stratification of their temperature has been analyzed, seeking to improve this last parameter. Consider two types of diffusers for the water inlet into the tank, in addition to a base case without a diffuser. The variables of the height and flow into the tank are also analyzed. Computational fluid dynamics and heat transfer simulations in transient state of the tank were developed, with cases for all variables. Simulations require a heat flow from the tank and ambient temperatures, and a global transfer factor, for each node in the pond wall. Along with this, an experimental validation of the tank was carried out, in order to ensure that the simulation results resemble reality. This involved the calculation, quotation, purchase and assembly of a test bench, on where a total of 6 experiments were processed, which expressed the thermal behavior of the tank in question. To objectively compare the thermal behavior of the tank with the different configurations, the stratification efficiency parameter defined by Haller (Haller et al., 2010) is used, with which it’s possible to directly assess the stratification, despite the of incoming and outgoing flows, and thermal losses to the environment. Based on the analysis of the results obtained, the following conclusions are established.

The thermal behavior is as expected in the tank, showing thermal stratification for practically all configurations. The variable with the greatest impact is the inlet height, showing that the higher it is, the more accentuated is the stratification. The results show a wide thermal range, and with this also shows a more pronounced stratification for the T-diffuser, followed by the elbow diffuser and finally the base case. The difference between these two cases is small, showing that the diffuser, T although it generates improvements in thermal behavior, its contributions are eclipsed by those of the elbow diffuser. It was also decided to analyze the variations in the outlet temperature of the tank for the different configurations, since it is finally the variable that has more relevance in terms of the utility that can be given to the storage system. With this analysis it is found that a very pronounced thermal stratification results in peaks of outlet temperature at the beginning of the discharge, but then it drops rapidly; on the other hand, configurations with less accentuated thermoclines generate output temperatures with less variation.

The calculation of stratification efficiency is quite simple when it works with data obtained from simulations, where it is possible to obtain the temperature and entropy of the entire tank for each time step, and calculate the entropy generated by thermal losses through the walls to the tank. The results of stratification efficiencies proved to be useful for quantitatively comparing simulation results, by quantifying the improvement of each configuration with respect to the base case. The different flows generated differences in the stratification efficiency peaks of up to 20%; the different diffusers, differences of up to 20%. This proves that using a flow inlet in the upper area of the tank, and the use of diffusers, particularly the type T diffuser, is a contribution in improving stratification efficiency. These recommendations are simple ways to improve thermal stratification, which has the potential to generate positive impacts on the performance of domestic hot water systems, helping to improve their competitiveness in the market.

6. References

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