THE ENERGY AND EXERGY CONTENTS OF STRATIFIED THERMAL ENERGY STORAGES

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Abstract. *The performance of energy and exergy analyses thermal energy storage systems (TES) incorporating thermal stratification are described, along with the resulting insights and benefits. Using temperature distributions obtained in a storage tank-refrigerator apparatus, it is shown that improving stratification can increase TES efficiency, and how the use of stratification can increase the exergy storage capacity of a thermal storage. This paper focuses on the energy and exergy contents of stratified storages. Consequently, energy and exergy analysis is shown to provide illuminating and meaningful assessments and comparisons of such TES systems that can assist in improving and optimizing designs. It is hoped that the results will facilitate the development of standardized methodologies for the evaluation and comparison of stratified TES systems.*

Keywords: *thermal energy storage, exergy methods, thermal stratification*

1. INTRODUCTION

The technology of energy storage has only recently been developed to a point where it can have a significant impact on modern technology. That is why energy storage is critically important to the success of any intermittent source in meeting demand. This problem is especially severe for solar energy because storage is needed the most when the solar availability is the lowest, namely in winter.

The energy storage systems can contribute significantly to meeting society's needs for more efficient, environmentally benign energy use in building heating and cooling, space power, and utility applications. The use of energy storage systems will result in some significant benefits as follows:

- Conservation of fossil fuels, by the switch to efficient generating plant
- Reductions in carbon dioxide emissions
- Reductions of CFC emissions.

Another significant advantage of an efficient energy storage is that, although it may have been designed primarily for the storage of solar energy, it is not restricted to that. It may be used to store surplus energy from the power plants, usually in the form of waste water, waste energy from air conditioners, waste energy from industrial processes and in this work waste energy from refrigerator condensers. It becomes a sort of energy sink into which we can throw any form of energy which is not needed for the moment. A common storage like this may not be so applicable for small houses but would be useful for large-scale central heating systems (Dincer 1999).

Solar energy is an important alternative energy source for current and future usage. The main factor which limits the application of solar energy is that it is a cyclic time-dependent energy resource. Therefore, solar systems require energy storage to provide energy during the night and overcast periods. The need for energy storage is not only for solar applications but also for many other thermal applications (Dincer, 1999).

Thermal energy storage systems for heating or cooling capacity are often utilized in applications where the occurrence of a demand for energy and that of the economically most favorable supply of energy are not coincident. Thermal storages are and essential element of many energy conservation programs, in industry, in commercial building, and in solar energy utilization. Numerous reports on thermal energy storage applications and studies have been published (Dincer, 1999 and Bejan, 1995).

Exergy analysis is a thermodynamic analysis technique based on the second law of thermodynamics. In particular, exergy analysis yields efficiencies which provide a true measure of how nearly actual performance approaches the ideal, and identifies more clearly than energy analysis the causes and locations of thermodynamic losses. Two advantages of exergy analysis over energy analysis in thermal energy storage applications are that exergy analysis recognizes differences in storage temperature, even for storages containing equivalent energy quantities, and evaluates quantitatively losses due to degradation of storage temperature towards the environment temperature (i.e., the cooling of heat storages and the heating of cold storages) and due to mixing of fluids at different temperatures, Rosen (2001).

The objectives of this paper are:

- Analyze the energy and exergy contents of storages tanks using analytical models
- Use experimental results for energy and exergy analysis, different from the study conducted by Rosen (2001), which use only analytical results
- The understanding of the second law analysis applied to storage tanks

2. STRATIFIED ENERGY AND EXERGY EXPRESSIONS

The total energy E and total exergy A in a thermal energy storage can be found by integrating specific energy e and specific exergy a over the entire storage-fluid as follows:

$$E = \int_m e\,dm \tag{1}$$

$$A = \int_m a\,dm \tag{2}$$

For a liquid, e and a are functions only of temperature T and can be expressed as follows:

$$e(T) = c(T - T_0) \tag{3}$$

$$a(T) = c[(T - T_0) - T_0 \ln(T/T_0)] = e(T) - cT_0 \ln(T/T_0) \tag{4}$$

Both the storage-fluid specific heat c and reference-environment temperature T_0 are assumed constant here. A horizontal element of mass dm can be approximated as:

$$dm = \frac{m}{H} dh \tag{5}$$

Since temperature is a function only of height, expressions for e and a in Eqs. (3) and (4), respectively, can be written as:

$$e(h) = c[T(h) - T_0] \tag{6}$$

$$a(h) = e(h) - cT_0 \ln[T(h)/T_0] \tag{7}$$

With Eq. (5), the expressions for E and A in Eqs. (1) and (2), respectively, can be written as:

$$E = \frac{m}{H} \int_0^H e(h)\,dh \tag{8}$$

$$A = \frac{m}{H} \int_0^H a(h)\,dh \tag{9}$$

With Eq, (6), the expression for E in Eq. (8) can be written as:

$$E = mc(T_m - T_0) \tag{10}$$

where:

$$T_m = \frac{1}{H} \int_0^H T(h)\,dh \tag{11}$$

T_m represents the temperature of the thermal energy storage fluid when it is fully mixed. This observation can be seen by noting that the energy of a fully mixed tank E_m at a uniform temperature T_m can be expressed, using Eq. (3) with constant temperature and Eq. (1), as:

$$E_m = mc(T_m - T_0) \tag{12}$$

and the energy of a fully mixed tank E_m is by the principle of conservation of energy the same as the energy of the stratified tank *E*:

$$E = E_m \tag{13}$$

With Eq. (7), the expression for *A* in Eq. (9) can be written as:

$$A = E - mcT_0 \ln(T_e/T_0) \tag{14}$$

where:

$$T_e = \exp\left[\frac{1}{H}\int_0^H \ln T(h)dh\right] \tag{15}$$

In general, $T_e \neq T_m$, since T_e is dependent on the degree of stratification present in the thermal energy storage, while T_m is independent of degree of stratification. $T_e = T_m$ is the limit reached when the thermal energy storage is fully mixed. This can be seen by noting (with Eqs. (2), (4), (12) and (13)) that the exergy in the fully mixed thermal energy storage, A_m, is:

$$A_m = E_m - mcT_0 \ln(T_m/T_0) \tag{16}$$

The difference in thermal energy storage exergy between the stratified and fully mixed cases can expressed with Eqs. (14) and (16) as:

$$A - A_m = mcT_0 \ln(T_m/T_e) \tag{17}$$

The difference given in Eq. (17) is always positive, that is, the advantage of use stratification by showing that the exergy of a stratified storage is greater than the exergy for the same tank when it is fully mixed, even though the energy content does not change, according to the first law of thermodynamics.

3. TEMPERATURE-DISTRIBUTION MODELS

Three stratified temperature-distribution models are considered in this work: linear model (*L*), stepped model (*S*) and continuous-linear model (C). For each model considered, the temperature distribution as a function of height is given, and expressions for T_m and T_e are derived. The distributions considered are simple and these are chosen because analytical solutions can readily be obtained for integrals for T_m in Eq. (11) and T_e in Eq. (15). The three stratified temperature-distribution models considered are based in the work of Rosen, 2001.

3.1. Linear model

According to Rosen (2001), the linear temperature-distribution model varies linearly with height *h* from T_b, the temperature at the bottom (i.e., at $h = 0$), to T_t, the temperature at the top (i.e., at $h = H$), according to Fig. 1a, and can be expressed as:

$$T^L(h) = \frac{T_t - T_b}{H} h + T_b \tag{18}$$

Substituting Eq. (18) into Eqs. (11) and (15), we have:

$$T_m^L = \frac{T_t + T_b}{2} \tag{19}$$

which is the mean of the temperatures at the top and bottom of the thermal energy storage, and:

$$T_e^L = \exp\left[\frac{T_t(\ln T_t - 1) - T_b(\ln T_b - 1)}{T_t - T_b}\right] \quad (20)$$

3.2. Stepped model

From Rosen (2001), the stepped temperature-distribution model consists of k horizontal zones, according to Fig. 1b, each of which is at a constant temperature, and can be expressed as:

$$T^S(h) = \begin{cases} T_1, h_0 \le h \le h_1 \\ T_2, h_1 < h \le h_2 \\ \quad \cdots \\ T_k, h_{k-1}, h \le h_k \end{cases} \quad (21)$$

where the heights are constrained as follows:

$$0 = h_0 \le h_1 \le h_2 \le \ldots \le h_k = H \quad (22)$$

It is convenient to introduce x_j, the mass fraction for zone j:

$$x_j = \frac{m_j}{m} \quad (23)$$

Since the thermal energy storage fluid density ρ and the horizontal thermal energy storage cross-sectional area S are assumed constant here, but the vertical thickness of zone j, $h_j - h_{j-1}$, can vary from zone to zone, we have:

$$m_j = \rho V_j = \rho S(h_j - h_{j-1}) \quad (24)$$

and that:

$$m = \rho V = \rho S H \quad (25)$$

where V_j and V denote the volumes of zone j and of the entire thermal energy storage, respectively. Substitution of Eqs. (24) and (25) into Eq. (23) yields:

$$x_j = \frac{h_j - h_{j-1}}{H} \quad (26)$$

With Eqs. (11), (15), (22) and (26), it can be shown that:

$$T_m^S = \sum_{j=1}^{k} x_j T_j \quad (27)$$

which is the weighted mean of the zone temperatures, where the weighting factor is the mass fraction of the zone, and that:

$$T_e^S = \exp\left[\sum_{j=1}^{k} x_j \ln T_j\right] = \prod_{j=1}^{k} T_j^{x_j} \quad (28)$$

3.3. Continuous-linear model

From Rosen (2001), the continuous-linear temperature distribution consists of k horizontal zones, according to Fig. 1c, in each of which the temperature varies linearly from the bottom to the top, and can be expressed as:

$$T^C(h) = \begin{cases} \phi_1^C(h), h_0 \le h \le h_1 \\ \phi_2^C(h), h_1 < h \le h_2 \\ \quad \cdots \\ \phi_k^C(h), h_{k-1} \le h \le h_k \end{cases} \tag{29}$$

where $\phi_j^C(h)$ represents the linear temperature distribution in zone j:

$$\phi_j^C(h) = \frac{T_j - T_{j-1}}{h_j - h_{j-1}} h + \frac{h_j T_{j-1} - h_{j-1} T_j}{h_j - h_{j-1}} \tag{30}$$

The zone height constraints in Eq. (22) apply here. The temperature varies continuously between zones. With Eqs. (11), (15), (26), (29) and (30), it can be shown that:

$$T_m^C = \sum_{j=1}^{k} x_j (T_m)_j \tag{31}$$

where $(T_m)_j$ is the mean temperature in zone j, i.e.:

$$(T_m)_j = \frac{T_j + T_{j-1}}{2} \tag{32}$$

and that:

$$T_e^C = \exp\left[\sum_{j=1}^{k} x_j \ln(T_e)_j\right] = \prod_{j=1}^{k} (T_e)_j^{x_j} \tag{33}$$

where $(T_e)_j$ is the equivalent temperature in zone j, i.e.:

$$(T_e)_j = \begin{cases} \exp\left[\dfrac{T_j(\ln T_j - 1) - T_{j-1}(\ln T_{j-1} - 1)}{T_j - T_{j-1}}\right], & \text{se } T_j \ne T_{j-1} \\ T_j, & \text{se } T_j = T_{j-1} \end{cases} \tag{34}$$

In Fig. 1 are shown the three temperature distribution models based on the work of Rosen (2001). These models are used here to analyze experimental results obtained from a cylindrical storage tank connected to a domestic refrigerator.

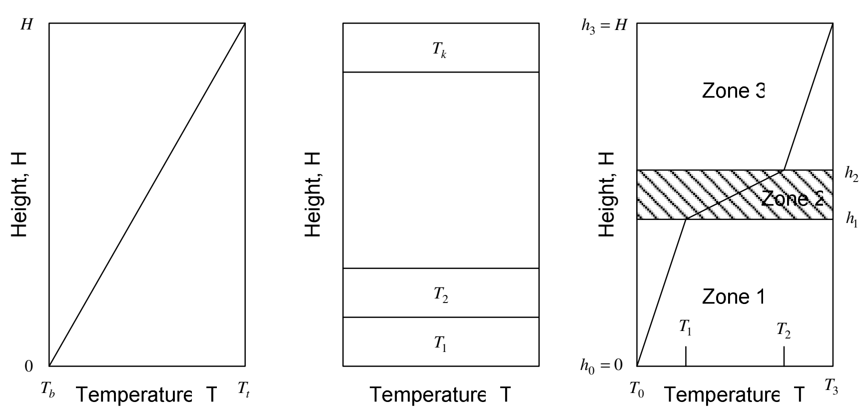


Figure 1 – A vertically stratified storage (a) having a linear temperature distribution (b) having a stepped temperature distribution (c) having a continuous-linear temperature distribution.

4. EXPERIMENTAL APPARATUS

The experimental apparatus consists of a domestic refrigerator with 263 liters for the refrigeration cabinet and 74 liters for the freezing cabinet. The refrigerator energy consumption are 4,5 KWh/month, and its original condenser was substituted by a countercurrent shell-tube heat exchanger, whose function is to condensate the refrigerant using water. This heat exchanger substitute the refrigerator finned condenser. Hot water is injected, by thermosyphon principle, in the top of a 122 liters cylindrical storage, constituted of a PVC tube with 0,3 m of diameter, 1,75 m of height and 4 mm of thickness, and it is stored by thermal stratification technique.

For the temperature measurements inside the tank, thermocouples T-type were used. They were calibrated with a standart thermometer coupled to a thermal bath. After calibration, water temperature profiles inside the storage were obtained. For this, a thermocouple tree was constructed for 31 thermocouples. A graphical recorder was used to collect and store data. The complete experimental apparatus can be seen in Fig. 2.

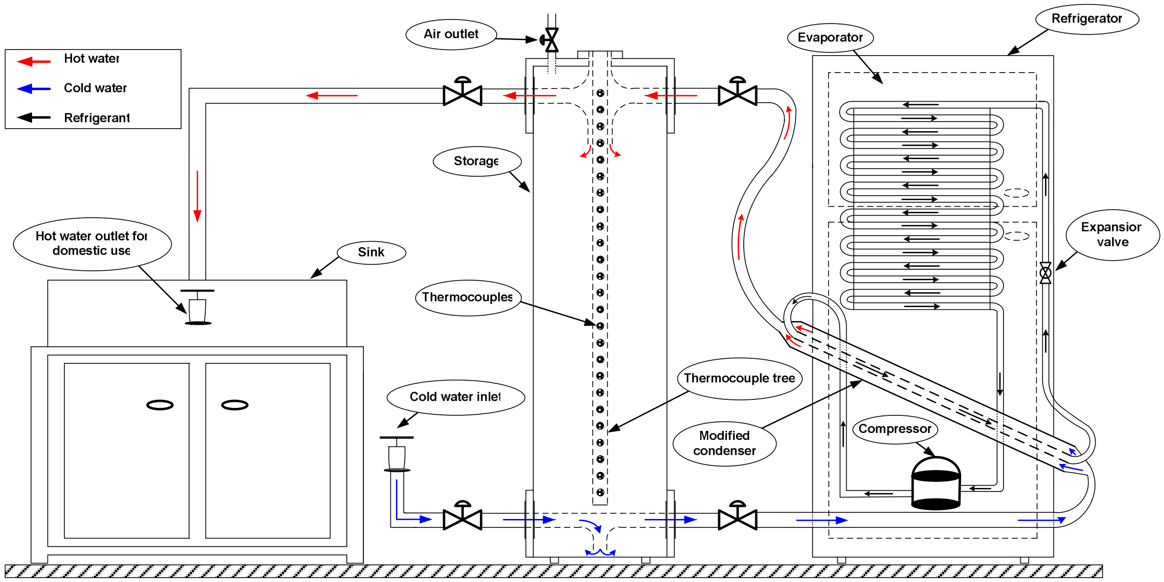


Figure 2 – Experimental apparatus.

5. RESULTS AND DISCUSSION

Energy and exergy quantities are determined using the linear, stepped and general-linear temperature distribution models to approximate the actual temperature distributions obtained experimentally. For comparative purposes, the exact values for these quantities are determined by numerical integration of the integrals in Eqs. (11) and (15) for the actual temperature distribution using Octave software. The thermal energy storage fluid is taken to be water. Specified general data are listed in Tab. 1, and additional data specific to the temperature-distribution models are 1×10^6 subdivisions for the stepped model and 5×10^2 subdivisions for the continuous-linear model. All calculations were done for the total duration of experiment.

Table 1. General data for the storage

Temperatures (K)	
At thermal energy storage top, $T(h=H)$	from 306,24 to 312,14
At thermal energy storage bottom, $T(h=0)$	from 298,22 to 302,98
Reference environment, T_0	from 298,29 to 303,12
Thermal energy storage fluid parameters	
Height, H (m)	1,5
Mass, m (kg)	122
Specific heat, c (kJ/kg K)	4,18

In Fig. 3 water temperature profiles in the tank are visualized for the loading time. Increasing the loading time, isoclines move to the right, pointing an increase of hot water amount inside the storage tank. However, in about 14 hours of experiment, it can be noticed that thermoclynes moves slowly, indicating a steady-state process. In Fig. 4 are shown temperature variations in the bottom and top of the tank. Bottom and top temperatures are increasing with time. Environmental temperature is almost constant during the experiment. The actual temperature distribution is shown in Fig. 3.

In Fig. 5 mixed and equivalent temperatures are shown, using the three analytical models of temperature distribution. It can be noticed, that the profiles are similar for the three cases considered. However, the computational effort is notable for the stepped and continuous-linear models. Moreover, no significant difference was noticed between mixed and equivalent temperature values. In Fig. 6 are shown the water energy contents using the three analytical models of temperature distribution. The energy quantity was calculated considering the storage with thermal stratification and another fully mixed. Based on the energy conservation principle, the energy contents are identical for the three cases. In the same way, similar behavior for the three analytical models was observed, with an energy peak after nearly 16 hours of experiment, which is equivalent to 19 o'clock.

In Fig. 7 are shown the water exergy contents in the tank. Calculations were performed considering a tank with stratification and another fully mixed. Clearly can be noticed that the exergy content of the stratified tank is greater than the exergy content of the fully mixed tank. These show the advantages of stratification and the utility of the exergy method, and demonstrate the usefulness of such analysis in providing insights into thermal energy storage behavior and performance. In Fig. 8 are shown the energy and exergy differences for stratified and fully mixed tank. This difference is positive in terms of exergy and zero in terms of energy. Finally, in Fig. 9 are shown the results of energy and exergy quantities, as well as energy and exergy differences for a stratified and fully mixed tank. These results are related with experimental data and were calculated through numerical integration. In this way, experimental results can be compared with results obtained by analytical models. Accuracy can be measured by comparing the results for the model distributions with the results obtained by numerical integration.

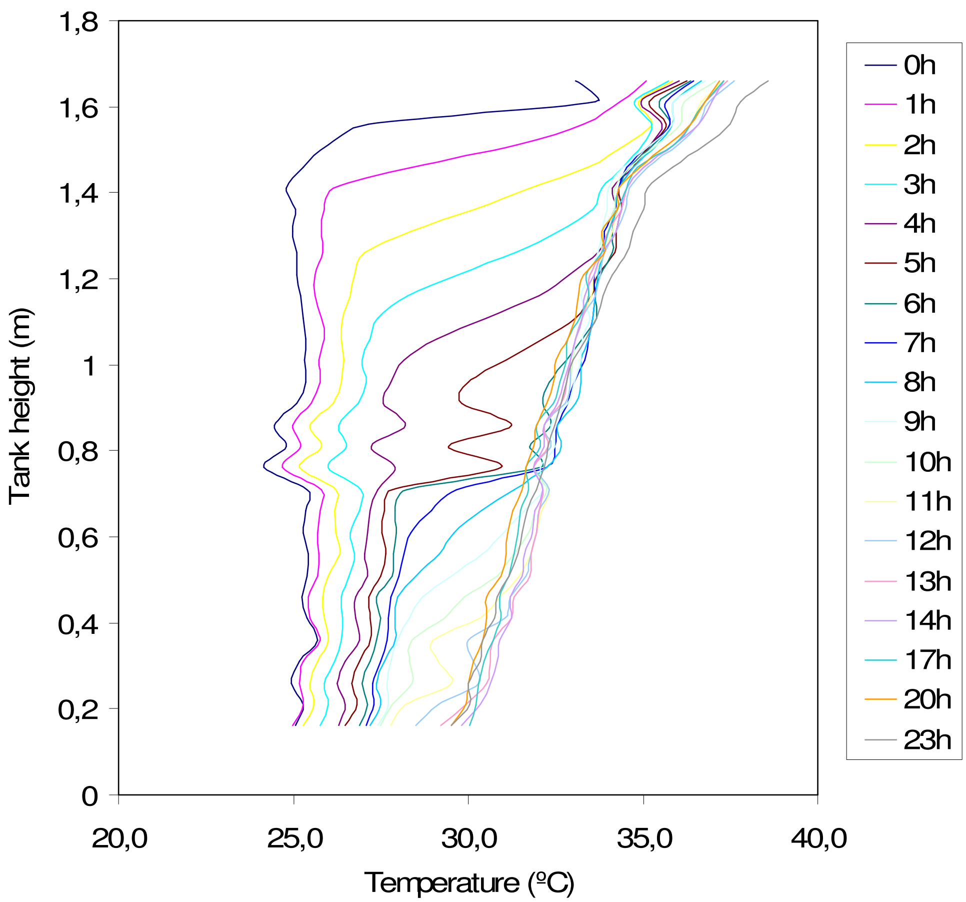


Figure 3 – Temperature profiles as a function of tank height.

Percentage errors are given for T_e and $A - A_m$ in this study. Only the maximum percentage error, which occurred during the experiment, is shown for each case.

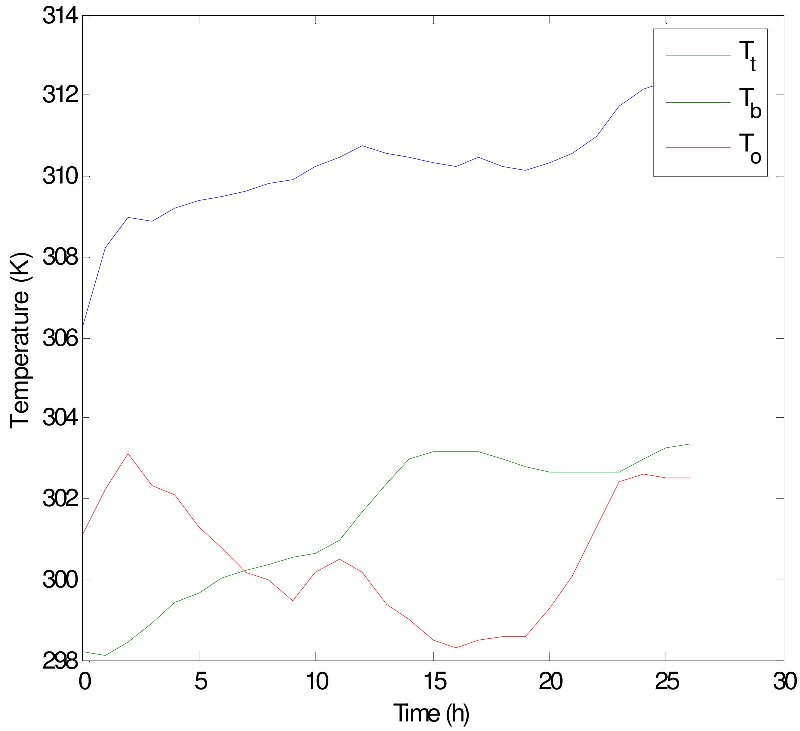
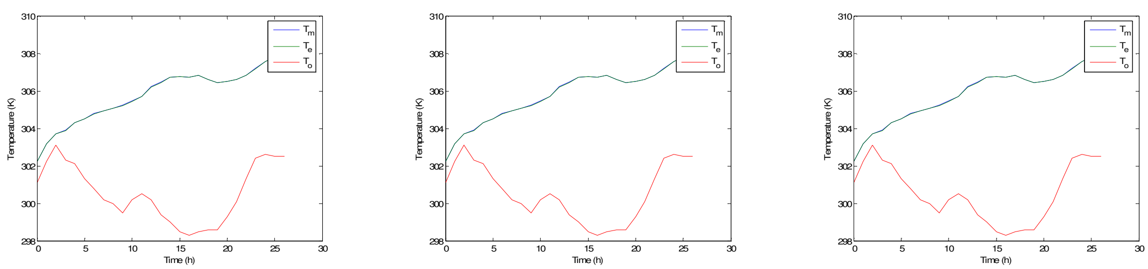
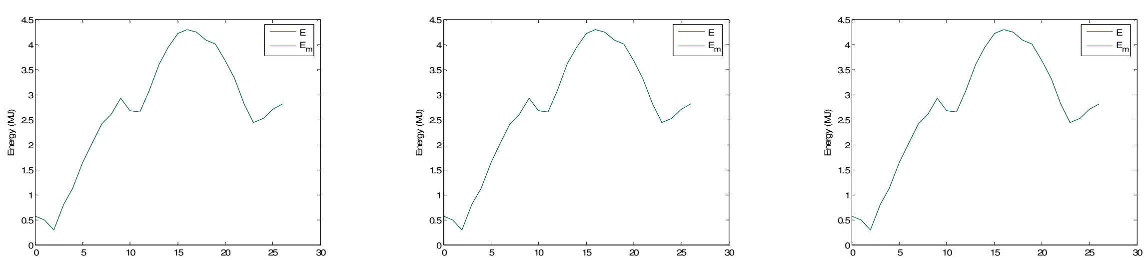


Figura 4 – Top, bottom and environmental temperatures over time.



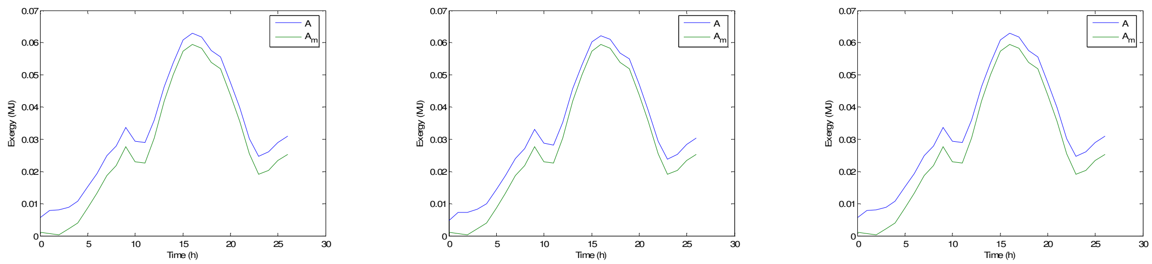
(a) (b) (c)

Figure 5 – Mixed, equivalent and environmental temperatures with time using (a) linear temperature distribution (b) stepped temperature distribution (c) continuous-linear temperature distribution.



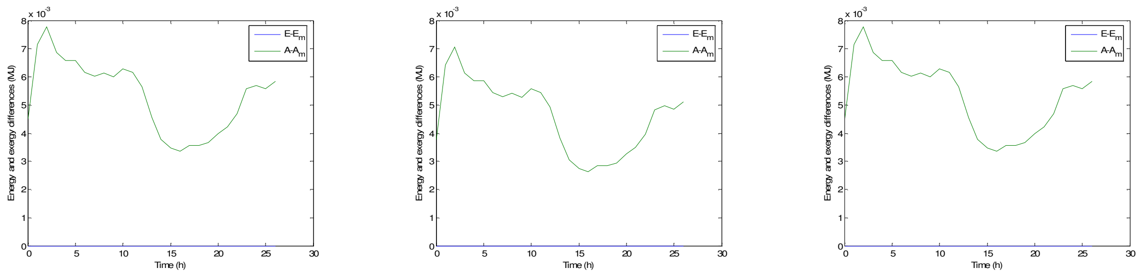
(a) (b) (c)

Figure 6 – Energy content for stratified and fully mixed tank using (a) linear temperature distribution (b) stepped temperature distribution (c) continuous-linear temperature distribution.



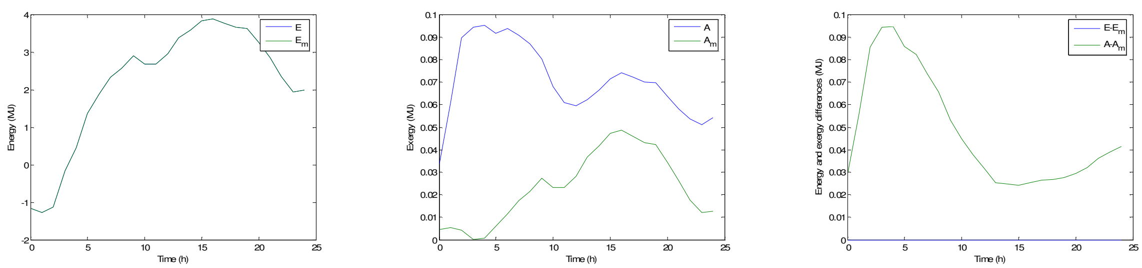
(a) (b) (c)

Figure 7 – Exergy content for stratified and fully mixed tank using (a) linear temperature distribution (b) stepped temperature distribution (c) continuous-linear temperature distribution.



(a) (b) (c)

Figure 8 – Energy and exergy differences for stratified and fully mixed tank using (a) linear temperature distribution (b) stepped temperature distribution (c) continuous-linear temperature distribution.



(a) (b) (c)

Figure 9 – Results obtained by numerical integration from experimental data (a) Energy content for stratified and fully mixed tank (b) Exergy content for stratified and fully mixed tank (c) Energy and exergy differences for stratified and fully mixed tank.

Table 2. Percentage errors in terms of T_e and $A - A_m$

Percentage errors	Linear	Stepped	Continuous-linear
In values of T_e	1,19 %	1,19 %	1,19 %
In values of $A - A_m$	18 %	16 %	18 %

6. CONCLUSIONS

An experimental apparatus consisting of a domestic refrigerator was used to get and analyze the results. The results obtained experimentally were used together with three temperature-distribution models described here and reported previously by other authors. These facilitate the evaluation of energy and exergy contents of vertically stratified thermal storages. Thermal energy storage exergy values, unlike energy values, change due to stratification, giving a quantitative measure of the advantage provided by thermal stratification. The experiment considered illustrate how the quantities of energy and exergy contained in a stratified thermal energy storage differ, and the exergy content of a thermal energy storage increase with thermal stratification, even if the energy remains fixed, according to the first law of thermodynamics.

7. REFERENCES

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