Generalized Assessment of Heat-Storage Accumulators Based on Exergy Profiles

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ABSTRACT

The analytical and experimental work described in this paper has to do with the development of a new and practical method for designing and rating heat-storage systems operating on a heat-capacity duty cycle of several days. It was carried out as part of a broader project evaluating equipment for exploiting solar energy and heat produced by animals on animal farms. Water-type heat accumulators were found to be an essential component of these systems; however, no generalized or specialized criteria were available for their effective design. Therefore, design optimization was carried out analytically, and the resulting approach was experimentally verified. This process led to the development of generalized criteria for rating the efficiency of stored heat utilization and to the development of reservoir design guidelines that, for practical design purposes, eliminated the need for knowing storage temperature histograms.

The analysis is based on defining the storage quality as the degree of perfection ($\zeta_e$) in terms of the initial and final exergy (available energy) ratios of the stored heat during the storage period. This function was determined analytically, experimentally verified for four design cases (with and without insulation), and related to the normalized design parameters, rate of temperature degradation, and fluid properties by time-dependent Fourier similarity number $F_o$. The resulting relationship of the form –

$$\zeta_e = k \log F_o + q$$

was correlated with the measurements. For a specified storage, the “degree of perfection” ($\zeta_e$) can then be optimized and the desirable dimensions of a reservoir selected by calculating the characteristic (or normalized) dimension from the Fourier number ($F_o$).

INTRODUCTION

To compare the thermodynamic quality of heat storage requires an assessment of temperature degradation of the storage medium. The time-dependent temperature profiles derived analytically and experimentally verified have been developed and used. However, such evaluations are specific to the design, and therefore, repeated calculations are required for each of the alternatives. After undergoing such an exercise, we found that a generalized solution to comparing various designs with some geometric similarity could be established. We defined effectiveness of the accumulated heat charge in a storage vessel in terms of availability of energy.
(exergy). Calling this effectiveness “degree of perfection,” we derived its functional relationship that could be used to compare and eventually optimize the storage tank designs. Such a relationship was found in correlating the degree of perfection ($\zeta_e$) with the Fourier number (Fo) of the system. The derivation and experimental verification of this relationship, and the benefits of using it for the comparison of geometrically similar designs, are described below.

**ASSESSMENT OF DEGRADATION OF ACCUMULATED HEAT**

In an ideal case, the reservoir is fully charged if the water temperature in the whole volume equals that of the source temperature. In operation, however, this state cannot ever be reached, as there are heat losses to the ambient, and the reservoir insulation can never be “perfect” for economic reasons.

The operation of the heat accumulator is usually characterized by alternate charging and discharging. The final states after the termination of the individual phases do not correspond to ideal states, and the processes may overlap in time. Due to an irregular temperature field in the reservoir, the temperature of discharged water at the end of the discharge phase is too low for use in a heating appliance.

Furthermore, the reservoir water temperature does not remain constant and drops as a result of heat transmission through the reservoir walls, heat conduction, and free or forced water convection inside the reservoir. These processes cause a certain degradation of accumulated thermal energy.

To quantify this degradation, we studied the time-dependent changes in the temperature field and the exergy of the systems. The observations and results then led us to develop a method of generalizing the functional relationships and effectively comparing storage tank designs.

To develop this functional relationship for assessing the heat-accumulation quality, a figure of merit was needed. We selected a storage “degree of perfection” to be such value and defined it as a ratio of the final and initial exergy of the heat brought to the reservoir given as –

$$\zeta_e = \frac{E_B}{E_A} = 1 - \frac{E_Z}{E_A}$$

Here, exergy is expressed as a product of the output heat ($Q$) and the so-called Carnot factor:

$$E = Q \left(1 - \frac{T_a}{T}\right)$$

It represents the usable part of energy ($Q$) due to the cooling of water from the temperature $T$ to the ambient temperature $T_a$. The exergy losses are given as –

$$E_Z = E_A - E_B$$

These losses will reduce the exergy of accumulated thermal energy because of the equalization of stratified water temperature in the reservoir and because of the temperature drop occurring spontaneously due to the inner blending and the thermal flow to the ambient.

Defining the value of the degree of perfection ($\zeta_e$) required the knowledge of the temperature gradient along the reservoir height and exergy profiles as a function of time. We have determined those experimentally for two vertical cylindrical reservoirs, both insulated and non-insulated. The experiment was followed by theoretical
assessment in which the non-linear regression method was used to smooth the temperature profiles. The processed data were then used to integrate the exergies and calculate the degree of perfection of the processes. Examples of measured and processed values of temperature profiles are given in Figure 1. The corresponding degree of perfection-time relationship is shown in Figure 2. These figures represent only one scenario of charging and discharging the storage vessel. In evaluating the accumulators and the evaluation method itself, many such measurements were carried out and analyzed. This lengthy process led us to the consideration of generalizing the results and developing a simpler assessment on the similarity basis which is described below.

![Diagram](image)

Figure 1. Histogram for Temperatures at the Axis of an Experimental Heat Accumulator at Free Cooling (No-Flow Conditions; Charged to Half Capacity at Initial Conditions of 80°C/Top, and 40°C/Bottom; Ambient Temperature = 22°C).

**GENERALIZATION OF RESULTS**

As indicated above, we set out to simplify the evaluation process and replace time as an independent variable in the assessment of storage quality. One approach was to apply the theory of similarity – an approach that proved to be quite practical. In applying it, we used the Fourier similarity number:

\[ Fo = \alpha \tau / t^2 \]
which characterizes the relation between the rate of temperature field changes, the physical (material) parameters, and the dimensions of the reservoir. For water at 60°C, a thermal conductivity of $a = 0.15 \times 10^{-6}$ sq m/s was considered.

The two vessels used in our work were not exactly geometrically similar, however. The ratio of their heights was 3/1, while the ratio of their diameters was only 0.6/0.25 = 2.4. Complete geometric similarity could not be achieved. In spite of this difference in similarity, the results in generalizing the storage characteristics were practical.

Certain attention was also given to the determination of the characteristic dimension of the reservoir, which can be, for example –

1. Height (H) – which has a dominant influence on free convection inside the reservoir.

2. Diameter (d) – which characterizes the area where molecular blending takes place; this is most significant for the exergy drop in an insulated reservoir.

3. Cube Root of Volume ($\sqrt[3]{V}$) – which, together with the diameter, has the decisive influence on temperature history of reservoirs without insulation.

The suitability of selecting the characteristic dimension was assessed on the basis of matching the curves of $\xi_e = f (Fo)$ in the region under investigation. Also considered were combinations of the above parameters in complex dimensions such as –
Because there are no studies which could be referred to for guidance, all six variants were elaborated on, and from the comparison of the histograms of $\xi_0$ for the 1-m and the 3-m models, the characteristic dimension that best approximated the behavior was selected.

The best correspondence of histograms occurred in insulated models with $l_B$ and $H$ and in uninsulated models with $l_A$. Some differences in the histograms may have been caused (apart from insufficient geometric similarity) by the changes of outside temperature (which varied within the limits of 6 K) and the different temperature profiles at the beginning of cooling.

Figure 3 gives all results determined by the measurements on the 3-m model for various initial temperatures carried out on an insulated and non-insulated vessel (sum of three measurements). Note that the slope of straight lines in the regular cooling phase is identical. Also, the dispersal of points is not large, so that a single straight line can be laid through all points for the given temperature range. The influence of the initial temperature is practically nil.
The linear histogram of the relation $\xi_e = f(Fo)$ in semilogarithmic coordinates for the cooling phase is described analytically by the relation –

$$\xi_e = k \cdot \log Fo + q$$

The points that are within this regular cooling phase region in the diagram of the relation $\xi_e = f(t)$ were taken into account in the calculation of the values of $k$ and $q$. By means of linear regression, the following constants were determined ($r$ being the correlation coefficient):

<table>
<thead>
<tr>
<th>Initial Temp. °C</th>
<th>Insulation</th>
<th>$-k$</th>
<th>$-q$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80/40</td>
<td>With</td>
<td>95.8</td>
<td>194.4</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td>Without</td>
<td>97.8</td>
<td>72.4</td>
<td>0.999</td>
</tr>
<tr>
<td>70/40</td>
<td>With</td>
<td>97.7</td>
<td>203.9</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td>Without</td>
<td>91.0</td>
<td>69.6</td>
<td>0.998</td>
</tr>
<tr>
<td>60/40</td>
<td>With</td>
<td>96.0</td>
<td>207.8</td>
<td>0.999</td>
</tr>
<tr>
<td></td>
<td>Without</td>
<td>113.6</td>
<td>98.4</td>
<td>0.999</td>
</tr>
<tr>
<td>60</td>
<td>With</td>
<td>84.7</td>
<td>164.0</td>
<td>0.997</td>
</tr>
</tbody>
</table>

The characteristic dimension in Fo was $H$ for insulated reservoirs and $l_A$ for non-insulated reservoirs.

The gradients of the lines are very close to each other (with the exception of 60/40 temperatures in the non-insulated reservoir).

**CONCLUSIONS**

The analysis of the results of this study shows the possibilities of the application of this methodology for the assessment of heat-reservoir quality. The generalization of results made it possible to eliminate (to a certain extent) the influence of temperatures in predicting the properties of heat-storage systems with an accuracy sufficient for design practice. The influence of the insulation thickness (or its thermal resistance, to be more accurate) on the speed of $\xi_e$ drop has not been investigated, however.

Although the methodology used to reach the verified and generalized results is not simple, their application to a range of practical cases is straightforward. It should be realized that this work could be further refined, for example, by considering the influence of insulation thickness on the storage quality ($\xi_e$). Also, when using the specific results presented, good engineering judgment should be exercised. For instance, stratified tanks would likely conform to guidelines different from those designs used in this study that allow mixing.