Assessment report corresponding to SUB UPC 2014 V0.1 ENG subcontracting from VITO to UPC

ECOVAT Thermal Analysis

0. Objectives

The objective to be covered by this report is to give a detailed scientific answer to the thermodynamic questions arisen during the KIC Review Committee on the Project 067-ECOVAT.

Specifically:

Q2: The claimed 93% efficiency needs to be argued better with calculations. This will surely depend on the density of the insulation.

Q3: The claimed stratification of the water layers with different temperatures needs to be argued scientifically (also on longer time scales, like months); if not the functioning of the system no longer holds.

As indicated in UPC offer, this report corresponds to the proposed Phase 1 of the work, expected to be carried out by the use of simplified models and bibliographic/knowledge based assessment, due to the strong restriction in time that not allows to deal with CFD simulations at this stage.

1. Brief state-of-the-art in seasonal thermal energy storage

Seasonal thermal energy storage (STES) technology enables the production of heat/cool during hot/cold weather to be used in the next season. The stored energy can then be recovered to heat or cool buildings.

However, the number of installations with seasonal storage is still limited [GUA13] while the number of large solar thermal systems (> 500 m2) is rising exponentially, e.g. 244 large solar thermal plants have been installed worldwide in the period 1985-2012; of which 138 in the last period since 2006 till 2012. In Denmark, only in 2013 9 plants have been installed with a total area of 81,000 m2. Yet, large solar thermal systems without seasonal storage can only produce a limited solar fraction, between 10% and 25%. To increase the solar fraction of these systems, the use of large seasonal storage would be necessary. This is especially true when it comes to avoid overheating problems during summertime due to a large solar field capacity to cover heating demand in winter. In this sense, STES can be seen as a solution to bridge the gap between the excess of heat production during summer time and excess of heat demand during the winter. Ecovat storage system introduces the use of electrical energy instead of solar thermal energy and its conversion to thermal energy by the use of heat pumps or under certain circumstances direct electrical heating.

In general, thermal energy storage can be classified by storage mechanism in sensible, latent and chemical mechanisms. Sensible heat storage is based on the change of temperatures of substances that experience a change in internal energy. The main properties of the material selected are therefore density and specific heat. Other important properties are: operational temperatures, thermal conductivity and diffusivity, vapour pressure, compatibility among materials, thermal expansion coefficient, stability, resistance to thermal cycling, and cost.

Latent heat storage is based on latent heat of phase change: heat of fusion (solid–liquid transition) or heat of vaporization (liquid–vapour transition). The solid–liquid transition is the most usually used. The substances suitable for solid-liquid transition are called Phase Change Materials (PCM). Latent phase change heat is high, so the size and cost of the TES devices would, in principle, be lower than in equivalent sensible heat units. However, there are a number of issues that would make the use of these materials difficult such as the low thermal conductivity of most of PCMs in the solid phase or the degree of degradation they may suffer after a certain number of periods of charge and discharge.

Chemical heat storage is a wide concept that can be understood in different ways. In [RIC10], solar-driven thermochemical processes are classified as: i) conversion of solar energy into chemical fuels that can be stored and transported, such as hydrogen; ii) processing of chemical commodities: use of solar energy for processing energy-intensive, high temperature materials and iii) detoxification and recycling of waste materials: use of solar energy for detoxification and recycling of hazardous waste and of secondary raw materials.

All these mechanisms can be used, in principle, in STES, but the most used ones are those based on sensible (liquid or solid or a combination of both) heat storage, as selected at this stage in the Ecovat storage tanks.

Among sensible heat storages, water tanks, water pits and underground thermal storages (UTES) comprising aquifer technology (ATES) and borehole thermal storage (BTES) are the most used ones. Extensive reviews of these technologies can be found in [NOV10, PIN11, XU14].

BTES technology uses ground/soil as TES. The ground is excavated and drilled to insert vertical or horizontal tubes. The inserted tubes serve as heat exchangers, the free soil is the storage medium and water is used as the transfer fluid. To provide good thermal contact with the surrounding soil, the space between the pipes and the borehole wall is usually filled with high thermal conductivity grouting material in order to enhance heat transfer. One of the main drawbacks of this technology is its high initial cost due to the expense of borehole heat exchangers and complex excavation work. Furthermore, it has also to be considered the low thermal capacity, around 15-30 kWh/m^3 and the long time required before achieving a quasi-steady state (about 3-4 years) [SCH03].

In ATES technology wells are used to carry water to/from the aquifer. At least it requires one well to work [PIN11,XU14]. During summer when cold water is needed for cooling buildings, groundwater is extracted from at least one cold well. In the process of cooling down the building, the extracted cold water absorbs the heat and is injected in separate warm well nearby. This process is reversed during winter. The heat capacity of aquifers is around 30-40 kWh/m^3 and acceptable water quality is necessary for them to work properly [SCH03]. It should be pointed out that in some cases, the temperature of the groundwater is not sufficient enough to heat a building so a heat pump might be installed to provide additional heat.

1.1 Large water tanks and pit-storages

Water is considered one of the best media for energy storage due to its high specific heat (compared with other sensible heat storage media) and, in general, its high volumetric energy density. Among the STES using water as media can be found large water storage tanks and pit storages. Ecovat expects to use water as storage medium as well.

Water tank/pit storages are artificial structures usually made of stainless steel or reinforced

concrete surrounded by a thick insulation. A variation of the later is the gravel-pit storage, where the volume is filled with some filler material (usually rocks) being the storage media a combination of both materials.

These tanks are built underground (pits) or close to the ground surface to avoid costly excavations. Top and lateral walls have to be insulated to avoid heat losses. Comprehensive summaries of the different projects involving these large structures so far can be found in Novo et al. [NOV10] and in Pavlov & Olesen[PAV11]. Ecovat tanks are a variation of this option in a configuration similar to a mantle heat exchanger heated tank, as the heat is transferred through wall mounted heat exchangers and not by direct injection of hot water.

The construction of such large structures must consider the optimization of heat losses and economic aspects. For instance, considering that the ratio of the volume to the heat transfer area increases with the size of the device, the larger the volume the lower the heat losses and thus the higher the thermal efficiency.

In general, gravel-pit storages reduce the cost of the upper part of the storage, as it is buried and the top can be used part of the residential area but needs more volume to store the same thermal energy than a water tank design (due to the lower volumetric capacity of the filler material). On the other hand, water tank technology does not need excavation operations or such a large surface but results more expensive due to the tank construction and the structure is quite visible.

Regarding the cost of these systems, it was shown by Pavlov and Olensen [PAV11] that most costly ones are those involving water tanks and water pits. However, the study also pointed out that the costs of those systems tend to decrease as the size of the storage is increased.

1.2 Thermal stratification

Thermal stratification, the natural separation of fluid layers of different temperature due to its difference in density, is one the most desirable property in a TES. Thermal stratification not only increases the thermal efficiency of system where the TES is installed (i.e. solar thermal systems, cooling systems with heat storage) but also reduces the heat losses and increases the overall exergetic efficiency of the TES [ROS01]. The research on thermal stratification within the tank has been studied intensively and different methods for its quantification have been proposed [CRI03, CON04, HAL10]. However, stratification is characterised by its extreme weakness. Among the several factors associated with the loss of stratification in a thermal liquid storage can be mentioned: the mixing produced by the inlet streams during the load or withdrawn phases; the heat losses to the ambient through the tank envelope; the heat conduction from the hot layers to the cold ones; thermal bridges along the tank walls; amongst other causes.

Usually, the stratification of a thermal storage is represented by the transient temperature profiles under different thermal, fluid dynamic and geometric conditions. However, quantitative measurements of the level of temperature stratification appear to be an attractive tool for reporting possible improvements in the optimisation process of these devices. In the last decade, different parameters to quantify the degree of thermal stratification have been defined and can be found in the literature.

Among the different studies can be cited that of Bahnflet and Musser [BAN98], who calculated an equivalent loss of capacity (or equivalent loss of tank height) evaluating the capacity lost due to mixing and conduction during the course of a cycle (charging and discharging). The lost capacity is

defined as the capacity that cannot be removed from a tank due to an outlet temperature limitation. They also used the thermocline thickness as an illustrative parameter to characterize the temperature distribution inside the tanks. The thermocline thickness is defined as the vertical region of fluid inside the tank which contains a thermal transition layer between warm and cool water volumes.

Davidson et al. [DAV94] and Adams and Davidson [ADA93] proposed a way to measure the level of temperature stratification by weighting the energy stored by its vertical location (which is similar to an energetic momentum). The dimensionless energetic momentum defined as MIX number is calculated as a function of the largest and smallest values of the energetic momentum (considering ideally fully stratified tank and completely mixed tank). These ideal situations are evaluated using analytical models. The completely mixed tank situation is obtained by means of a global energy balance in the tank, whereas the plug flow model is used to predict tank temperature distribution for the fully stratified situation.

Various works in the literature report that an energy analysis could not be sufficient to compare different temperature distributions. Energy analysis cannot distinguish between tanks with different levels of temperature, even if these tanks have equivalent energy quantities, i.e. energy analysis cannot account for the degradation of the energy stored. In this sense, the Second Law of Thermodynamics provides an alternative way to evaluate the quality of the stored energy. The process of loss of stratification (due to fluid mixing, environment losses, etc.) creates entropy and, by consequence, a degradation of the energy stored. Exergy analysis can be then a tool for evaluating this degradation, quantifying its quality. The works carried out by Rosen [ROS99,ROS01] are an example of this kind of analysis. In his works, he has defined exergy efficiency over a closed system, considering both charging and discharging processes. Exergy efficiency is then defined as the ratio of the exergy of the discharge process to the charge process. This parameter shows the importance of temperature stratification in the performance of the storage tank. The higher the storage stratification the higher the value of the exergy efficiency. However, this parameter is only useful after a complete cycle of charging and discharging of the store, being difficult to consider the transient nature of the process

A quite complete review about the different ways of quantifying thermal stratification can be found in [HAN09].

Additional comments on the particularities of Ecovat regarding the exergy analysis and the thermal stratification are introduced in the results section.

1.3 Modelling of thermal storage tanks

The design and optimisation of thermal stratified storage tanks requires a profound knowledge of the thermal and fluid dynamic phenomena involved. The complex phenomena associated with the behaviour of these devices, make optimised design a challenge for researchers and designers.

Designs are very often based on simple mathematical models (analytical methodologies based on global mass and energy balances or one-dimensional models), and/or expensive experimental trial-and-error analysis using prototypes to provide the necessary information for these models (i.e. heat transfer coefficient in convection, pressure loss coefficient, mixing parameters, etc.).

The importance of one-dimensional models relays in the fact that they are computationally more efficient in terms of CPU time cost and suitable for use into overall energy-system simulation

programs which allow long-term simulations. For this reason, one-dimensional modelling has been the focus of attention of many researchers. A great number of simplified models to account for stratification have been developed. Some of these models are based in the multi-node approach [KLE93], being the degree of stratification determined by the choice of the number of temperature levels. Other kind of one-dimensional approaches to account for mixing at the inlet have been proposed in the literature (e.g. [ZUR88,NEL99]). The main problem of such kind of models is the necessity of empirical-based information to evaluate mixing at the inlets. Thus, the validity of such results depends on the accuracy of the experimental coefficients and their suitability for such models.

On the other hand, detailed models based on the multi-dimensional resolution of the Navier-Stokes and energy equations should be capable of describing the thermal and fluid dynamic behaviour of storage tanks. In the last decades, detailed numerical simulations using computational fluid dynamics and heat transfer (CFD&HT) codes have emerged as a powerful tool for the prediction of these systems. However, detailed numerical simulations demand large computational resources and in spite of the use of parallel computers and efficient parallel algorithms, long term simulations are still very costly. Yet, there are some works which take advantage of CFD&HT simulations. Furthermore, due to the lack of empirical information about the heat transfer coefficients in thermal storage tanks, CFD&HT have been also used in order to obtain correlations capable of characterising the transient heat transfer process inside such equipment. Among of these works can be mentioned [CON04, ROD09, ROD09b, PAP09, ROD13].

2. Definition of the cases of study. Aim and scope

The present study focuses on the thermal and exergetic study of the ECOVAT concept. This study addresses the questions posed by the Kic Review Committee which are specifically:

i) Regarding the efficiency of the device, which is claimed to be of 93%
ii) Regarding the stratification of the storage.

In order to address the main issues raised by the Kic Review Committee a model based on reasonable simplifications but which allows estimating the long-term performance of the ECOVAT concept is here used.

To carry out the performance analysis, a study of the charging, idle and discharging phases of the storage will be carried out. However, considering the limitations of the computational time required for performing a thorough study of the prototype, the scope of this study is limited to a one-dimensional modelling of the store and a series of hypotheses in order to simplify the complex problem under study. The main hypotheses considered are:

- The model used for simulating the behaviour of the tank is the multi-node model [KLE93]. As aforementioned, this is a one-dimensional model where the tank volume is divided into different levels of temperatures which can be or not of the same size. In this approach, it is considered that the volume of each temperature level is the same.
- The fluid in the tank has a one-dimensional behaviour, i.e. only axial temperature differences are considered whereas radial and azimuthal temperature variations are here neglected. Although the multi-node model originally did not consider the axial conduction between the different levels of temperatures, the present approach

considers axial conduction between the different layers and the heat transfer between tank walls and the fluid.

- Even though the tank is divided into N temperature layers it has to be borne in mind that when a high number of temperature layers are imposed it does not necessarily imply a high level of accuracy, as the model used cannot consider the mixing between layers due to advection, nor the laminar or turbulent boundary layers developed close to the tank walls. In this kind of approach, the instantaneous behaviour of the flow obtained numerically does not always reproduce the actual behaviour of the tank. On the other hand, what this kind of modelling provides is a fair agreement with the long term behaviour of the system. Thus, the outcomes of such models should be devised as a forecast of the average performance during a period of time.
- As the number of temperature levels is imposed and advection mechanisms are neglected, among other simplifications, 1D models such as those used here do not allow the quantification of the stratification in the tank. If this property has to be evaluated, multi-dimensional models considering the detailed fluid dynamic and thermal behaviour of the storage should be used instead.
- The heat exchangers at the tank walls are considered with an adapted ε-NTU model, taking a uniform tank side temperature for each Ecovat layer. The model considers the convective thermal resistances on both fluids (by applying laminar+turbulent heat transfer correlations and variable thermal properties on both sides) and the conductive thermal resistance due to the concrete layer existing between the serpentine coil and the water surface. The heat losses to the environment are not considered in the model.
- Heat transfer coefficient between the tank walls and the fluid, although variable with the temperature difference, are taken from literature available correlations.
- For the heat losses at the different tank walls an overall heat transfer coefficient is imposed.

Regarding the second issue, the scope of this study cannot give a conclusive answer as in order to evaluate properly the degree of stratification either ad hoc experimental set-ups or detailed CFD&HT modelisations should be carried out. It is important to remark that the model used can only consider axial conduction and the mixing it produces, which is not by far the major cause of de-stratification in storage devices. As will be observed later, only sensitivity analysis by modifying the water thermal conductivity can be done to evaluate the de-stratification impact of an increased conductive heat between layers. In the corresponding section in the results, a qualitative analysis of the stratification issue is given.

2.1 Description of the ECOVAT concept

A more detailed description of the ECOVAT concept can be found in [BER14]. Hereafter, the main characteristics dimensions and working conditions are briefly summarized.

ECOVAT concept is proposed in 4 main dimensions dubbed **ECOVAT S,M, L and XL**. In the table below the sizes of each of them are given. The main concept consists of a cylindrical buried tank, with outer concrete walls. Another internal wall with embedded heat exchangers is the means for charging and discharging the storage medium. These inner walls are constructed by assembling different modules of heat exchangers. This modularity is what allows easily constructing and assembling different sizes of the ECOVAT concept (Table 1).

Table 1: Dimensions of the ECOVAT models

ECOVAT model	Height[m]	Diameter[m]
S	16	11
M	16	18
L	16	39
XL	16	58

Given the dimensions of the different ECOVAT models, a geometric estimation of their volume and heat transfer areas are given in the Table 2. Notice that the ECOVAT XL concept was not included in the table as the present study is carried out for the first three prototypes.

Table 2: Geometric estimation of the volumes and heat transfer areas of the prototypes

ECOVAT model	Volume [m^3]	Total heat transfer area [m^2]	Lateral surface [m2]	Top/bottom surfaces [m^2]
S	1520.53	742.99	552.92	95.03
M	4071.50	1413.72	904.78	254.47
L	19113.45	4349.54	1960.35	1194.59

In this study, the walls are considered as layers of different materials, i.e. the thermal resistance of the different layers composing the lateral walls are taken into account (e.g. concrete, foam glass, EPS, sand-water, soilmix concrete, etc.). Overall heat loss coefficients are then dynamically evaluated within the code evaluating also the heat transfer coefficient between the wall and the fluid as a function of the temperature of the storage medium.

Taking advantage of ECOVAT modularity, these models are also segmented in the vertical direction, i.e. the total height of the tank is segmented into 5 levels, which can be charged/discharged independently and /or at different temperatures. This distribution into different segments which can work and be charged/discharged at different temperatures might be interesting from a stratification point of view. However, the level of mixing (loss of stratification) that would be produced within layers at different temperatures during the charging/discharging phases and also in the idle phase has to be determined by using detailed models or ad-hoc experimentation for the working conditions of these devices. In this study, only a rough estimation of the mixing due to the axial heat conduction between the temperature levels can be given. Mixing due to developed turbulent boundary layers near the walls, thermal bridges caused by the walls of the heat exchangers, convective plumes due to

temperature gradients or eventual thermal inversion, flow entrainments due to jets effects caused by the boundary layers descending along the walls and irrupting into a layer at similar temperature cannot be considered with the level of modellisation used in the present study.

2.2 Methodology used

The implementation of the storage tank methodology has been made within the existing NEST platform (see [DAM11]) which allows the linking between different elements to perform a specific system or configuration. This platform has been previously used for modelling the behaviour of a storage tank for concentrated solar power tanks with good results. Validation and results obtained using this methodology can be found in [ROD13].

The main advantages of a modular object-oriented tool are

i) any basic element programmed in a general way can be used in a given configuration and re-used in other systems;
ii) the elements which form a determined system interacts only through its boundary conditions, being solved independently which allows the change of a given model (e.g. a 1D approach by a 3D approach) while the rest of the elements which form the system remains unchanged and,
iii) Each element of a given system can be solved using a different parallelization paradigm without any need of re-writing any part of the code.

In the present implementation the storage tank is considered as the sum of different parts e.g. bottom wall, embedded heat-exchanger lateral walls, top wall, storage medium, etc. For each element of the storage more than one model approach can be considered. For example, for modelling the storage medium, different levels of modellisation can be considered. Due to time constrains, in the present study the storage medium is treated with a one-dimensional model (multi-node model), but the present methodology can readily be extended to multi-dimensional models such as those used in [ROD09] by substituting the object “multi-node” by a CFD&HT module which can be axial 2D or fully 3D. This is one of the advantages of a modular methodology, as each element can receive a special treatment from the physical point of view (i.e. different hypothesis can be considered). Furthermore, each of these elements (objects) is capable of solving itself given determined boundary conditions, which can be obtained from the neighbouring elements (objects).

At each time step, the governing equations of each object are solved taking the boundary conditions from the linked elements whereas at the same time, the outputs of each element are used as the boundary conditions for its neighbours. The algorithm used for the resolution of the whole system of equations is a Gauss-Seidel like algorithm, in which iterations are carried out until convergence is attained. Then, after updating the variables, the algorithm goes to the next time step. For more details about the general algorithm the reader is referred to [DAM11].

2.3 Description of the tests.

In order to study the thermal behaviour of the ECOVAT storage, four different tests have been carried out. The definition of the tests is given hereafter.

Test 1: Cool-down of the storage. In this test, the tank is initially at a temperature of 90ºC

and is submitted to heat losses to the environment (soil) at 12ºC during a long-term period of 180 days, according to [BER14], from which performance indicators in KIC questions where obtained. The study has been carried out for ECOVAT S, M and L but for comparison with [BER14] detailed results are shown for ECOVAT M.

Test 2: Full cycle of charging/discharging. In this test, the tank is initially charged at constant temperature and mass flow rate through the heat exchangers embedded in the tank walls. The charging process duration is 2000 hours, and the initial tank uniform temperature is considered at 12ºC. The charging is accomplished by circulating the hot heat transfer fluid (HTF) through the heat exchangers in the wall. The load of the tank takes place from top to bottom. As the tank has five heat exchangers operating at different heights, the hot fluid is first circulated through the topmost level heat exchanger, up until the temperature in the core of the tank at the topmost level is 92.6 % of the maximum temperature difference (75ºC level in the range 12-80ºC). Otherwise, it is supposed that a huge time would be required in order to raise the temperature in the tank at the inlet temperature of the HTF. Once the first (topmost level is charged), the next heat exchanger layer is activated, with the fluid circulating now through the second level whereas through the other levels no fluid is circulating. The next fluid layers are charged in a similar form as the topmost one. The whole duration of the process is 2000h.

After that, the tank is submitted to a cool-down process of 180 days. The third phase of this test consists of discharging the tank at constant temperature and mass flow rates during 2000 hours. With these three phases a complete charge/discharge cycle is accomplished. The details of the mass flow rates have been adapted from conversations with Ecovat company, while temperature levels of these phases are taken from [BER14] (all summarised in the Table 3).

Table 3: Inlet conditions for tests 2 and 3

ECOVAT model	Volumetric flow rate through 1 layer [m^3/h]	Charge inlet temperature [ºC]	Discharge inlet temperature[ºC]
S	6.50	80	12
L	23.64	80	12

The charging/discharging of this test have been designed so as to mimic one of the possible working conditions of the tank. Of course, due to the possibilities the modular heat exchangers offer, this is not the only possible operating modes for this concept, but the optimum which better adapts to the system in which it is installed should be found for each case. This aspect has been explained in detail in the results section.

Test 3: full cycle charge/discharge. This is another possible operating mode of ECOVAT concept. In fact, this test is similar to test 2, but in this case, once the temperature in the topmost level reaches an 80% of the maximum difference, the next level starts being charged but the top one is still being charged. In this case, as the following levels are being charged, the total mass flow rated circulating through the lateral heat exchangers increases as more levels are being charged in parallel at constant rate at the same time.

Test 4: heat exchanger influence on the charge/discharge operation; series connection As the results of Tests 2 and 3 outlined the importance of the charge/discharge control

in terms of energy/exergy management, the case of the heat exchangers connected in series from top to bottom (charge) and bottom to top (discharge) has been analysed because it is known to be the most adequate to obtain the outlet water temperatures closest to the tank limit temperature. This study has been done by using the heat exchanger model in a five layer-five exchanger approach (not by the 1D multimode). The situation has been simplified to one charge of 2000h (serpentine top layer inlet at 80ºC to buffer at 12ºC) immediately followed by an equivalent discharge period (serpentine bottom layer inlet at 12ºC to buffer at final conditions of the charge period).

The development of the heat exchanger model and its testing against a one buffer layer indicated some important conclusions on its performance and the inter-relation buffer-heat exchanger. Those conclusions are highlighted in these charge+discharge results on the whole Ecovat (flow rate dependence, importance of concrete distance between serpentine and water surface, tank size).

3. Results

3.1 Test 1 results

The average temperature variation and cumulative heat losses during the cool-down of the storage is given in Figure 1 for Ecovat S, M and L. For comparison with [BER14] (from where performance indicators cited by KIC questions where obtained) these results are plotted also for ECOVAT M. As expected the average temperature in the store during the cool-down process follows a negative exponential with time. At the end of the cool-down process the average temperature in the store was about 80ºC. This value is a tad lower than that obtained by [BER14]. However, it has to be pointed out that in [BER14] heat losses through the top of the device were neglected and the wall layers where simplified (only one layer of 300 mm insulation considered vs. the multilayer considered in current study), resulting in a slight difference in the overall heat losses and a slightly lower thermal efficiency of the device.

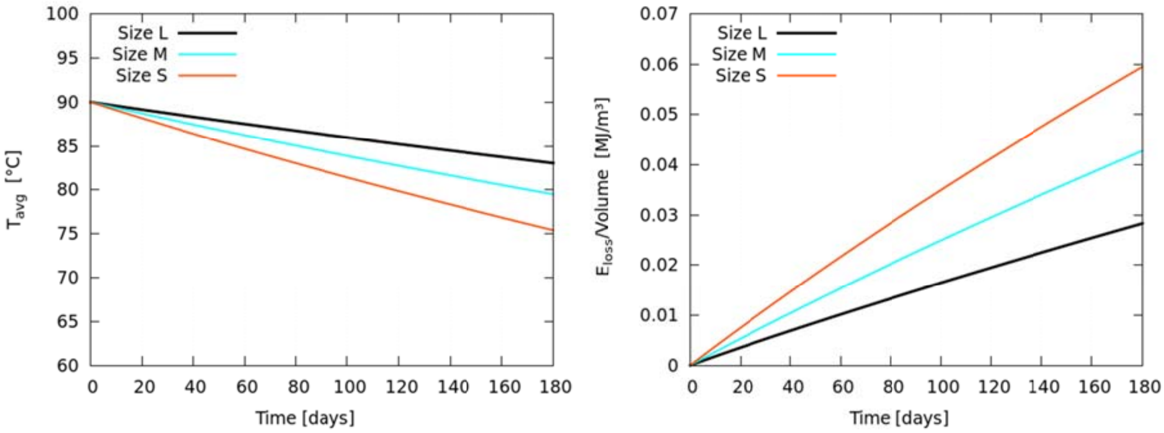

Figure 1 - ECOVAT Test 1 results. (left) Average temperature variation along the cool-down process. (right) Cumulative heat losses per unit volume.

Being the thermal efficiency of the device defined as the ratio of the energy contained at the end of the cool-down process to that contained at the beginning of it,

$$\eta = 1 - \frac{\int_{t=0}^{t} \dot{Q}_{loss} dt}{\rho V C_p (T^0 - T_{env})}$$

The energy efficiency of the ECOVAT concepts S, M and L is given in the following table.

Table 4: Cool-down test. Energy losses and efficiency of the ECOVAT concept

ECOVAT concept	Q_{loss} [MJ]	Q_{loss}/V [MJ/m^3]	η
S	90.47	0.06	81.50
M	174.18	0.043	86.72
L	540.97	0.028	91.22

Notice that the efficiency of ECOVAT M is lower than that claimed at [BER14] (86% vs. 90 %). These differences can be attributed to two different sources: i) in [BER14] energy losses through the top are neglected and ii) here thermal resistance of the walls is considered accounting for all the layers which form the composite wall. Nonetheless, the efficiency of the devices is rather high, especially for those of larger volumes, in which due to the larger volumetric thermal capacity, volumetric energy losses are lower.

Another issue to be considered is the distribution of the energy losses through the different walls of the tank. In the following table, these losses are given.

Table 5: Cool-down test. Energy losses through walls.

	Q_{loss}	Q_{loss} lateral wall		Q_{loss} top wall		Q_{loss} bottom wall	
ECOVAT	[MJ]	[MJ]	[MJ/m^2]	[MJ]	[MJ/m^2]	[MJ]	[MJ/m^2]
S	90.47	68.03	0.123	6.54	0.069	15.90	0.167
M	174.18	112.29	0.124	18.05	0.071	43.83	0.172
L	540.97	243.31	0.124	86.92	0.073	21.073	0.176

When it comes to the distribution of the energy losses through the walls, it can be observed that even when the larger device is the one with larger energy losses (due to a larger heat transfer area), the ratio by square meter of wall area is the same in all devices as the structure of the layered walls is nearly the same and the influence of the temperature of the fluid in the wall resistance is negligible. However, analysing these losses it is evident that the poor bottom insulation or the lack of thereof makes energy losses by heat transfer area through the bottom the largest of the three. This aspect would be considered as an improvement in these devices, but of course it has to be a trade-off between the extra cost of the bottom insulation and the cost of the energy saved for this concept.

As a final comment, the influence of the thermal bridge caused by the polymeric joint between Ecovat wallparts has been analysed by considering the indicated width and depth, and a thermal conductivity of 0.034 W/mK. Although the joint gives a relatively low insulation compared to the

wallpart, the high width ratio between both makes the influence of the joint very small (estimated in a 1.5%). Nevertheless, the continuity-integrity of this joint in avoiding any leakage between the in-tank water and the sand-water behind the wallpart is a key aspect to avoid a thermal bridge that would bypass the wallparts insulation in a serious way.

3.2 Test 2 + Test 3 results

The exergy efficiency of the whole cycle can be defined as,

$$\eta_{ex} = \frac{\Xi_{end}^{charge} - \Xi_{ini}^{charge}}{\Xi_{ini}^{discharge} - \Xi_{end}^{discharge}}$$

Being

$$\Xi = \int_V (\rho\xi)_i dV$$

$$\xi = (h - h_0) - T_0(s - s_0)$$

In the above equations, Ξ is the exergy at the given states, $\xi$is the specific exergy, V is the volume, h and s are the specific enthalpy and entropy whereas the sub-index '0' indicates the dead state, i.e. the state of thermodynamic equilibrium with the natural surroundings.

Similarly, an exergy efficiency for the charging phase can be defined as the ratio of the actual exergy change during the charging process to that it would theoretically be if the tank would be whole charged at the temperature of the inlet fluid. This way, it would give an idea of how close or far the charging process is from the ideal situation. In other words, is the system capable of storing energy at the temperature at which it is being charged?

The obtained results show a great difference between Ecovat S and L temperature diagrams (Figures 2 and 3) and exergetic efficiencies (Table 6). The focus here should be given to Ecovat S, as the time range of 2000 h was selected in comparison to the previous indicated value from the report [BER14] to which the questions from KIC where formulated. For this time range, the Ecovat S is almost fully charged, while Ecovat L is still far from this status. However, it can be readily observed how the charging and discharging strategies have a direct impact on the temperature, energy and exergy evolution within the tanks. Apart from the heating evolution, it is also observed the layer by layer heating-up process, as in this case a heat exchanger covering each layer is switch on/off depending on the layer average temperatures and the control strategy. During the charge of one layer, the temperature mainly varies in that part of the buffer, remaining almost unchanged for the rest of the tank. For test 2 (Figure 2), the passive layers slightly diminish their temperature due to heat losses through the wall. For test 3 (Figure 3), as all the active layers maintain their activity, the temperature of upper layers continues their heating up to the limit temperature.

The reported energy and exergy efficiencies for the four cases considered are depicted in Table 6. As can be observed, the energy efficiencies are high and similar to test 1 results. The exergetic efficiency comparing the injection of charging phase with the extraction of discharging phase is giving values between 50% (Ecovat L at test 2) to 80% (Ecovat S or Ecovat L at test 3). The heating efficiencies are related with the charge/discharge level of the tank. As outlined above, the exergetic efficiencies show a strong link with the charge/discharge mode and the achieved charge level.

Table 6: Test 2 + 3 performance results.

Case	Conditions	η	$\eta_{ex,charge-discharge}$	$\eta_{ex,charge}$
1	S-Test 2	80.53	77.38	95.96
1b	S-Test 2 Keff=1	80.23	77.99	96.43
1c	S-Test 2 Keff=3	80.09	78.23	82.80
1d	S-Test 2 Keff=10	79.52	73.72	67.64
2	S-Test 3	80.49	79.67	99.86
3	L-Test 2	91.84	50.72	36.99
3b	L-Test 2 Keff=1	91.83	50.36	36.10
3c	L-Test 2 Keff=3	91.43	40.12	27.22
3d	L-Test 2 Keff=10	90.80	35.11	34.19
4	L-Test 3	92.93	88.31	58.64

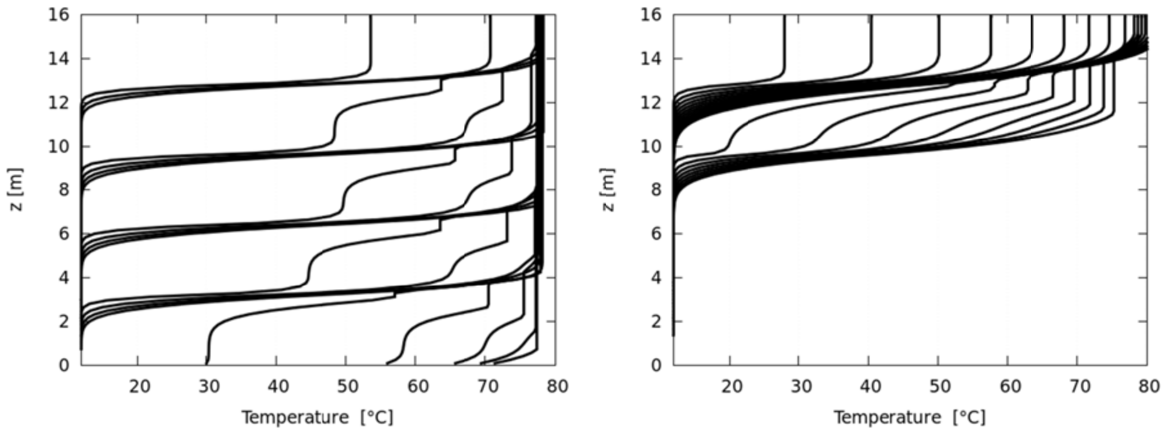

Figure 2 -Test 2: Water tank temperature evolution with time (each line covers a 100h range). (left) Ecovat S. (right) Ecovat L.

Regarding the effective thermal conductivity tests, the results indicate an important influence of the equivalent turbulence mixing for enhanced conductivity values higher than 3 W/mK. The energetic performance is slightly reduced, while the charge/discharge exergetic efficiency is affected in a more or less relevant way depending on the tank size and charge/discharge mode. In Figures 4 and 5, the mixing effect of the increased thermal diffusion is clearly observed. These are only indicative results of an equivalent enhanced mixing by diffusion, as convective effects could be much more complex showing local behaviours like boundary layers at the walls that would lead to significantly different temperature maps than those reported here.

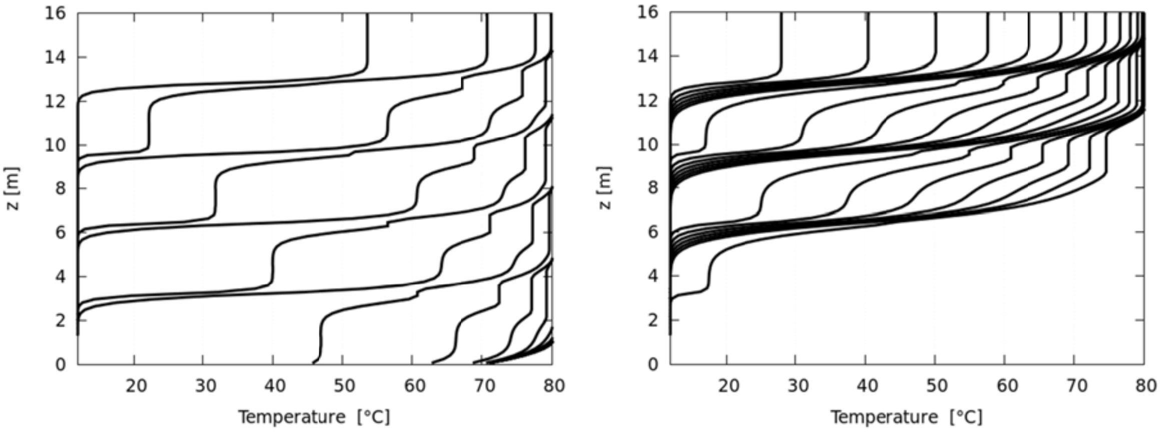

Figure 3 - Test 3 : Water tank temperature evolution with time (each line covers a 100h range). (left) Ecovat S. (right) Ecovat L.

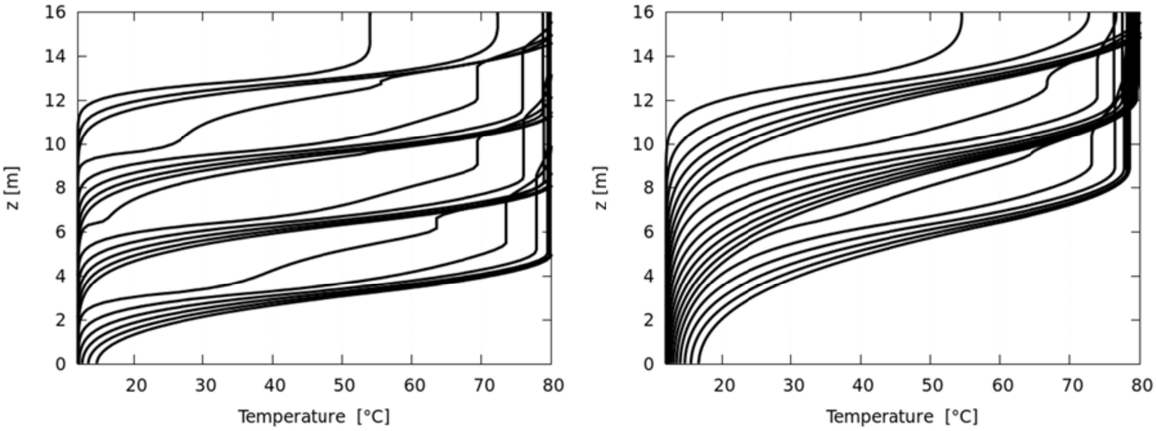

Figure 4 - Test 2 Keff Ecovat S: Water tank temperature evolution with time (each line covers a 100h range). (left) Keff=3W/mK. (right) Keff=10W/mK.

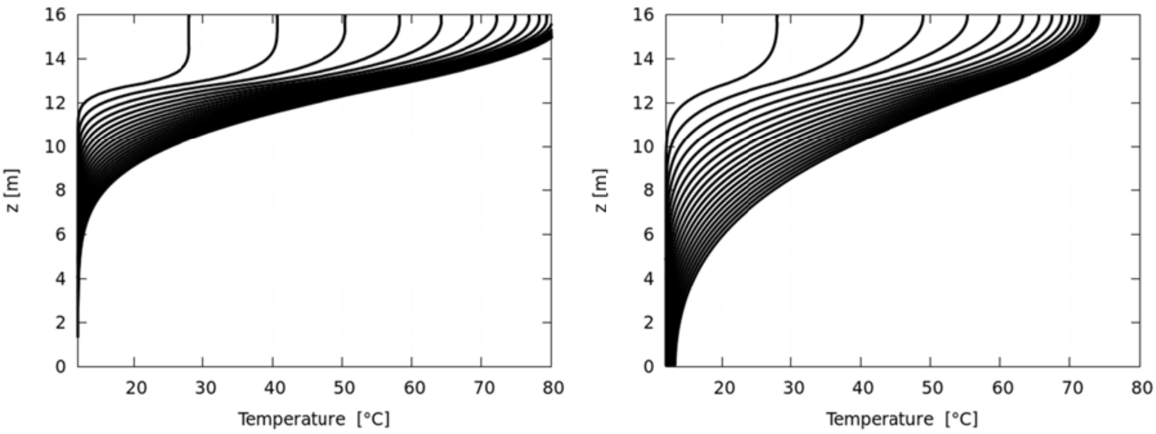

Figure 5 - Test 2 Keff: Water tank temperature evolution with time (each line covers a 100h range). (left) Ecovat L Keff=3W/mK. (right) Ecovat L Keff=10W/mK.

3.4 Test 4 results

As introduced previously, in this case the heat exchangers of the five layers have been connected in series, which is expected to be the mode of maximum heat transfer operation at a fixed flowrate (otherwise full charge with all layers in parallel will be the fastest) if the tank is expected to work as a single temperature buffer.

The reference case has taken Ecovat S at the maximum indicated flowrate for the charging period (6.5m^3/h), and the average indicated flowrate for the discharge period (2.0 m^3/h) in a reference building floor heating case. On the other hand, an average concrete thickness between the center of the serpentine coil to the tank water surface has been considered from the submitted drawings from the Ecovat company.

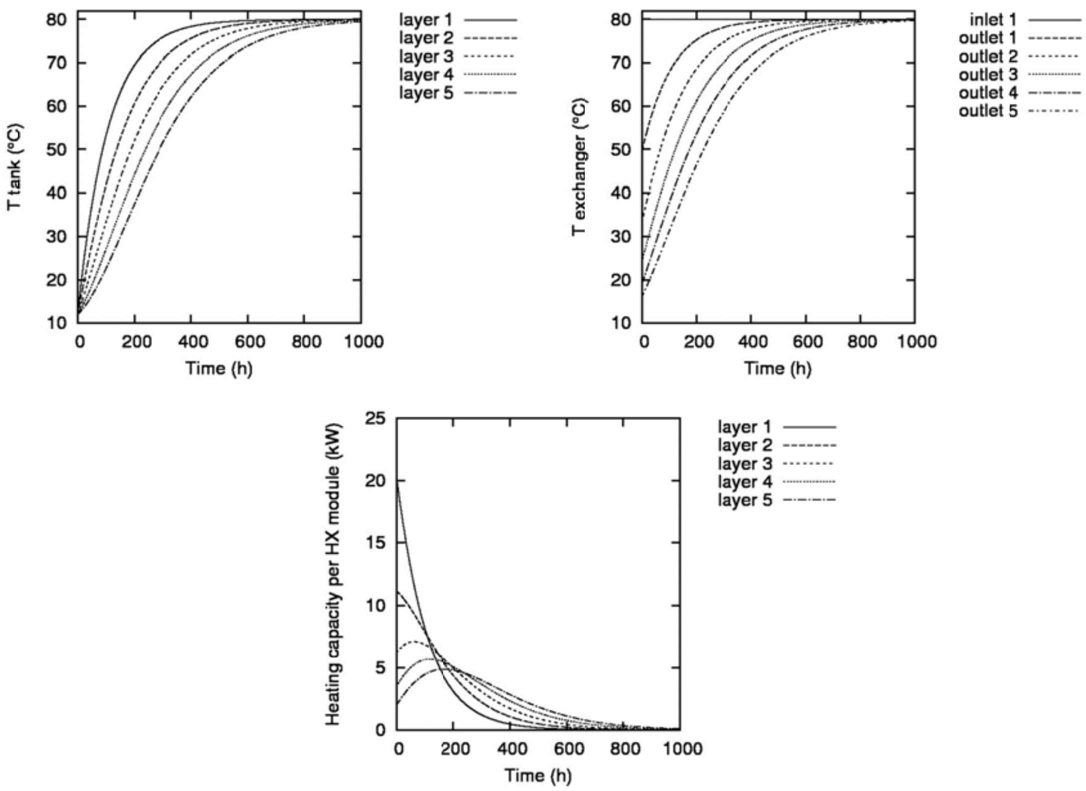

Figure 6- ECOVAT S Test4-charge: baseline geometry and flowrate.

The obtained results (Figures 6 and 7) show the evolution (charge+discharge) of the average temperature of each layer, the intermediate inlet/outlet heat exchanger temperatures and the heat transferred by layer. It can be immediately identified that with this connection method the whole tank is heated faster than with the considered charge methods in test 2 and test 3 (layer by layer). As an example, look how, at initial time, the first layer (top) heat exchanger in the charge mode has a change in temperature from 80ºC to 50ºC, while adding the other layers contribution in this series mode, the water leaves (layer 5, bottom) the Ecovat with a temperature of about 18ºC. The relative contributions in heat transfer from each layer have also been shown, depicting the evolution of each layer with time. The outlet serpentine water temperature roughly follows the temperature of the bottom tank layer.

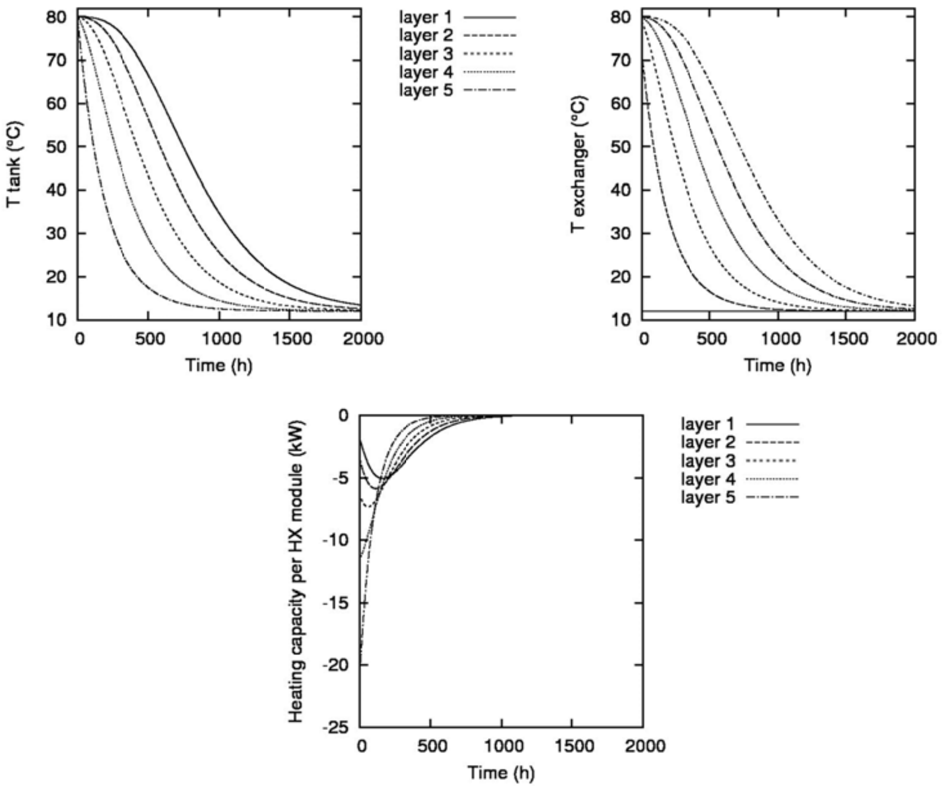

Figure 7 - ECOVAT S Test4-discharge: baseline geometry and flowrate (2 m3/h).

For the discharge mode, one can readily observe how the time needed to discharge the tank has been increased substantially due to the reduction in flow rate comparing to the charge process (6 to 2 m3/h). The rest of conclusions are similar to the charging process but in an inverse way (bottom to top). The leaving serpentine water temperature again follows the last buffer layer in contact, in this case layer 1; with a redesign of the serpentine circuit and considering in that case in the model the local temperature variation within the tank, the outlet temperature will probably extend the region at highest temperatures. However, in this case, as long as the heat is extracted from the tank upper layers, the in-tank water reduces its temperature and this is translated to the outlet serpentine water temperature. An important comment comes at this point: Ecovat is not an open storage tank where it is expected to recover the mass of water stored at one temperature at the closest possible temperature after a certain period of time (as in Domestic Hot Water tanks). Conversely, Ecovat acts as a heat accumulator, increasing the energy stored density by rising its temperature vs. the initial temperature; as long as heat is extracted the temperature drops, in an analogous way as an electric condenser loses voltage as current is extracted from it. From our point of view, here the exergetic focus should be moved to the real water outlet temperature needed in the Ecovat application, that is, useful energy is that which covers the temperature level needed in the particular application (for example in floor heating around 30ºC), independently from the maximum temperature on the Ecovat (which is desired to be maximum to reach the limit in energy stored density).

As assumed as an interesting and relevant result, the effect of serpentine water flow rate has been analysed in the discharging process. In the Figure 8 it can be observed how with an increased flow rate, the discharge process is accelerated, while the corresponding serpentine water temperatures also leave the tank at lower temperatures, following the tank temperature decay.

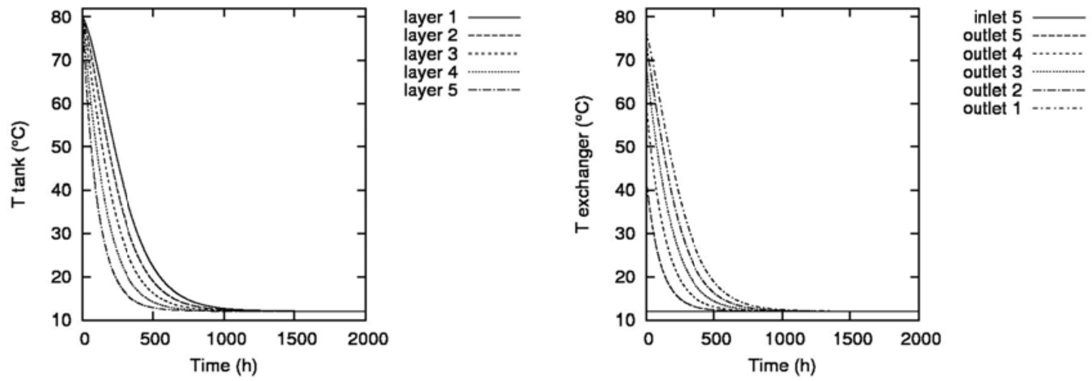

Figure 8 - ECOVAT S Test4-discharge: baseline geometry and maximum flowrate of 6.5m^3/h.

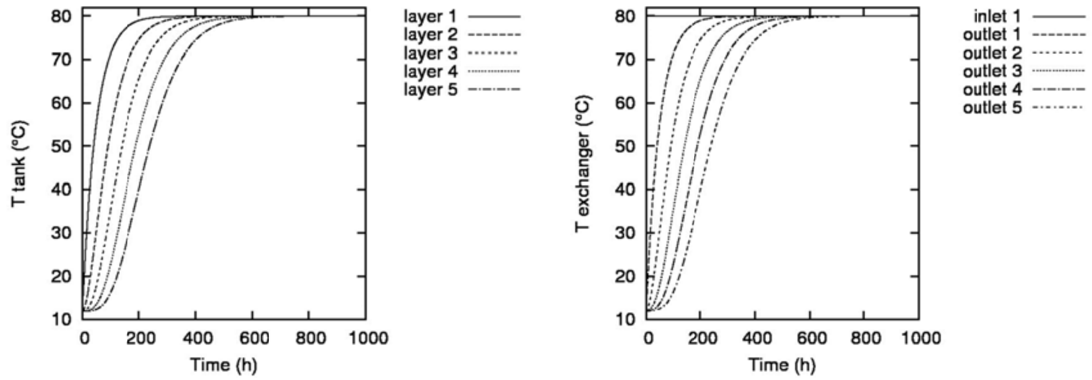

Figure 9 - ECOVAT S Test4-charge: minimum concrete geometry and baseline flowrate (6.5 m^3/h).

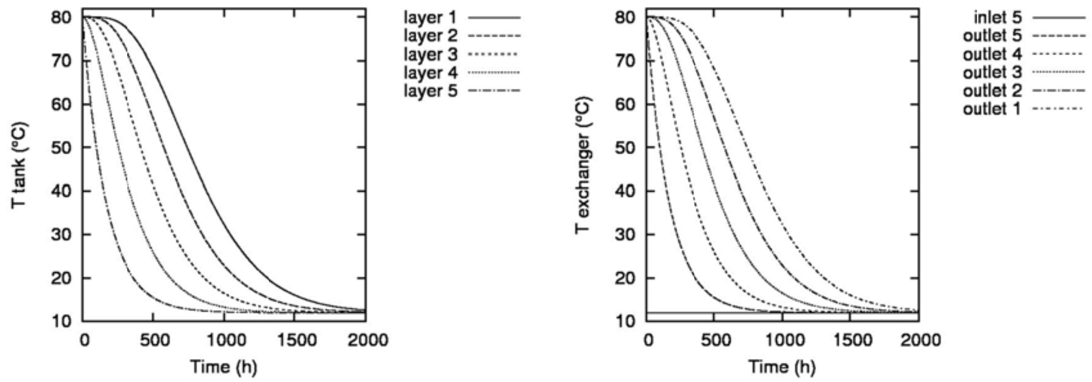

Figure 10 - ECOVAT S Test4-discharge: minimum concrete geometry and baseline flowrate (2 m^3/h).

Another interesting aspect of the heat exchanger vs. tank interaction analysis has been the identification of the dominant heat transfer resistance. Depending on the case, the limiting factor is the natural convection within the tank, but in other cases, for example when an important concrete layer separates the serpentine from the tank water, this insulation-like concrete layer acts as the dominant factor. In Figures 9 and 10, a situation with negligible concrete thickness has been simulated in order to visualize the possible improvements that can be devised in the Ecovat by

addressing this aspect. If we focus on the charge process, it can be seen how the heating-up is accelerated in an important way (from 1000 h to 600 h). However, in the discharge process the effect is clearly less relevant, only extending the maximum serpentine water outlet temperature interval. The reason of this asymmetric behaviour is based on the impact of the water serpentine flowrate in the heat exchanger effectiveness, and if this value is already saturated (maximum heat flow rate given) when applying an improvement on the heat exchange process.

A case on the Ecovat L is finally shown in Figures 11 and 12, in order to compare the charging times with those outlined in tests 2+3. The flowrates have been maintained at the maximum level for both charging and discharging processes, as applied in the cited tests. The results show how the series connection increase the charge and discharge rhythm in an important way, indicating again that the charge and discharge strategies together with the heat exchanger geometry and operating conditions are the key issue to improve Ecovat performance to each particular case needs. Another charging/discharging option to obtain the fastest energy exchange ratio could be to charge/discharge in parallel all layers at the same time; this highlights the flexibility of Ecovat and the importance to analyse the energy/exergy recovery within a clear statement of the Ecovat goals in every installation.

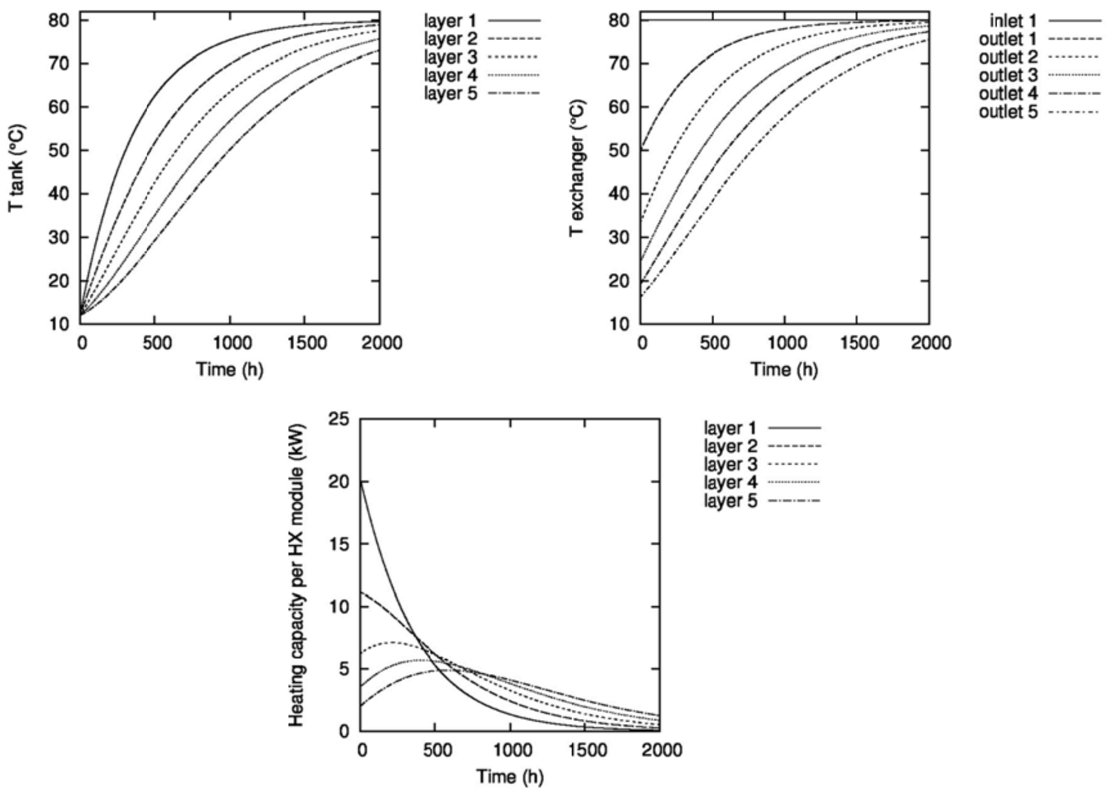

Figure 11 -ECOVAT L Test4-charge: baseline geometry and maximum flowrate.

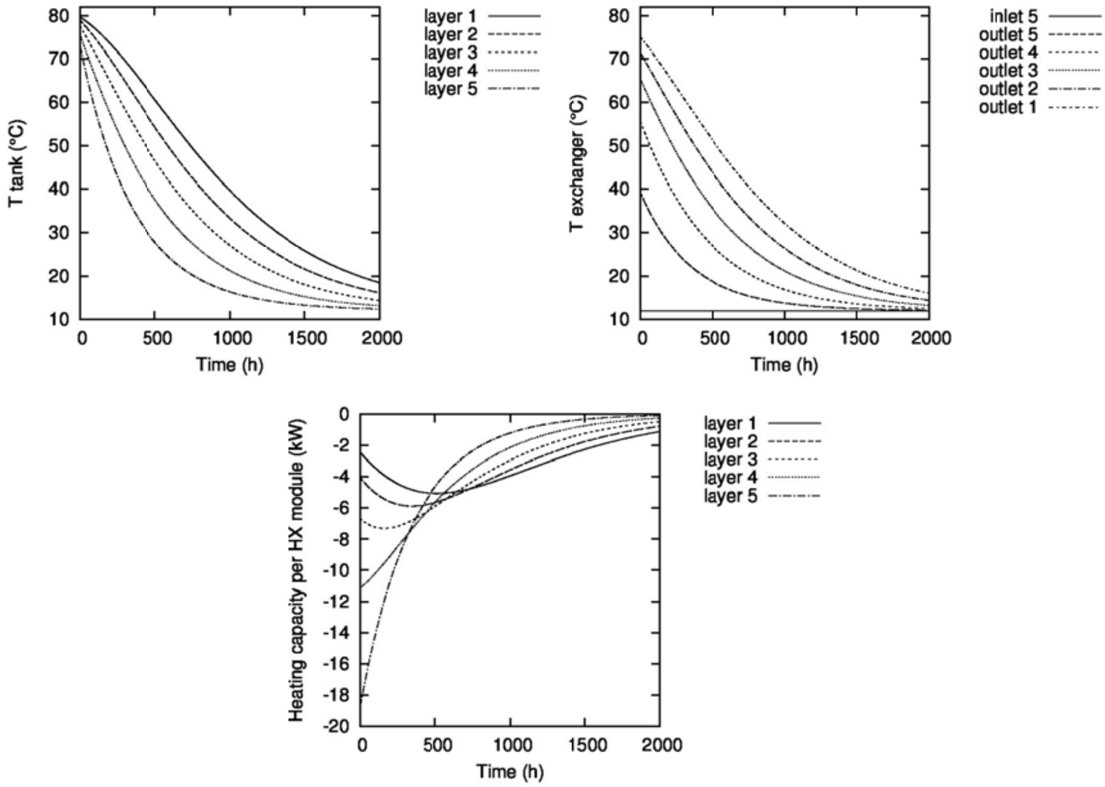

Figure 12 - ECOVAT L Test4-discharge: baseline geometry and maximum flowrate.

3.5 Stratification analysis

As already introduced previously, complex flow structures like mixing due to developed turbulent boundary layers near the walls, thermal bridges caused by the walls of the heat exchangers, convective plumes due to temperature gradients or eventual thermal inversion, flow entrainments due to jets effects caused by the boundary layers descending along the walls and irrupting into a layer at similar temperature cannot be considered with the level of modellisation used in the present study. Only a sensitivity analysis can be carried out with the 1D-model by enhancing the thermal conductivity of water, substituting the real convective effect by an increased axial diffusive mixing. This has been done in Tests 2+3 by raising the conductivity from 0.6 to 10 W/mK. For range below 1 W/mK no important de-stratification effects have been observed, although for higher values relevant changes in both the exergy performance (up to 4% for Ecovat S; for Ecovat L the low charge level makes difficult to take conclusions of these results) and in stratification level have been detected (dependent on Ecovat size and charge/discharge strategy).

The quantification of the thermal stratification degradation in large-size heat storage tanks is a very complex task that needs the use of CFD and/or experimentation. Even in the CFD case, the huge time scale associated with large units makes the prediction of stratification and its disturbance a challenging task and restricted to small time ranges and certain Ra numbers. The CFD researchers

usually look for analysis of particular tank zones, analyse the problem scaled at lower Ra numbers, and/or design statistically stationary representative tests to reduce the time scale of the problem.

What we can introduce and analyze at this stage are some comments on the Ecovat design that are indirectly associated with the stratification and its disturbance. These indications are qualitative and coming from our knowledge and experience in natural convection processes.

The pure conductive effects produced in still stratified water (like those in lakes, basins,etc.), which are those predictable by simplified 1D 'multinode' codes, are well-known to be typically small compared to the convective effects occurring in storage tanks due to the interaction with the solid boundaries. This has been confirmed by the effective thermal conductivity tests where some influence has been detected only for thermal conductivities 5 times of water value.

In passive or cool-down mode, the heat losses through the insulation create a natural convection movement because of the temperature differences between the wall and the fluid. In the lateral walls, a boundary layer is created all along the tank height, creating vertical movements that degrade progressively the tank temperature level and somehow the existing stratification. On the top walls, descending flow structures develop due to the existing temperature differences, which also degrade the existing stratification. Figure 13 from a research carried out at CTTC [ROD09b] illustrates qualitatively the previous comments for a cool-down process starting at isothermal condition, calculated for a very small tank (200 l) in a laminar flow case (Ra=$6x10^{11}$).

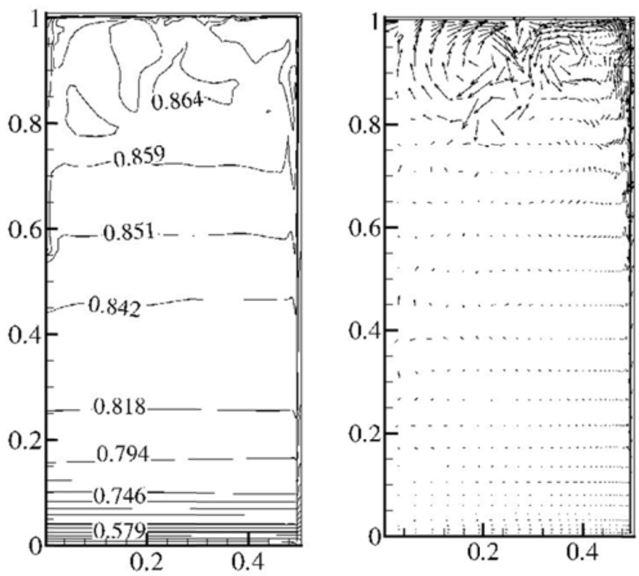

Figure 13 - CoolDown of small tank (200 l): temperature (left) and velocity (right) maps for a representative time step during the cool-down process.

For the Ecovat case, the temperature differences are expected to be relatively small because of the important insulation level. However, the large tank height is expected to impact on developing a stronger natural convection movement (higher Ra numbers). Unfortunately, the combination of both aspects together with the geometrical particularities of the Ecovat wallpart (double T protuberances on each heat exchanger level) and the small aspect ratio (height/width) of the tank,

makes the end de-stratification effect of this convective movement only predictable by challenging high computational demand CFD studies (even in this case with restricted scope as indicated above).

During the charge and discharge modes, boundary layers develop all along the lateral heated/cooled surface, creating a vertical 'plume-like' flow movement. The nature of these flow structures is strongly dependent on the configuration, creating cases where the boundary layer is predominantly laminar and other where turbulence (and consequently mixing) is enhanced. Depending on the boundary layer strength and the tank aspect ratio these plumes interact at different level with the core region. Just as an example of the mentioned phenomenon, Figure 14 shows the results obtained at CTTC for a challenging turbulent natural convection case [TRI13].

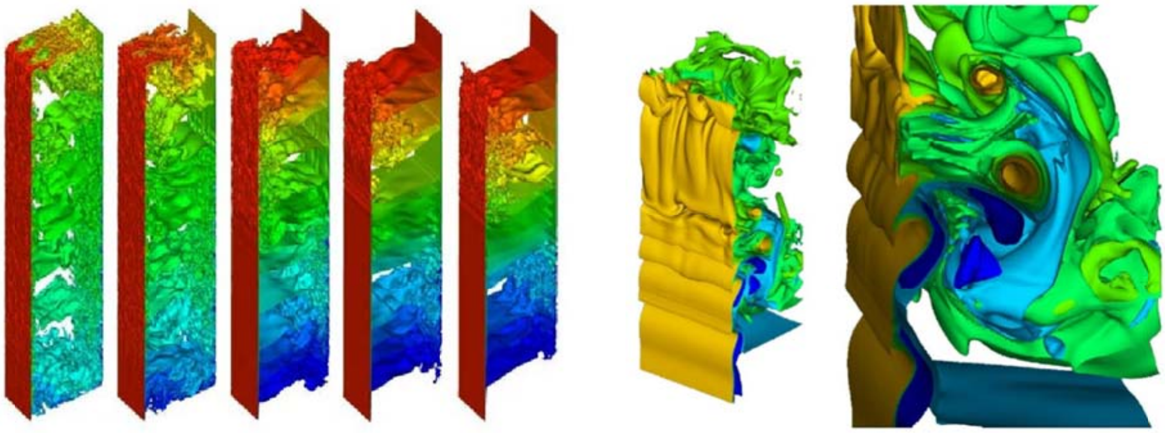

Figure 14 - Heat-Up: Temperature and flow structures found in a turbulent natural convection cavity (aspect ratio 5, Ra=4.5×10^{10}).

A particularity of Ecovat is that only one part of the wall is being heated, therefore the developed boundary layer will probably penetrate in the higher layer, destroying at certain level the existing stratification, and difficulting the heating of the corresponding layer core region. On the other hand, the design of the wallpart, having a protuberance at the top of the heated region, could play a role in changing the direction of the main plume from vertical to some inclination towards the tank center. Here, a combination of smart wallpart design together with a refined control to reduce wall-fluid temperature differences, will probably mitigate those undesired mixing effects. As an example of possible future actions in the design of Ecovat coming from this phenomenological assessment, could be the use of horizontal baffles to reduced the de-stratification processes, as already pointed out by [ALT05].

Another innovative action already considered by Ecovat designers is the use of inter-layer water-to-water heat pumps to recover the stratification levels within the tank by transferring energy from one layer to the other. This action allows the cooling of the Ecovat lower layers below the minimum useful temperature level and heating of the upper layers to allow this energy to be delivered to the heating needs, thus strongly spreading the total amount of useful energy.

From previous comments and from the exergy and heat exchanger-fluid studies carried out, it has been already pointed out the strong influence of the charge/discharge policy (series-parallel) and the heat exchanger design and conditions in the development of the tank stratification and the exergy

recovery ratio. Again, the combination of a smart heat exchanger design (concrete thickness, coil lay-out, heat exchangers connectivity) and a refined control strategy are expected to optimize these parameters.

4. Conclusions

Regarding the efficiency (performance) of the ECOVAT concept:

- The cool-down test showed the rather high thermal efficiency of the devices, being between 80 and 90%. The lowest value corresponds to ECOVAT S whereas the largest is for ECOVAT L. The relative impact of the energy losses is higher through the non-insulated bottom wall. If this aspect is considered, should be a compromise between the extra cost of insulation and the cost of energy saved for this concept.
- The influence of the thermal bridge caused by the polymeric joint between Ecovat wallparts has been analysed, showing small impact on the heat losses. Nevertheless, the continuity-integrity of this joint is a key aspect to avoid a thermal bridge that would bypass the wallparts insulation in a serious way.
- The full cycle tests have shown that even when high efficiencies can be achieved in the cool-down process, charge and discharge phases are important. The charge/discharge cycles should be designed so as the optimum strategy for achieving temperatures close to that at the inlet of the heat exchangers. It has to be borne in mind that an efficient store is that which can store the energy at a temperature closer to that at the charge phase. Thus, from that point of view the store working under Test 3 conditions behaves better than under Test2 conditions.
- In the light of those results, optimum control strategies for charging/discharging the store should be devised. For instance, a charge/discharge process in which the embedded heat exchangers are working in series, i.e. the outlet of the topmost heat exchanger is the inlet of the second one and so on, might be an optimum cycle if only one heat source at a single temperature is used. However, if different heat sources are available (at different temperatures), then an optimum for such situation should be found. Thus, the behaviour of these devices cannot be fully isolated from the system in which they will be installed, being their efficiency linked to the control strategies of the thermal system as a whole.
- As observed in the test 4 results, the water outlet temperature in the serpentines during the discharge process in series show a progressive decreasing, following the temperature of the upper layer as heat is extracted from it. Ecovat is not an open storage tank where it is expected to recover the mass of water stored at one temperature at the closest possible temperature after a certain period of time (as in Domestic Hot Water tanks). Conversely, Ecovat increases the energy stored density by rising its temperature vs. the initial temperature away from the useful temperature level. From our point of view, here the exergetic focus should be moved to the real water outlet temperature needed in the Ecovat application, that is, useful energy is that which covers the temperature level needed in the particular application, independently from the maximum temperature on the Ecovat (which is desired to be maximum to reach the limit in energy stored density).

Regarding the thermal stratification:

- Complex flow structures like mixing due to developed turbulent boundary layers near the walls, thermal bridges caused by the walls of the heat exchangers, convective plumes due to temperature gradients or eventual thermal inversion, flow entrainments due to jets effects caused by the boundary layers descending along the walls and entering into a layer at similar temperature cannot be considered with the level of modellisation used in the present study. Only a sensitivity analysis of the mixing effect can be carried out with the 1D-model by enhancing the thermal conductivity of water, substituting the real convective effect by an increased axial diffusive mixing. This has been done in Tests 2+3 by raising the conductivity from 0.6 to 10 W/mK. For range below 1 W/mK no important de-stratification effects have been observed, although for higher values relevant changes in both the exergy performance (up to 4% lower for Ecovat S) and in stratification level have been detected.
- From the exergy and heat exchanger-buffer studies, it has been observed the strong influence of the charge/discharge policy (series-parallel) and the heat exchanger design and conditions in the development of the tank stratification and the exergy recovery ratio. A combination of a smart heat exchanger design (concrete thickness, coil lay-out, heat exchangers connectivity) and a refined control strategy are expected to improve the energy quality.
- From previous experience, although only qualitatively, some effects are foreseen to degrade the tank stratification, like cool-down and heat-up convective flow patterns. Some actions on the design of the heat exchangers geometry and their control, as well as mitigation actions like the implementation of baffles are considered possible measures to reduce the de-stratification effect.
- The use of inter-layer water-to-water heat pumps are considered in Ecovat design to recover the stratification levels within the tank by transferring energy from one layer to the other. This action allows the cooling of the Ecovat lower layers below the minimum useful temperature level and heating of the upper layers to allow this energy to be delivered to the heating needs, thus strongly spreading the total amount of useful energy.
- The importance of Ecovat stratification should be revised depending on the difference between the maximum storage temperature (to increase storage energy density) and the required useful temperature for each application. If this difference is big, the importance of getting outlet water temperatures at the highest temperature is not as relevant as in other storage devices. In these applications, the capacity of the Ecovat of deploying useful energy from the highest temperature down to a situation when most of it is below the useful temperature level gets more relevance.

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