

The role of the saver in a HPLCs heat transfer process: a transient analysis

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Abstract. This work describes the experimental validation of a mathematical model implemented in Matlab/Simulink®, which is used to investigate energy consumption in the production process of high-pressure laminate composites (HPLCs). First, experimental onsite temperature measurements are used to determine parameters for the core component, i.e. the package, consisting of several layers of different materials. These otherwise hard to assess quantities are the generated power due to exothermal reactions in the cross-linking phase, and the piecewise approximation for the variable heat capacity of the impregnated paper over the heating phase of the process. The capability of the whole model (including the hot and cold water storage tanks) to replicate the behaviour of the actual production process has been verified. The validated model has been employed to investigate the influence of a saver tank for the spent hot water to be employed in the early stage of the heating phase of the process, with the load and discharge phases lasting three or five minutes each. Computations demonstrate that significant savings in energy (up to 34) can be obtained.

1. Introduction

High-pressure laminate composites (HPLCs or HPLs), also known by the trademark name of Formica™ [1], have a wide range of applications in furniture and as building material. HPLs are normally made of a decorative layer of impregnated melamine paper and a sturdier, thicker core (Kraft paper impregnated with resins) for structural purposes. Research and development in HPLs has so far focused mainly on their mechanical characteristics, in particular on their stiffness and strength, both tensile and flexural [2], and on the way in which high-pressure curing affects these properties [3]. In the last decade, owing to the constant drive to reduce production costs, attention has also been devoted to the production process of impregnated paper (with melamine formaldehyde (MF) and urea formaldehyde (UF) resins) as the surface quality of decorative low-pressure laminates is strongly affected by this [4]. Contrary to other materials employed for similar uses produced at lower pressures, HPLs require thermal cycling for resins to reticulate.

In particular, the paper is pressed between two plates (at about 7-10 MPa) and heated to a given temperature (between 160 and 180 °C depending on the type of material), where it stays for some time



(about fifteen minutes as a rule), then cooled back to ambient temperature while still being pressed in order to avoid buckling problems when the press plates are released.

A single press accommodates a number of openings (ten to twelve in standard realizations), in each of which the components of the so-called package are laid (figure 1). The package consists of a platen (carbon steel) working as tray, a number of Kraft paper sheets (called blanket or cushion, to even the heat flux distribution and compensate possible unevenness of the surface which often occur in the production).

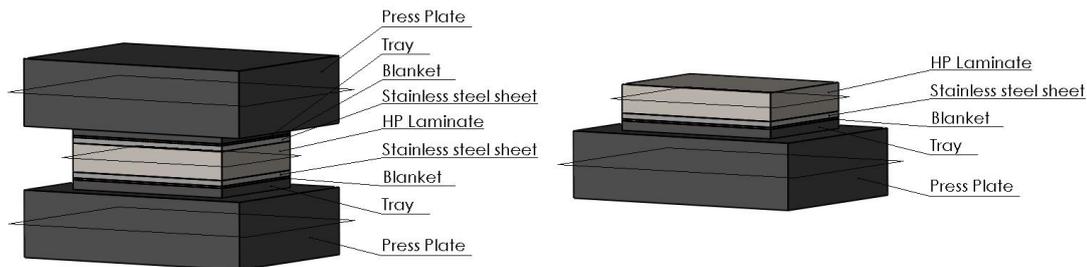


Figure 1 – Sketch of the package (left) and of the half which is simulated (right).

Above them, a modular assembly is laid; this consists of a stainless steel sheet with high surface finish (to give the decorative paper the proper surface appearance and pattern) a sheet of decorative paper, one of support material (consisting of several Kraft paper sheets), a detach pad (that also constitutes the symmetry layer for the assembly) to avoid the HPL sticking to the one immediately above, another support-decorative pair and another stainless steel. Depending on the size of the openings and on the thickness of the HPL, the modular assembly may be repeated a number of times for each opening (from one to ten). The package is topped by another series of Kraft paper sheets and by a lid to make the package symmetrical. Heating and cooling of the package is achieved through channels machined in the press plates, through which the heat transfer fluid (usually subcooled water at high pressure) flows. Heating and cooling strategies are often dictated by economic and layout constraints, and may include one or several storage tanks for the spent fluid in order to employ part of the waste heat.

High-pressure lamination is over half a century old, yet the process is still managed empirically and with massive resort to rules of thumb and workshop experience. This attitude is now starting to be changed due to more pressing energy saving demands, which call for a reduction in process inefficiencies. In the case of HPLs, little exists in the open literature, regarding the characterization of the production process and possible ways to reduce its energy consumption without significantly increasing production times.

In a previous work [5] a Simulink® [6] model of the thermal cycle through which HPLs are produced was employed to study the influence on temperature distribution in the laminate, in particular in the heating phase, of the thermal conductivity and thickness of the different components of the package: it was concluded that the thermal conductivities of the tray and stainless steel sheet are of little significance in modifying the temperature distribution in the laminate, while that of the blanket is decisive: if it is low, the temperature over the thickness of the laminate tends to be more uniform, and *vice versa*. Moreover, reducing the blanket's thickness high temperatures in the laminate are achieved in shorter times but the gradients increase as well, to values which may lead to local burns in the HPL due to overheating.

This work is a continuation of the previous investigation, moving from the behavior of the package to that of the whole process loop. In order to validate the model previously obtained of the press station experimental measurements of the temperature history of the process were carried out during an actual production run. Once the validity of the model was proven and some of its parameters fine-

tuned, a storage tank for spent hot water was added and its influence on the process in terms of energy savings and increase in process times investigated

2. Model validation for the package and for the complete circuit

2.1. Model parameters to be fine-tuned

The model which was employed to investigate the influence of the different components of the package on the temperature distribution along the thickness of the laminates was described in detail in [5]. Here, only the part relevant to validation, namely the laminate within the package, is discussed, namely the package consisting of the tray, the blanket, the stainless steel sheet and half of the HPL. Every component is divided into several layers for each of which the temperature is computed.

The number of layers into which the package is divided depends on the thickness of every component, the thermal conductivity and thermal capacity of the material. In the present case, the blanket is divided into four layers, whilst the half of the HPL has eight layers. For each component of the package and for each layer a time-dependent equation is obtained from the energy balance [7] for the layer and discretized using finite differences [8]. For the inner nodes, the equations have the form customary for non-stationary conduction with internal generation (due to evaporation of the moisture in the soaked paper), so at node m

$$\frac{kA(T_{m-1}-T_m)}{\Delta x} + \frac{kA(T_{m+1}-T_m)}{\Delta x} - hL\Delta x(T_m - t_A) + \dot{q}'''A\Delta x = \rho A\Delta x c \frac{dT_m}{d\tau} \quad (1)$$

where:

- k ($\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$) is the thermal conductivity of the element ;
- Δx (m) is the thickness of the layer
- A (m^2), L (m) are the area and the perimeter of the layer;
- T_m , T_{m-1} and T_{m+1} (K) are the temperature of the considered layer, and the ones of the two adjacent layers;
- h ($\text{W}\cdot\text{m}^{-2}\text{K}^{-1}$) is the convective heat transfer coefficient (obtained from [5]) with the surrounding air at temperature t_A (K);
- \dot{q}''' ($\text{W}\cdot\text{m}^{-3}$) is the thermal power generated inside the layer due to exothermal reactions during the cross-linking phase;
- ρc ($\text{J}\cdot\text{m}^{-3}\text{K}^{-1}$) is the volumetric thermal capacity of the material.

At the interface of adjacent layers continuity of the heat flux is imposed, while the contribution due to contact resistance was neglected, as it would not be significant for the present calculations and also considering the high pressures that keep the materials together.

In Eq.(1), \dot{q}''' is not known *a priori*, so some experimental data are needed to determine it. The specific heat capacity c for the laminate is also unknown, and varies depending on the stage of the process: it starts at rather high values (due to moisture and impregnating agents in the paper), and progressively drops as the laminate is heated, to reach a minimum in the end phase of the cross-linking and remains constant during the successive cooling step. In order to have an estimate of the two quantities discussed above, temperatures were measured experimentally at a plant during batch operations.

2.2. Experimental measurements and package model validation

A short description of the plant where measurements were carried out is now given: this is relevant to the validation procedure, as layouts may differ significantly depending on the production site. The plates are heated with hot water at constant temperature from a storage tank, until cross-link temperature, T_k , is reached (in this case $T_k=122$ °C), then warm water is shut off and cold water from another storage tank is forced through the press plates. The cooled water is recirculated to the storage tank, where it is heated up again, while during the cooling phase the hotter water out is sent to a storage tank for reuse, till its temperature drops below a threshold value: below this, the fluid is circulated directly to the cooling tower and returned to ambient temperature. In order to validate the

model, temperature measurements of the ambient air, inlet and outlet water, blanket and laminates were carried out by means of K-type, calibrated thermocouples with a total uncertainty of ± 0.5 K. Data were acquired every 10 seconds with a 5^{1/2}-digits multimeter and recorded to file. Temperatures for the blanket were measured at several layers, around 0.15 m from the border of the plate on both short and long sides, while for the laminate three layers were chosen, the temperature being measured on both the long and short sides for each of them. The values obtained for the water outlet temperature coincide with that of the plate, as was demonstrated previously [5] and were therefore employed to represent the temperature history of the latter. The temperatures of the central layer of the laminate were averaged and employed to obtain values of heat generation due to cross-linking (in the interval 80-122 °C in the experiment). The results of measurements are reported versus time τ in figure 2, where error bars are not shown as they would be tiny and just hamper the readability of the plots. Plate temperature (light blue) exhibits the behaviour typical of lumped-capacitance bodies, while the laminate has a strong lagging in temperature (orange).

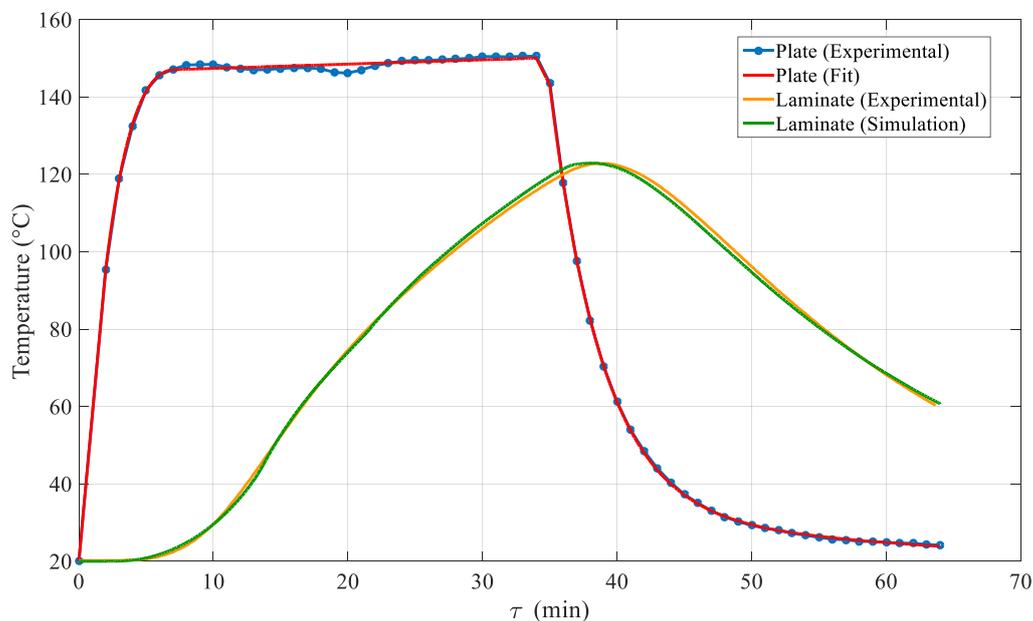


Figure 2 – Experimental temperature data and approximating temperature curve.

Experimental plate temperatures are used to obtain a functional approximation for the plate temperature (continuous red line in figure 2), which is used as input temperature for a reduced model consisting of the package only: this allows the determination of cross-linking heat generation and of specific heat capacity. The former is $\dot{q}''' = 22 \text{ kW} \cdot \text{m}^{-3}$, while the trend of c in the heating phase is shown in figure 3: it must be remarked that once c reaches its minimum value, its heat capacity becomes constant and remains so over the whole cooling step.

With the values just determined, the simulated temperature evolution within the laminate is shown again in figure 2: a very good agreement with the experimental data can be appreciated. It is also to be noticed that the maximum temperature in the laminate is reached almost five minutes after the hot water has been shut off.

2.3. Validation of the complete model

In order to test the whole Simulink model, which comprises the hot and cold water storage tanks, the heat generation due to cross-linking and the thermal capacity just determined have been employed as parameters for the package, and a simulation of the batch process has been run. In order to replicate the behavior of the actual production process, which involves feeding hot water to the plates at almost constant temperature, the capacity of the storage tank has been increased accordingly.

The results of the simulation are shown in figure 4: again, the agreement between numerical and experimental data is quite satisfactory.

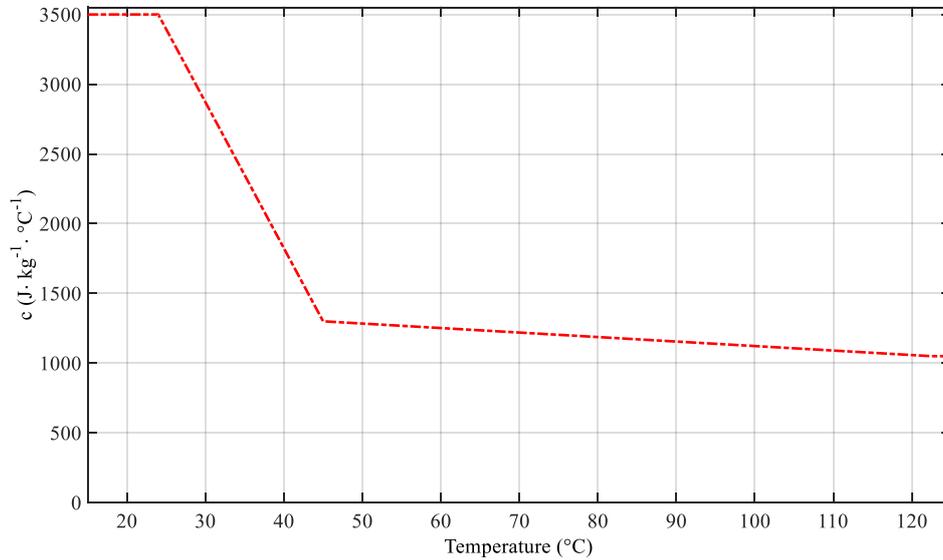


Figure 3 – Change of specific heat capacity of the laminate with temperature in the heating phase.

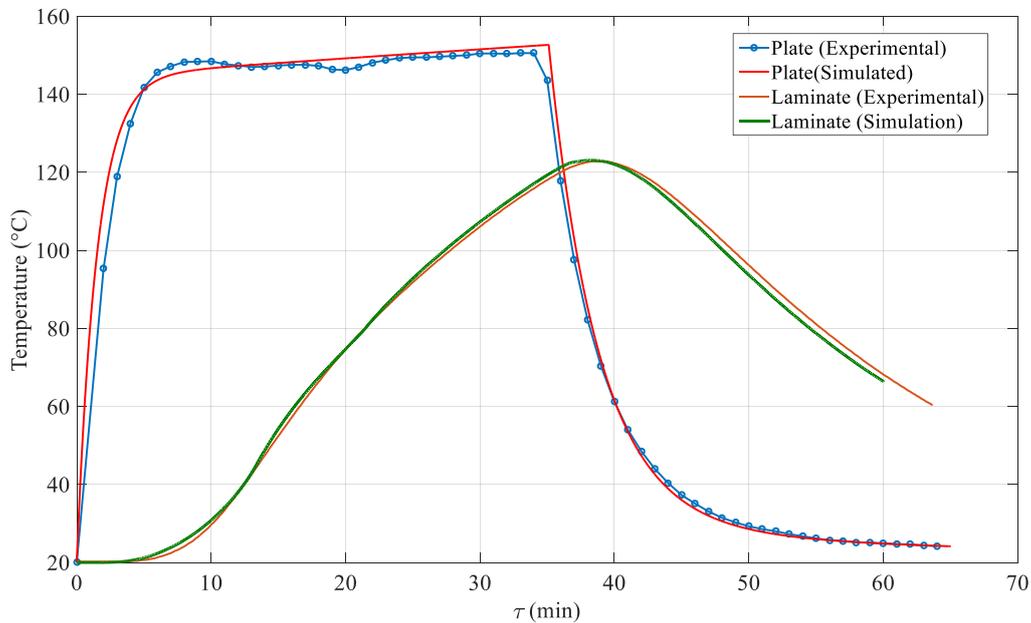


Figure 4 – Comparison between experimental data and simulation of the whole plant.

3. Auxiliary hot water storage tank

To decrease energy consumption, a tank (saver) to store the spent hot water from the plates during the cooling phase is added to the model. The saver has a storage volume $V=10 \text{ m}^3$, makes the hot water available for heating the plates in the initial phase of next press run. As a consequence of this, the times needed to complete the process increases because of the lower temperature of the hot water

supplied to the plates. As an example, simulations have been run keeping all parameters unchanged and imposing two equal values for the load and discharge times of the saver, namely $\tau_s=3$ min and $\tau_s=5$ min. Simulations have been run for a number of cycles such that the system gives the plates about the same energy during the heating phase as it receives from them during cooling. Results in terms of temperature versus time for both the plates and the laminates at the fourth cycle and $\tau_s=5$ min are shown in figure 5.

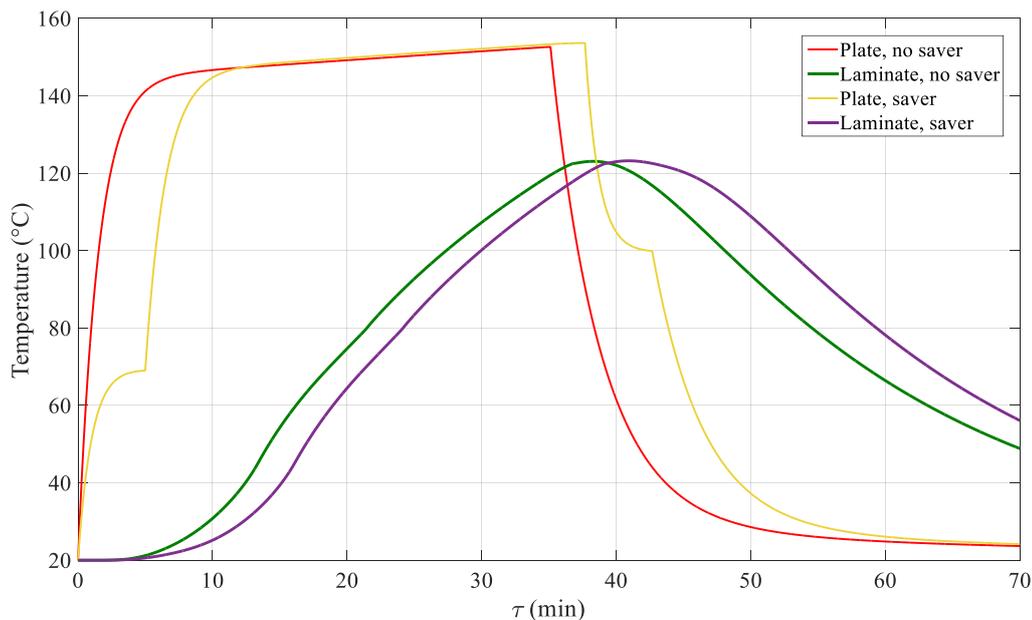


Figure 5 – Temperature profiles with and without saver, $\tau_s=5$ min.

Comparison of the temperature profiles of the plate with and without saver evidences that how the use of the storage tank delays the process, which lasts a few minutes (between two and four) longer. The time when the saver ceases to be used is clearly visible both for the heating and the cooling steps. When the temperature curve flattens (this meaning that the plates are roughly at the same temperature as the water fed to them), hot water must be supplied at a higher temperature, i.e. from the hot water tank, and temperature steeply increases. During cooling, when the water from the saver has been warmed to the temperature of the plates, heat removal becomes ineffective, and colder water must be supplied, i.e. from the cold water tank. Again, the temperature drops sharply and reaches its steady-state value. The sharp change experienced by temperature when the saver is no longer used is not seen in the laminate: this is due to the lagging behaviour of the heated mass, but an increase in the time needed to reach a certain temperature is visible – from two to four minutes for the conditions investigated in this work – and affects production times adversely.

The advantage of using a saver lies in the reduction of energy consumption, as shown in table 1, which refers to $\tau_s=3$ minutes, and table 2, which is for $\tau_s=5$ minutes. Each table bears in the top row the cycle from the start of the production process to which the data in columns refer. During the first run, the saver is assumed to be at ambient temperature, so that it cannot be used in the first heating of the plates, but only after the hot water flowing from the plates during the cooling process has been made available. During cooling, hot water is stored in the saver, which makes the average water temperature increase, which corresponds to recovery of some thermal energy from the hot stream, before this is sent to the cooling towers.

As can be seen from table 1, this recovery is around 45% of the total energy needed. At the start of the second cycle, the hot water in the saver, which has a temperature of roughly 70°C, is used to heat the plates up for three minutes, thus supplying about 18% of the whole heating load and decreasing the

temperature in the tank. At the start of the cooling phase the process starts again, with an increase in the percentage of the heating load covered by the water from the saver, which is 29% in this case.

Table 1. Energy performance of saver, $\tau_s=3$ min

| | | I | II | III | IV | V | VI | VII |
|---------------------------------------|------|------|------|------|------|------|------|------|
| Saver (Heating Phase) | | | | | | | | |
| Initial temperature | (°C) | -- | 70.0 | 85.9 | 93.1 | 96.4 | 97.9 | 98.6 |
| Final Temperature | (°C) | -- | 53.4 | 64.0 | 68.9 | 71.1 | 72.1 | 72.5 |
| Energy recovered | (MJ) | 0 | 692 | 914 | 1016 | 1062 | 1084 | 1092 |
| Percentage recovery | (-) | 0% | 18% | 24% | 27% | 28% | 29% | 29% |
| Saver (Cooling Phase) | | | | | | | | |
| Initial temperature | (°C) | 30.0 | 53.4 | 64.0 | 68.9 | 71.1 | 72.1 | 72.5 |
| Final Temperature | (°C) | 70.0 | 85.9 | 93.1 | 96.4 | 97.9 | 98.6 | 98.7 |
| Energy recovered | (MJ) | 1670 | 1360 | 1218 | 1154 | 1126 | 1112 | 1106 |
| Percentage recovery | (-) | 45% | 36% | 32% | 31% | 30% | 30% | 29% |
| Energy supplied through boiler | (MJ) | 3748 | 3056 | 2836 | 2736 | 2690 | 2670 | 2660 |

Table 2. Energy performance of saver, $\tau_s=5$ min

| | | I | II | III | IV |
|---------------------------------------|------|------|------|--------|------|
| Saver (Heating Phase) | | | | | |
| Initial temperature | (°C) | -- | 72.4 | 88.1 | 97.8 |
| Final Temperature | (°C) | -- | 53.9 | 64.0 | 70.3 |
| Energy recovered | (MJ) | 0 | 774 | 1009 | 1154 |
| Percentage recovery | (-) | 0% | 21% | 27% | 31% |
| Saver (Cooling Phase) | | | | | |
| Initial temperature | (°C) | 30.0 | 53.9 | 64.0 | 70.3 |
| Final Temperature | (°C) | 72.4 | 88.1 | 97.8 | 98.9 |
| Energy recovered | (MJ) | 492 | 1435 | 1290.4 | 1202 |
| Percentage recovery | (-) | 13% | 38% | 34% | 32% |
| Energy supplied through boiler | (MJ) | 3748 | 2972 | 2740 | 2596 |

If the water in the saver is used for a longer time, as is the case for Table 2, which corresponds to $\tau_s=5$ minutes, the percentage of energy recovered is slightly higher, around 31%; as a drawback, the time needed to complete a cycle increases to about four minutes as compared to when no saver is employed.

4. Conclusions

This work describes the experimental validation of a Simulink model used to investigate the production process of high-pressure laminate composites. For the core component, i.e. the package, consisting of several layers of different materials, experimental temperature measurements have allowed the determination of two otherwise hard-to-compute quantities, namely the generated power due to exothermal reactions in the cross-linking phase, and the piecewise approximation for the variable heat capacity of the impregnated paper over the heating phase of the process. The parameters thus determined have been used to check the capability of the whole model (including the hot and cold water storage tanks) to replicate the behaviour of the actual production process. The validated model has been employed to investigate the influence of a storage tank for the spent hot water (a so-called saver) to be employed in the early stage of the heating phase of the process, with the load and discharge phases lasting three or five minutes each. Computations demonstrate that the process times increase between two and four minutes, with average savings slightly higher for higher saver operation times ($\tau_s=5$ min) and averaging 34 % of the total energy consumption.

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