Dampening of wood batch combustion heat release using a phase change material heat storage: Material selection and heat storage property optimization

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Abstract

The use of wood stoves for space heating in energy effective residential buildings can be problematic due to the batch combustion giving a highly transient heat production and the limited regulation of the combustion process. Increasing the heat storage capacity and lowering the maximum heat release from the stove has been proposed to improve the utility of wood stoves. Latent Heat Storage (LHS) solutions will lower and even out the heat release from stoves. However, finding a suitable Phase Change Material (PCM) for a LHS solution can be problematic. In this work an analytical method for ranking PCM candidates for LHS solutions is proposed. The method takes into account PCM properties, in addition to LHS properties that have to be tailored to the selected PCM. The method is validated with numerical models using realistic heat production profiles from wood stoves. The numerical results show significant benefits of using PCMs in LHS solutions over traditional solutions. There exists significant work on PCMs and their properties, but little work on how to select a PCM for a given application. This work contributes to a more efficient selection process, decreasing the work required to select the optimum PCM for a LHS.

Keywords

Wood stoves, Latent heat storage optimization, Phase change material selection, Optimized heat release

Abbreviations used in this article:
MAD: Mean absolute deviation, LHS: Latent heat storage, SHS: Sensible heat storage, HTE: Heat transfer enhancement

Nomenclature

Abbreviations

MAD	Mean absolute deviation	-
LHS	Latent heat storage	-
PCM	Phase change material	-
SHS	Sensible heat storage	-
HTE	Heat transfer enhancement	-

Symbols

b/L	Geometry parameter used by Equation 13 [21]	[-]
Bi	Biot number	[-]
c_p	Specific energy density at constant pressure	[kJ/kgK]
C_r	Latent heat ratio	[-]
C_{crit}	Critical overcharging ratio	[-]
c	Heat transfer constant	[$WK^{4/5}/m^2$]
ε	Porosity, volume fraction of PCM	[-]
e_v	Volumetric energy density	[J/m^3]
h_{cold}	Cold side heat transfer coefficient	[W/m^2K]
H_{sl}	Heat of fusion	[kJ/kg]
k	Thermal conductivity	[W/mK]
L	Heat storage thickness	[m]
T_{amb}	Ambient temperature	[K]
T_m	Melting temperature	[K]
$\dot{q}''$	Heat flux	[W/m^2]
$\overline{q''}$	Average heat flux	[W/m^2]
ρ	Density	[kg/m^3]
r	Geometry parameter used by Equation 13 [21]	[-]
T_m	Melting temperature	[K]
ΔT	Temperature difference	[K]
Δt_{cycle}	Duration of one firing cycle (1.5 hours)	[s]

Subscripts

crit	Critical	-
cold	Denoting the cold side (facing the ambient)	-
eff	Effective, taking PCM and HTE properties into account	-
foam	HTE – metal foam	-
hot	Denoting the hot side (facing the stove)	-
ideal	Ideal	-
l	Liquid	-
m	Melting	-
s	Solid	-

1 Introduction

In Norway, a large share of the electricity produced is used for residential heating in resistance heaters. The national power consumption is increasing, while the power production is stagnating [1]. To increase the energy sustainability and security Norway has decided to encourage the use of more biomass for heating purposes. The goal is to increase the bioenergy production by 100% from 2008 to 2020 [2]. To achieve this goal, the consumption of biomass must increase. For this to happen there must be viable ways for biomass (wood) combustion to replace non-sustainable electrical resistance heating. This means that the versatility of wood stoves must increase. Modern wood stoves have thermal efficiencies of 70%-80% at nominal loads [3], and stoves are therefore a good and economic source of heat during extended periods of cold weather. Wood stoves do not operate as well at outputs lower than their nominal load, as this causes less efficient combustion conditions and higher emissions of unburnt particles and gases. Wood combustion in a wood stove is a batch combustion process and will give a heat production that is highly transient, due to the heterogeneous composition and successive thermal decomposition nature of logs of wood [4]. In addition, the combustion process is difficult to regulate without proper control equipment. Wood stoves in Norway are generally natural draft stoves, and without electric connection for control purposes. Heating during periods of moderate ambient temperatures and low heat requirements is therefore less beneficial, as overheating or inefficient combustion limit the viability of the stove.

The latest building standard in Norway includes new heat insulation requirements that will decrease the heating demand of new houses. Research has showed that this will be difficult to handle for current wood stoves on the market [5]. Using wood stoves as the main heating source, stoves having nominal loads below 4kW should be developed, as the heat requirements are in the order of 3-5kW for houses in cold climates [6] and about 2.5kW for Central European houses [5].

If the heat release pattern is dampened, the heating season for wood stoves can be lengthened, and the utility of wood combustion as a heat source will increase. The combustion chamber in a stove does not necessarily need to be altered to lower the heat release from a stove system. A heat storage system can be used to absorb the heat produced and dampen the heat release to the room, as shown in Figure 1. In the figure a relatively flat LHS is placed in such a way that the heat released from the stove has to be intermittently stored in the LHS before it can be released to the ambient.

Traditionally, and currently, soapstone is used as sensible heat storage (SHS), due to its relatively high density, thermal conductivity and heat capacity. The soapstone is usually lining the stove so that the heat transferred to the room from the stove is first intermediately partially stored in the stone and then released primarily by convection and radiation. Hence, the heat is stored as sensible heat in the stone and the heat released to the surrounding is dampened.

It is possible to flatten the heat release more by storing heat latently, by the use of a Phase Change Material (PCM). This will anchor the heat storage temperature to the phase change temperature as long as a phase change is occurring. This will flatten the heat release, as a stable temperature will cause a stable heat release. PCMs with high volumetric and gravimetric energy densities will result in a Latent Heat Storage (LHS) being relatively small and lightweight compared to sensible heat storage solutions [7]. There are many possible

PCM candidates suitable for wood stove applications, with differing melting points and thermal properties. The choice of material will affect the geometry and composition of the heat storage, and the functionality of the final solution.

There are consumer and practical design considerations to take into account when designing a stove which inevitably results in a certain amount of heat that will bypass the heat storage and be released to the ambient directly. The heat production that a heat storage has to dampen is therefore lower than the nominal effect of the wood stove. Typical heat input and typical heat output from a LHS and SHS were generated and is shown in Figure 2. The heat input plotted is an average heat flow of 1kW over a period of 1.5 hours. The shapes of the heat release from a sensible and a latent heat storage system are as described above. It can be observed that the PCM provides a more stable heat release than soapstone.

The objective of the present work was to develop a method for early stage screening of PCMs that takes into account the wood stove heat production profile and the possible methods of heat transfer enhancement in a latent heat storage.

2. PCM and Heat Storage Properties

The application of PCMs in wood stoves is new, and relevant literature on the subject is therefore lacking. PCMs have been used in building applications as heat storage, mainly to increase the thermal inertia of the building, and in solar heating applications [8, 9, 10, 11, 12]. These applications have long timescales, and low heat fluxes. PCM heat sinks are also the subject of research in electronics cooling, but this use is not directly analogous to a LHS for wood stoves. The objective of electronics cooling is to keep the electronics temperature under a threshold value [13], while the wood stove LHS objective is to keep a constant cold side surface temperature. Electronics cooling PCM heat sinks have shorter time scales and higher heat fluxes than a LHS for wood stoves.

The specific application is new, but the technology, problem formulation and general application is well documented [14, 15], thus the principal problem is selecting the optimum PCM for a LHS.

PCM properties can be grouped into the following categories; thermal properties (melting temperatures, heat of fusion, thermal conductivity), physical properties (density variation, subcooling), chemical properties (toxicity, corrosiveness, stability) and economical properties (cost, availability) [16]. All of these groups determine if a PCM will be suitable in a LHS. In the present work the focus was on methodology for optimum selection based on the thermal properties.

A solid/liquid phase change is desired as this gives the smallest change in volume between phases, hence liquid/gas phase change and chemical energy storage is not included in the present work.

The solid/liquid phase change temperature must be at a suitable level in order to absorb heat from the combustion process and subsequently release it to the ambient. For a heat storage to absorb as much heat as possible, the melting temperature should therefore not significantly exceed the minimum desired flue gas temperature, which is 100°C for natural draft wood stoves in order to ensure sufficient draft and to prevent water vapor condensation. Moreover, to facilitate heat loss from the storage to the ambient, the melting temperature should be significantly higher than the ambient temperature. This defines the range of melting temperatures for this application to be roughly between 40°C and 120°C.

Many possible candidates for phase change materials are available, but there are also many restrictions caused by melting temperatures and degradation of the material [17]. It is vital to ensure that the phase change material does not reach its degradation temperature. This can be achieved by e.g. limiting the heat flux to the heat storage. However, it is difficult to control the actions of the end user of a wood stove, and it is therefore difficult to ensure good control of the heat production. This means that the heat flow to the heat storage must be controlled. There are several ways to achieve this, but in order for the heat storage to be in good contact with the stove, and work efficiently and safely, a heat transfer regulation mechanism is required.

With so many factors having an influence on the heat storage performance, it becomes difficult to choose a suitable PCM material. It is therefore necessary to create indicators for how well a PCM material will work as a PCM heat storage material, and such indicators are developed and discussed in this paper.

The first of these indicators is the energy density of the material. The material should be able to store large amounts of energy in a limited volume. Latent heat storage materials have a soft cap on the upper heat storage capacity; this is when the material has melted. A temperature increase after all the material has melted is not desired. A gravimetric energy density can be calculated by calculating the sensible heat capacity from an ambient temperature up to the melting temperature and adding it to the heat of fusion of the material. For a volumetric energy density this value is multiplied by the density of the material, Equation 1.

$$e_v=(c_p(T_m-T_{amb})+H_{sl})\rho_s \ [J/m^3]$$ *Equation 1*

For a comparison between a latent and a sensible heat storage material a reference/maximum temperature is needed. Alternatively, Equation 1 can be divided by the temperature difference between the melting and ambient temperature to get a quasi-specific volumetric energy density. The energy density should be high, as a small and lightweight heat storage is desired.

In addition to the energy density, the ratio of latent to sensible heat storage capacity is important. If the latent heat storage capacity is small compared to the sensible heat storage capacity, the behavior of the heat storage will be close to a sensible heat storage solution. The ratio of latent to total heat storage is defined in Equation 2:

$$C_r=H_{sl}/(H_{sl}+c_p(T_m-T_{amb})) \ [-]$$ *Equation 2*

This ratio can vary from $C_r=0$ for a sensible heat storage to $C_r=1$ for melting temperatures equal to the ambient temperature. This ratio is important in scenarios where the PCM melting temperature is far from the ambient temperature, and when the heat storage cycles complete from fully charged to empty. There would be significant benefits if the heat storage could cycle from solid/liquid at the melting temperature without significant overheating or undercooling.

The thermal conductivities of PCMs are generally low, and the heat fluxes and heat amounts that a wood stove heat storage system must handle are large. This combination is not beneficial for a uniform heat release, which requires the temperature in the heat storage to remain as constant as possible. This is easily seen from Fourier's law of heat conduction, Equation 3. To successfully use a PCM in a heat storage solution a heat transfer enhancement method (HTE) should be considered to increase the effective thermal conductivity and lower the temperature gradients in the heat storage.

$$-dT/dx=\dot{q}''/k_{eff}. \ [K/m]$$ *Equation 3*

The bulk transport of energy into the heat storage must be partly via a heat transfer enhancement mechanism, such as fins. The transport of heat from the fins to the PCM material is limited by the PCM thermal conductivity and it is therefore important to minimize the thermal resistance from the fin to the PCM by minimizing the distance the heat has to travel. If this distance can be reduced sufficiently, the thermal resistance from the fin to the bulk PCM material is small compared to the thermal resistance between the hot and cold ends of the heat storage. In this work it is assumed that this is the case, hence an isotropic effective thermal conductivity (k_{eff}) can be assumed. An illustration of a possible fin and metal foam configuration is shown in Figure 3.

It is important to keep the effective thermal conductivity (k_{eff}, see Equation 3) high and the thickness of the heat storage small to keep the Biot number low. The Biot number, defined in Equation 4, represents the ratio between internal conductive thermal resistance and the cold side external thermal resistance (a combination of convective and radiative heat loss) [15]. The solid PCM properties are used when calculating the Biot number.

$$Bi=h_{cold} \cdot L/k_{eff} \text{ [-]} \qquad \textit{Equation 4}$$

If the Biot number is large (>>1) the temperature difference from the hot to the cold side of the heat storage will be much larger than the difference between the cold wall and the ambient air. This will cause the heat release from a LHS to be similar to a sensible heat storage heat release due to the heat of fusion being masked in the temperature gradients caused by a low effective thermal conductivity.

Temperature degradation is a severe limitation for the use of PCM materials in wood stove heat storages as the combustion process is not actively regulated, and the user is not well trained in the correct use of stoves/heat storage systems. The critical temperature should therefore be unobtainable during standard operation. The temperature gap between the degradation temperature and the melting temperature should therefore be large, and the energy required to reach the degradation temperature should be large. An indicator for how difficult the degradation temperature is to reach would be the overcharging of the heat storage required to reach the degradation temperature, given a lumped heat capacity calculation. An overheating indicator is defined in Equation 5.

$$C_{crit}=(H_{sl}+c_{p,s}(T_m-T_{amb})+c_{p,l}(T_{crit}-T_m))/(H_{sl}+c_{p,s}(T_m-T_{amb})) \text{ [-]} \qquad \textit{Equation 5}$$

The heat storage size will be designed to fill the heat storage to its capacity given a mean input power and duration. If the indicator calculated from Equation 5 is significantly large (and the effective thermal conductivity is significantly large), critical overheating is not a concern during standard cycling including normal deviations.

The gravimetric energy density has little impact on the thermal performance of a material, but the volumetric energy density controls the size of the heat storage. The heat storage size will be roughly proportional to the amount of heat supplied to the hot side of the heat storage. This causes the thickness of the heat storage to be inversely proportional to the volumetric energy density. In addition, if the Biot number is to be kept low, the effective thermal conductivity must be increased by increasing the proportion of HTE material. This will further lower the volumetric energy density of the system.

With several indicators and a multitude of material properties, it is often difficult to pinpoint an optimum material, even if only thermal properties and indicators are used. In the effort to find an accurate selection method, several materials were selected based on melting temperature and availability of material data, and their indicators calculated. The results are tabulated in Table 1. These materials will be used as a validator for the material selection method developed in this work.

***Table 1** – Material indicators for selected phase change materials [14,15,18].*

Material	**$e_{v,PCM}$[MJ/m^3]**	**$C_{r,PCM}$[-]**	**T_m[^oC]**	**$C_{crit,PCM}$[-]**
Lauric Acid	440.6	0.85	42	1.5
$MgCl_26H_2O$	606.3	0.44	116.7	2.1
Erythritol	828.2	0.61	117.7	1.2
Paraffin 53	229.1	0.70	53	2.3
SunTech P116	288.8	0.75	49.5	1.9
RT 60 Rubitherm	212.7	0.86	59	1.2
EPS ltd E48	368.4	0.91	48	3.4
Sodium Acetate	519.7	0.71	58	1.3

3. Theoretical basis

To fully evaluate the performance of PCM's in a heat storage for a wood stove application, a transient spatial analysis is required. The analysis is not complete with only a lumped sum capacitance assumption, as this method fails to include the effects of low conductivity in the heat storage. The convective effects in PCM materials can be significant in systems with pure PCM. The effects become less significant when the use of heat transfer enhancement increase (proportion of fins or metal foam in the storage). As a first order approach, the convective effects are not included as the conductive heat transfer is dominant. Modelling the convective effects also increases the complexity of the models. When a full evaluation using a numerical method is completed, the merit of the less complex models can be evaluated.

For pure PCM systems, the equivalent heat capacity method described by Faghri [19] is used to calculate the heat transfer. With this method, the energy equation for a one-dimensional problem is expressed as in Equation 6.

$$\rho c_p(\partial T/\partial t)=-\ \partial/\partial x(k(\partial T/\partial x)) \qquad \textit{Equation 6}$$

The PCM specific heat capacity and thermal conductivity are defined as in Equation 7 and Equation 8 respectively. The method adds the heat of fusion to the specific heat capacity over a temperature interval ($2\Delta T$) around the melting temperature. This means that the melting process starts at $T_m-\Delta T$ and ends at $T_m+\Delta T$. This will accurately model the phase transition if the temperature interval is small. A similar method was used by Velraj et al. [20], and the model is explained in more detail there. The thermal conductivity will also change from the solid to the liquid thermal conductivity over this temperature interval.

$$c_p(T)=\begin{cases} c_{p,s} & T<T_m-\Delta T \\ H/(2\Delta T)+(c_{p,s}+c_{p,l})/2 & T_m-\Delta T<T<T_m+\Delta T \\ c_{p,l} & T_m+\Delta T<T \end{cases} \qquad \textit{Equation 7}$$

$$k(T)=\begin{cases} k_s & T<T_m-\Delta T \\ k_s+(k_l-k_s)/(2\Delta T)\cdot(T-T_m-\Delta T) & T_m-\Delta T<T<T_m+\Delta T \\ k_l & T_m+\Delta T<T \end{cases} \qquad \textit{Equation 8}$$

When fins or similar HTE are included in the system, the material properties are substituted with effective system properties, detailed in Equations 9-12. Here ε is the ratio of PCM volume to total volume, k is the thermal conductivity, ρ is the density and H_{sl} is the heat of fusion.

$$k_{eff}=\varepsilon k_{PCM}+(1-\varepsilon)k_{HTE} \qquad \textit{Equation 9}$$

$$\rho_{eff}=\varepsilon\rho_{PCM}+(1-\varepsilon)\rho_{HTE} \qquad \textit{Equation 10}$$

$$c_{p,eff}=\varepsilon\rho_{PCM}c_{p,PCM}/(\varepsilon\rho_{PCM}+(1-\varepsilon)\rho_{HTE})+(1-\varepsilon)\rho_{HTE}c_{p,HTE}/(\varepsilon\rho_{PCM}+(1-\varepsilon)\rho_{HTE}) \qquad \textit{Equation 11}$$

$$H_{eff}=H_{sl}\varepsilon\rho_{PCM}/(\varepsilon\rho_{PCM}+(1-\varepsilon)\rho_{HTE}) \qquad \textit{Equation 12}$$

It is further assumed that the heat transfer is one-dimensional (i.e. the distance between HTE and PCM is assumed to be short).

When metal foam is used as an alternative HTE device to fins, the effective density, specific heat capacity and latent heat of fusion are defined by Equations 10-12, but the effective thermal conductivity is calculated using the method developed by Calmidi and Mahajan [21], Equation 13. The model takes into consideration the fact that roughly 2/3 of the metal fibers are not effectively contributing to the heat transfer in the principal direction of the heat flux, and that a significant portion of the metal can be concentrated in a way that is not effectively contributing to heat transfer.

$$k_{eff}=((2/(3^{2/3}))*(r(b/L)/(k_{PCM}+(1+b/L)(k_{foam}-k_{PCM})/3))+(1-r)(b/L)/(k_{PCM}+2/3(b/L)(k_{foam}-k_{PCM}))+(3^{1/2}/2-(b/L))/(k_{PCM}+4r/3^{3/2}(b/L)(k_{foam}-k_{PCM}))))\hat{}-1 \qquad T<T_{melt}\ k_{PCM}=k_{PCM,s} \qquad T>T_{melt}\ k_{PCM}=k_{PCM,l} \qquad \textit{Equation 13[21]}$$

In Equation 13 the effective thermal conductivity is calculated using the PCM and HTE thermal conductivities, in addition to the geometric parameters r and b/L, describing the makeup of the metal foam.

With the above equations, the conductive heat transfer and temperature development of a one-dimensional LHS system can be simulated for pure PCM, and PCM enhanced with fins or metal foam. The commercial finite element method program COMSOL Multiphysics was used to solve the equations numerically. An analytical solution for one-dimensional heat transfer in a semi-infinite body with a fixed temperature boundary condition was compared to an equivalent numerical solution using the above equations with satisfactory accuracy. Matlab with Livelink was used to vary parameters and to evaluate solutions.

The heat going to the heat storage is assumed to have the same time variation as the heat produced by a wood stove (see Figure 2), and it is assumed that it is conducted one-dimensionally through the heat storage and eventually released to the ambient (Figure 1). The heat enters the latent heat storage having a total hot side surface area of 0.27m^2. An illustration of a transient heat flow produced by a wood stove with an average value of 1kW is shown in Figure 2. If higher heat fluxes are used, they can be assumed to be multiples of the same basic heat flow, but having the same duration. The heat flux profiles are calculated by Fuelsim Transient [22] and are based on realistic heat production profiles from wood batch combustion. The heat storage calculations and the combustion calculations are not coupled; i.e. it is assumed that the heat storage does not affect the combustion and the combustion temperature. One heat cycle has a duration of 1.5 hours, and the amount of heat produced is highly transient.

The cold side of the heat storage is subject to a convective cooling boundary condition, where the heat transfer coefficient was calculated in such a way that the desired heat loss (q''_{ideal}) is obtained with the cold side wall temperature equal to the melting temperature. Assuming the same temperature dependence as natural convection over a vertical plate, the heat transfer coefficient at the melting temperature is defined by Equation 14, where the constant c is defined by Equation 15.

$$h_{cold}=c\Delta T^{1/4}\ [W/m^2K] \qquad \textit{Equation 14}$$

$$c=q''_{ideal}/(Tm-Tamb)^{5/4}\ [WK^{4/5}/m^2] \qquad \textit{Equation 15}$$

The heat transfer coefficient (Equation 14) is set based on the heat loss and the melting and ambient temperatures. A large heat loss and a low melting temperature will result in a larger heat loss than can be achieved by pure convective cooling. It is assumed that the ambient side of the heat storage needs fins to increase the outside surface area, and that the calculated heat transfer coefficient is a product of the outside heat transfer coefficient and the area ratio of external surface area divided by the internal surface area. This means that high heat fluxes and low melting temperatures requires a large external surface area.

The desired target heat release, q''_{ideal}, is set as a constant heat release of 25% of the average heat input applied to the storage, i.e. a wood stove producing 4kW for 1.5 hours would have a desired heat release of 1kW for 6 hours. The optimum heat release depends on the concrete applications of the stove, and an optimum solution for a given system does not have a universal application, therefore 25% of the intensity and a quadrupling of the time is selected as a baseline.

The HTE material used is aluminum having a density of 2700kg/m^3, a specific heat capacity of 0.9kJ/kgK and a thermal conductivity of 200W/m/K, unless otherwise stated.

4. Optimization results of a latent heat storage solution

In real world applications wood stoves are used very diversely, the stove may be used continuously, but batch-wise or only started from a cold condition, and the combustion airflow may be controlled to change the intensity and the duration of a single firing cycle. Many of these conditions are valid for the optimization of a heat storage solution; however, the present work is limited to a single firing cycle with an initial temperature equal to the ambient temperature.

If a lumped capacitance analysis of the problem is performed (i.e. assuming $k_{eff}=\infty$) with the system as described above, some basic insights can be obtained. The capacity of the heat storage (e_vL) and the incoming heat ($\Delta t_{cycle}\bar{\dot{q}}''_{hot}$) should be of the same order of magnitude. If the storage capacity is too large (given that the ratio of latent to sensible heat storage is not unity), a large portion of the heat will remain as sensible heat in the solid (i.e. there is insufficient heat to melt the PCM). Likewise, if the heat storage is too small, the heat added will cause overheating and heat will be stored as sensible heat in the liquid phase. This fact causes the optimum thickness of the storage to be inversely proportional to the volumetric energy density. A high e_v is generally desired because it decreases the heat storage size and weight. A smaller size is also beneficial because the added heat has a shorter distance to travel. This reduces the problems caused by the generally low conductivity of PCMs.

If it is assumed that the heat storage has a heat capacity equal to the heat supplied minus the desired heat loss during one cycle, the thickness of the heat storage is defined by Equation 16, where $\bar{\dot{q}}''_{hot}$ and $\dot{q}''_{ideal}$ is the average heat flux entering the heat storage and the ideal heat flux released from the heat storage, respectively, and Δt_{cycle} is the duration of one cycle.

$$L=\Delta t_{cycle}(\bar{\dot{q}}''_{hot} - \dot{q}''_{ideal})/e_v \, [\mathrm{m}] \qquad \textit{Equation 16}$$

In Equations 1, 2, 4 and 5 the PCM indicators are defined using PCM properties. If the indicators are calculated using system properties, as defined by Equations 9-12, the indicators now describe the system of PCM and HTE. The indicators can now be used to describe the LHS performance, and are therefore called performance indicators. If an attainable Biot number is set, and a length is defined, the porosity and C_r is easily calculated.

A C_r value equal to 1 will cause the heat loss to be constant (assuming lumped sum capacitance), as all the heat is stored at the melting temperature. The more C_r deviates from unity, the larger is the discrepancy from (the optimum) constant heat loss, first noticeable by a slow start in the heat loss and a long exponential decay. None of these effects are desired, but impossible to eliminate. It is important to notice that a good PCM solution has a high value of both e_v and C_r, as one without the other can cause overheating and a poor heat release. A high value of e_v can also be deceiving since the value is proportional to the melting temperature. A high melting temperature causes a low value of C_r due to the increased sensible heat storage.

Preliminary calculations show that the Biot number has a high influence on the LHS performance. A high Biot number results in large temperature differences in the heat storage, and the heat release to be very variable. A low Biot number causes the temperature difference between the heat storage and the ambient to be much larger than the temperature differences in the storage, yielding a more constant heat release. The Biot number is a function of the cold side heat transfer coefficient, the thickness of the heat storage and the effective thermal conductivity, see Equation 4. In order to decrease the Biot number for a system where the cold side heat transfer coefficient is constant, it is necessary to add more HTE material. This will increase the effective thermal conductivity, but it will also increase the thickness of the heat storage.

Changing the porosity (ε) changes the Biot number and the latent heat ratio (C_r). An example of this is shown in Figure 4, where the porosity is changed and the effects on C_r, e_v and Biot number is plotted for Lauric acid with fins, and an average heat input of 1kW. The data were generated analytically using Equations 1, 2, and 4, using system properties defined by Equations 9, 10, 11, 12 and 16. This method will be referred to as the performance indicators method in this work.

As can be seen in Figure 4, the optimum porosity is not readily apparent, as the minimum Biot number gives a Cr number that is far from the maximum.

A Biot number less than approximately 0.1 is required for a lumped capacitance calculation to be valid [19, 23]. A lumped capacitance calculation assumes that the internal conductive resistance is negligible compared to the external convective resistance, i.e. that the internal temperature difference is negligible compared to the external temperature difference. A lumped capacitance behavior is desired, as this minimizes temperature differences in the heat storage, and ensures a cold side wall temperature approximately equal to the melting temperature if a phase change is in progress. The material with the highest C_r at or below a Biot number of 0.1 is the material that will give the best heat release profile compared to the ideal heat release. Using this reasoning, the optimum porosity in a LHS system is the porosity that gives a Biot number <0.1. The porosity for a Biot number of 0.1 in Figure 4 is 0.93, and decreasing the porosity lower than 0.93 will yield negligible benefits.

If the numerical one-dimensional (1D) model is used (Equation 6), and Equation 16 is applied, the transient heat release can be calculated for different porosities. The heat release profiles for each porosity are compared to the baseline, and the mean absolute deviation (MAD) is calculated for each transient heat release using Equation 17. The transient solver in COMSOL Multiphysics saves data at every six minutes, and the comparison is done for each saved time step.

$$\mathrm{MAD}=1/N*\mathrm{sum}_n(\mathrm{abs}((\dot{q}''_{real}-\dot{q}''_{ideal})_n))\ [\mathrm{W/m^2}] \qquad \textit{Equation 17}$$

The solution that gives the minimum value of the MAD is the solution that best fits the ideal heat release. The result of the porosity variation is plotted in Figure 5, using the same assumptions, materials and HTE as in Figure 4. As seen from the figure, the MAD and the Biot number are closely related. C_r decreases as the porosity decreases, and a minimum value of MAD is therefore reached when the reduction in Biot number is not enough to compensate for the decreased C_r.

The numerical solution used for Figure 5 gives an optimum Biot number of 0.0882 and an optimum porosity of 0.92. The difference in the MAD between the optimum numerical solution (optimum at a porosity of 0.92) and the optimum solution calculated by performance indicators with Bi=0.1 (optimum at a porosity of 0.93) is negligible, indicating that the optimum porosity gained from the performance indicators with a Bi=0.1 is close to the real optimum value for the porosity.

Equation 16 has been used to define a thickness, L, in the previous calculations. The equation does not take into account all of the effects that give the optimum length, and is therefore only approximate. The equation does not account for the fact that a certain amount of overheating on the hot side is not necessarily negative, as it will keep the cold side temperature from dropping below the melting temperature for a longer period of time than if no overheating had occurred. The thickness calculated from Equation 16 is therefore slightly larger than the length that will give the optimum MAD. The optimum thickness can be found by calculating the MAD for a spectrum of porosities and lengths near the optimum point found from the LHS indicators.

Additional checks should be performed when selecting the thickness for a heat storage. Organic PCM materials usually have degradation temperatures that are obtainable if the heat storage is too thin, or the Biot number too high. The MAD is relatively insensitive to changes in thickness close to the optimum value, and a thickness higher than the one that yields the minimum MAD should be considered. A criterion for the maximum hot side temperature could be used to exclude solutions that will cause, or come close to PCM overheating.

The approximate optimum configuration of porosity and thickness can be selected for a given PCM and incoming heat flux, by calculating the required porosity for a Biot number of 0.1 using the performance indicators method. The system C_r, based on the porosity, is therefore known. This enables a quick comparison of PCMs, as the porosity is calculated by a simple goal seek algorithm, and the C_r is a simple function of the porosity. The optimum material, from a thermal performance point of view for a given incoming heat flux is the material having the highest value of C_r at a Biot number that results in a lumped capacitance behavior. The numerical computations required are generally too time consuming to do for every material in order to find the optimum candidate for a LHS. The performance parameter method can be used to find the most prospective PCM candidates, while a full numerical analysis should be performed to verify the results and find the optimum material among the top candidates.

The PCMs listed in Table 1 are ranked according to LHS performance in Tables 2 and 3. The rankings are based on a Biot number of 0.1 and the performance indicators method described earlier, and on the numerical 1D model.

As can be seen from Table 2, the performance indicators method using Bi=0.1 is able to rank materials successfully relative to the full numerical solution shown in Table 3. The two materials that are not ranked equally in the two tables are Lauric Acid and RT 60 Rubitherm. The materials are expected to give roughly the same performance, based on the analytical analysis (the C_r value for both materials are close). The difference in MAD is less than 1%. This indicates that the performance indicators method is good for a first sorting of materials, but can be inaccurate when C_r values are close while e_v values being significantly different.

***Table 2** – Material ranking based on performance indicators and a Biot number=0.1, 1kW and fins*

Material	L	ε	Biot	C_r	Ranking
Lauric Acid	0.031	0.94	0.1	0.84	2
$MgCl_26H_2O$	0.022	0.99	0.1	0.44	8
Erythritol	0.016	1.00	0.1	0.61	7
Paraffin 53	0.060	0.92	0.1	0.68	6

SunTech P116	0.048	0.93	0.1	0.74	4
RT 60 Rubitherm	0.064	0.93	0.1	0.83	3
EPS ltd E48	0.037	0.94	0.1	0.90	1
Sodium acetate	0.026	0.97	0.1	0.71	5

Table 3 *- Material ranking based on COMSOL, 1kW and fins*

Material	MAD	L	ε	Biot	C_r	Ranking
Lauric Acid	157.7	0.035	0.94	0.09	0.84	3
$MgCl_26H_2O$	241.7	0.023	0.95	0.02	0.43	8
Erythritol	200.3	0.017	0.96	0.02	0.60	7
Paraffin 53	191.2	0.061	0.92	0.10	0.68	6
SunTech P116	178.2	0.049	0.93	0.11	0.74	4
RT 60 Rubitherm	156.7	0.067	0.93	0.11	0.83	2
EPS ltd E48	142.2	0.041	0.94	0.10	0.90	1
Sodium acetate	182.8	0.026	0.96	0.07	0.71	5

The optimum LHS heat release profile alongside an optimized soapstone heat storage solution (SHS) is shown in Figure 6. As can be seen, the LHS gives a more uniform heat release profile than the SHS, but a certain lag in the beginning and a tail in the end is difficult to avoid.

The results from Tables 2 and 3 are calculated using fins as HTE. Similar results can be achieved for metal foams using Equation 13 for the thermal conductivity. The general trend for the metal foams is that more HTE material is needed to get a Biot number of 0.1, and that the performance is therefore lower than for fin based solutions. The benefit of foam as a HTE is that one dimensional heat transfer is easier to achieve than if fins are used.

As can be observed in Figure 4, the Biot number has a minimum value. If the heat input is increased, the minimum Biot number increases due to the increased required thickness of the LHS. It can be shown that the Biot number is proportional to the square of the applied heat flux at a constant porosity. A heat flux exists where the minimum value of the Biot number is equal to 0.1, and this represents the largest heat flux that can be applied while maintaining a lumped capacitance behavior in the heat storage. A LHS exposed to higher heat fluxes will have significant internal temperature gradients and the performance of the heat storage will degrade.

A PCM with a high e_v can maintain a Biot number of 0.1 at higher heat fluxes than materials with a low e_v. If the applied heat flux is significant, a Biot number of 0.1 will be impossible to achieve. If all materials being compared cannot obtain $Bi \leq 0.1$, they cannot be compared by the method described above with sufficient accuracy. The performance indicators method is limited to comparing lumped capacitance systems (i.e. $Bi \leq 0.1$); for higher Bi a full numerical analysis will be required.

Increasing the heat flux makes it more difficult to compare materials, and it also changes the requirements of the material. At low heat fluxes the need for HTE material is low, and e_v is therefore not that important in the ranking of materials. At high heat fluxes, a material having a high e_v requires less HTE material, which again keeps the C_r value of the material high. Materials with a low e_v needs a significant portion of HTE material to maintain a Bi≤0.1, and C_r decreases accordingly. This can cause the optimum material to shift as different heat fluxes are tested.

Ranking of materials were also performed for heat flows of 2kW and 4kW using both with the performance indicator method (using Bi=0.1) and the numerical 1D model. If a material could not achieve a Biot number of 0.1, the C_r number at the minimum Biot number was used in the comparison. It was observed from these rankings that the performance indicators were still able to provide predictions of PCM performance, but the deviation between the rankings increased with increasing heat flux.

5. Conclusions

Selection of the optimum PCM material and optimum heat storage thickness and porosity for a LHS can be obtained with performance indicators when lumped capacitance behavior can be attained (Bi≤0.1). This allows material selection to be made early, greatly simplifying the design process.

When lumped capacitance behavior cannot be assumed, material candidates can still be ranked using performance indicators, but more care has to be taken when materials are ranked. Finding optimum materials must be done by comparing the results of numerical calculations.

Numerical models were used to verify the simplified analysis. A full numerical analysis of the optimal LHS proposed by the performance indicators proved that a LHS has significant benefits over sensible heat storage when a uniform heat loss is desired.

In a review by Zalba [14] there are approximately 70 PCMs having melting temperatures between 40ºC and 120ºC. Using the method developed in this work, the most attractive candidates for a LHS (subjected to sufficiently low heat fluxes) can easily be ranked based on their thermal performance. Further review of the best ranked materials can then be performed to exclude candidates based on physical, chemical and economical grounds to select a PCM that will give the overall best performance LHS for a specific application.

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Figure 1 - Position of heat storage in relation to the stove and ambient environment

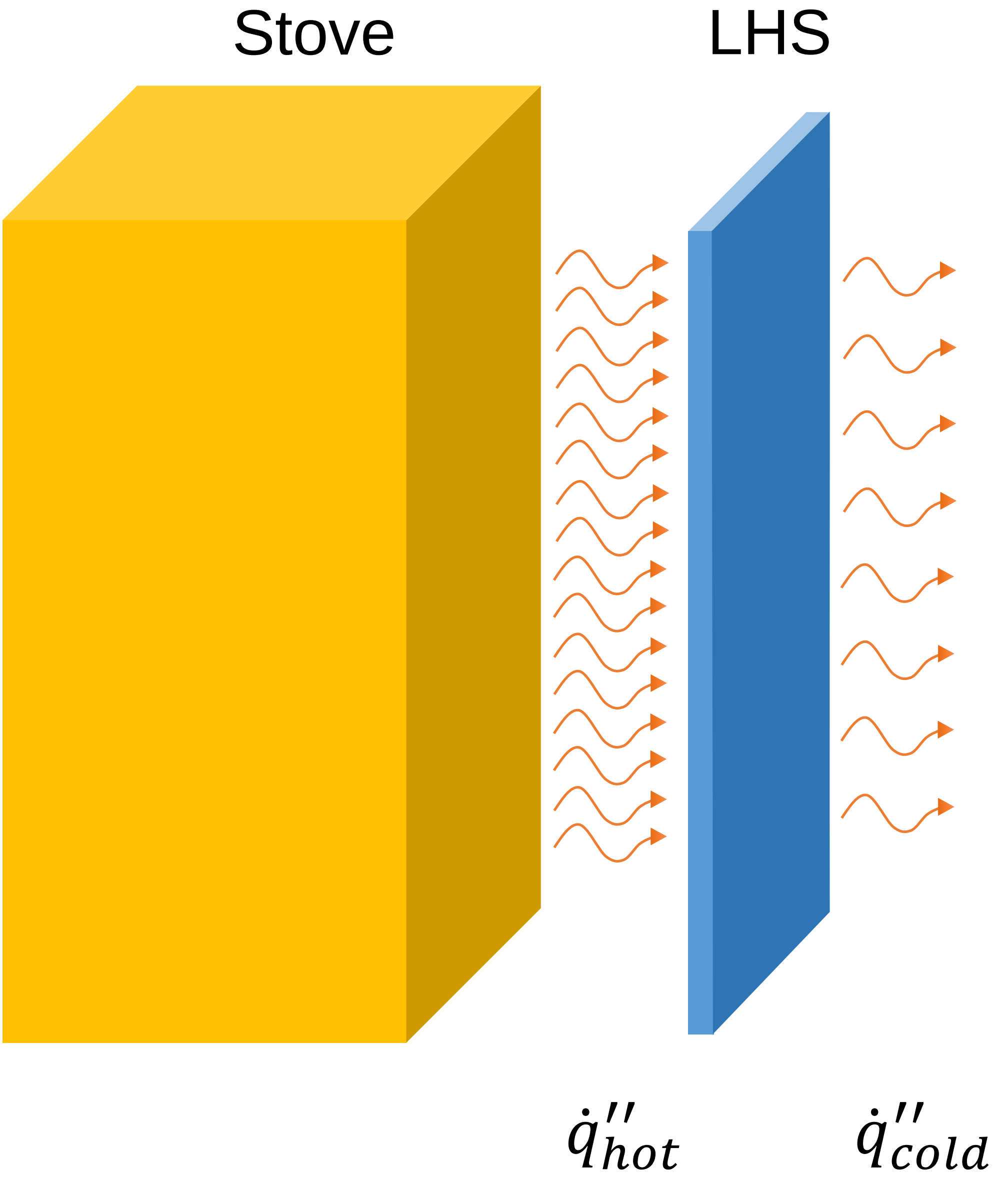
Figure 2 - Heat release from a latent heat storage (LHS) and a sensible heat storage (SHS), subjected to a transient heat flow from wood batch combustion

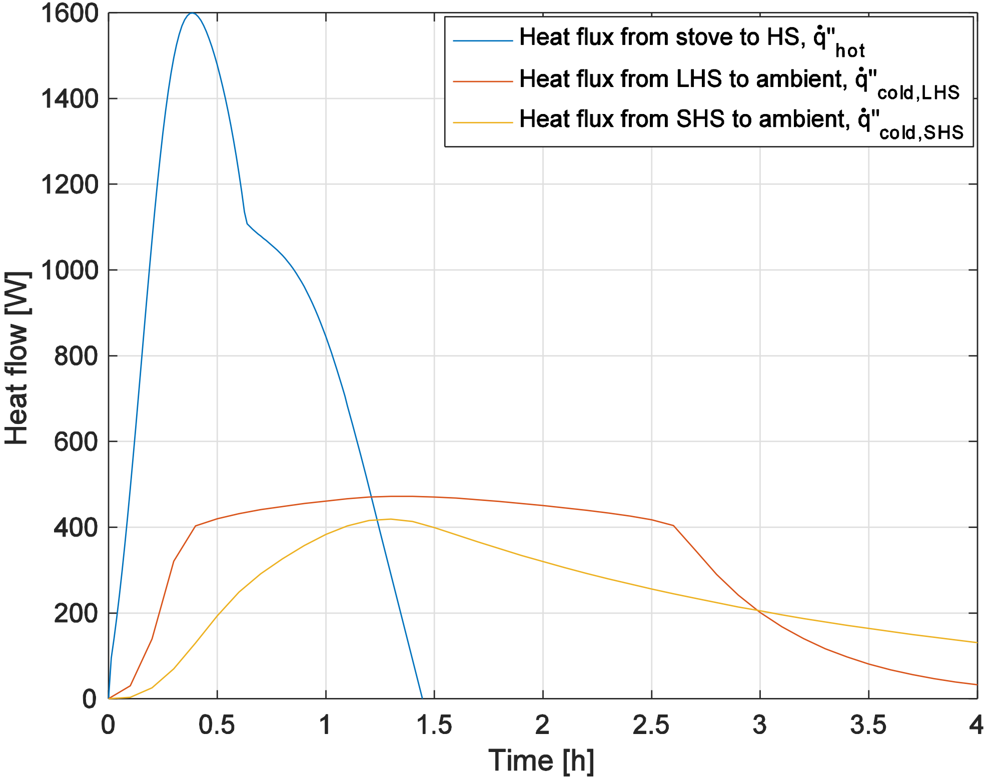
Figure 3 - Fin and metal foam configuration in the heat storage

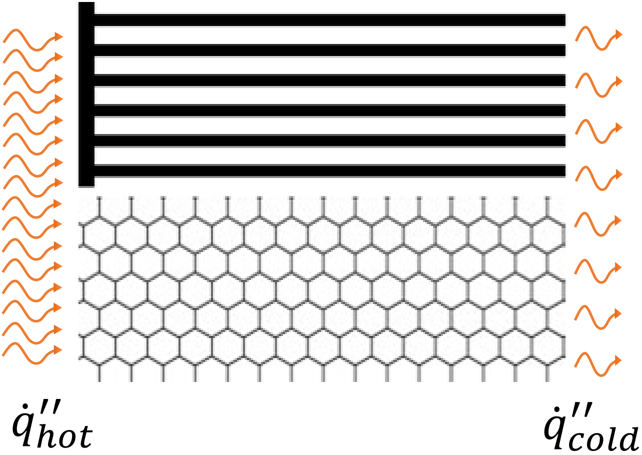
Figure 4 - Biot number, Volumetric energy density and Latent heat ratio as a function of the porosity, using fins as a HTE, with a 1kW average heat flow over an area of $0.27m^2$ and sing Lauric acid as the PCM

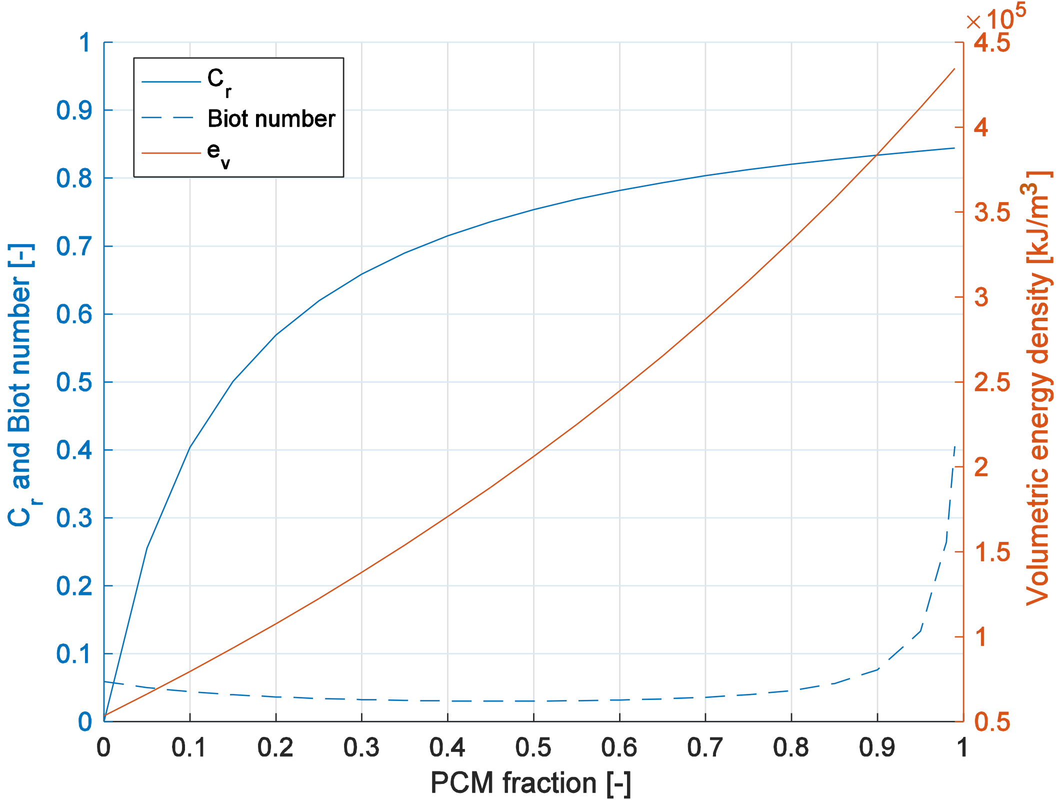
Figure 5 - MAD, Biot number and C_r number plotted against the porosity. The porosity that gives the lowest MAD is $\varepsilon=0.92$. This gives a Biot number of 0.0882

Figure 6 - Heat release profiles from an optimized LHS using EPS ltd E48 and an optimized SHS using soapstone

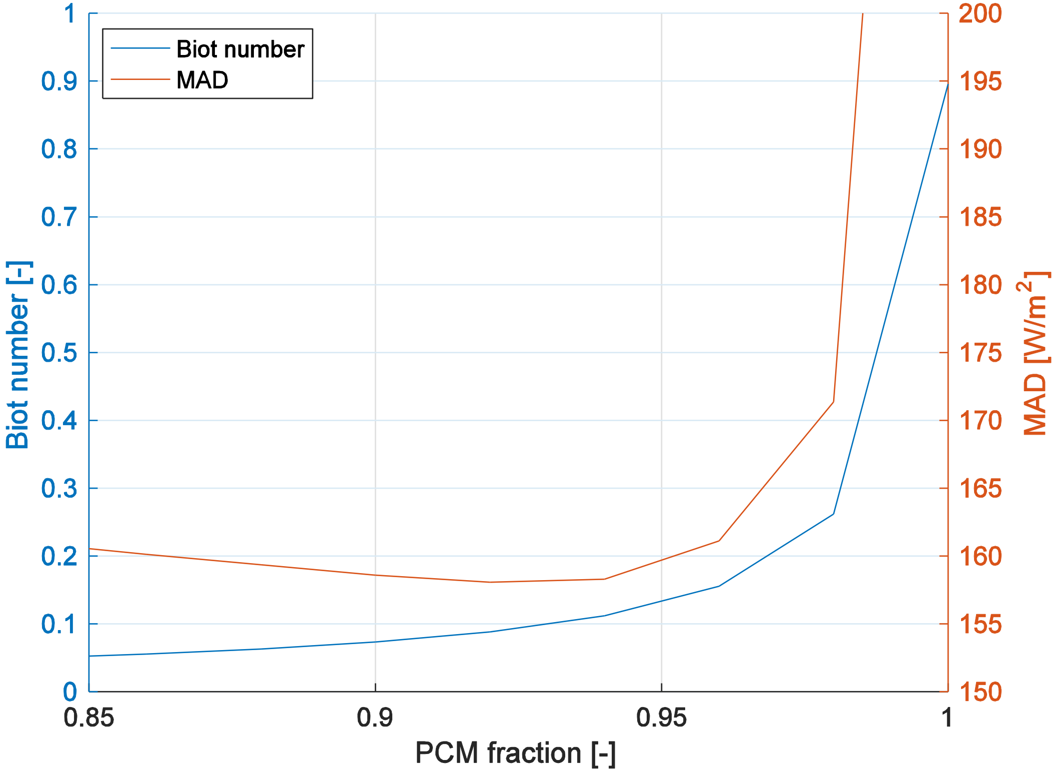

Stove
LHS
$\dot{q}''_{hot}$
$\dot{q}''_{cold}$

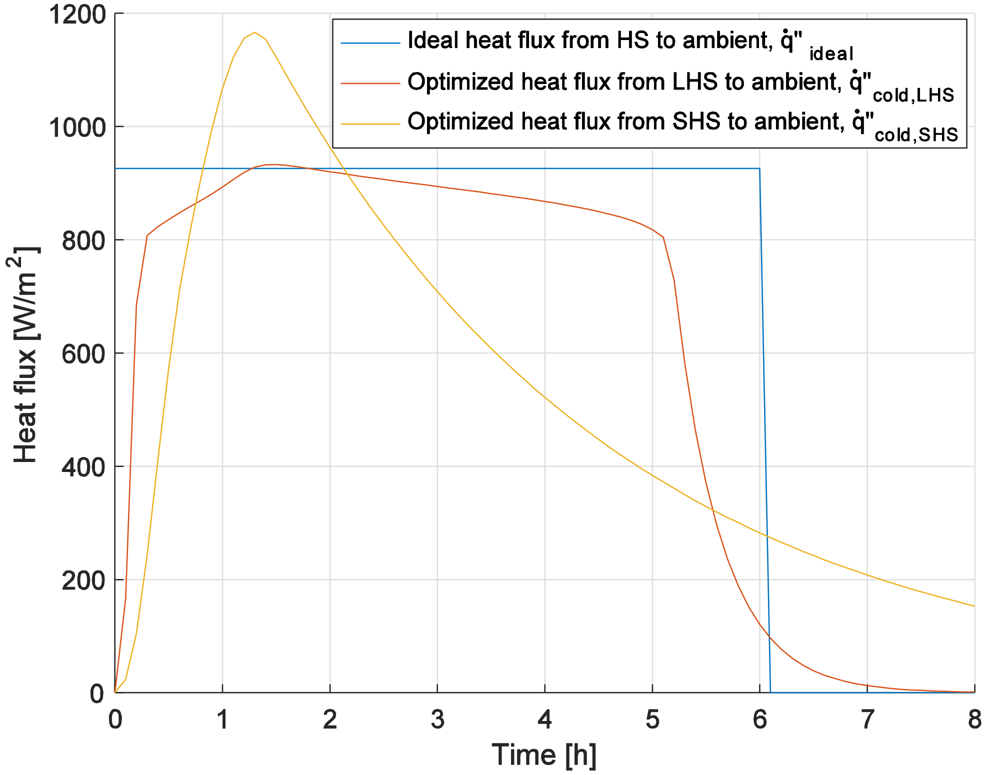

Heat flux from stove to HS, $\dot{q}''_{hot}$
Heat flux from LHS to ambient, $\dot{q}''_{cold,LHS}$
Heat flux from SHS to ambient, $\dot{q}''_{cold,SHS}$
Heat flow [W]
1600
1400
1200
1000
800
600
400
200
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Time [h]


$\dot{q}''_{hot}$
$\dot{q}''_{cold}$



$\times 10^5$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4.5
4
3.5
3
2.5
2
1.5
1
0.5
C_r
Biot number
e_v
C_r and Biot number [-]
Volumetric energy density [kJ/m^3]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
PCM fraction [-]


Biot number
MAD
Biot number [-]
MAD [W/m^2]
PCM fraction [-]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
150
155
160
165
170
175
180
185
190
195
200
0.85
0.9
0.95
1



Ideal heat flux from HS to ambient, $\dot{q}''_{ideal}$
Optimized heat flux from LHS to ambient, $\dot{q}''_{cold,LHS}$
Optimized heat flux from SHS to ambient, $\dot{q}''_{cold,SHS}$
Heat flux [W/m^2]
Time [h]
0
200
400
600
800
1000
1200
0
1
2
3
4
5
6
7
8