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Wood stove material configurations for increased thermal comfort

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Abstract

In this work, a numerical model of the heat transfer through composite wood stove walls has been used to study the effect of material configurations on the heat storage and the heat release profile to the room, to arrive at improved thermal comfort performance. Cast iron and soapstone have been compared, showing that soapstone is a good material from a thermal comfort point of view, while cast iron (for the typical stove weights of today) exhibits a comparably higher peak and faster heat release. Applying a Phase Change Material (PCM) for such a cast iron stove changes this picture. It makes it possible to reduce peak heat release and achieve a more stable as well as an extended heat release period. 53% reduction in peak and 43% reduction in average heat release was demonstrated during the combustion cycle using Erythritol as PCM. However, the selection and use of a PCM must be optimized. Its capacity should be utilized to a maximum extent without overheating the material as it will cause irreversible damage to most PCM.

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Keywords: Wood stove; Cast iron; Soapstone; Heat storage; PCM; Thermal comfort; Highly-insulated buildings

1. Introduction

Different materials are used in wood stoves. In practice, they also act as a temporary heat storage. A major challenge with wood stoves from both a thermal comfort and a combustion performance point of view is their batch combustion operational principle, giving varying heat release to the room in which the stove is placed throughout one combustion cycle. Modern types of residential buildings, like low-energy buildings and passive houses, need less power for space heating. Recent works have shown that wood stoves can have a future in these highly-insulated buildings [1-3]. However, the average heat release from new wood stoves should be decreased and their heat release profile to the room should be flattened as well. Depending on the stove material properties, they will to some degree contribute to flattening the heat release profile (e.g. in kW).

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Cast iron and plate steel are commonly used materials in wood stoves, while soapstone is commonly used in larger and heavier heat storage stoves. However, more advanced materials could also be used, such as phase change materials (PCM) [4]. PCM can store much more heat per mass unit and per volume unit, due to their energy intensive phase change. The PCM store heat at a constant phase change temperature, which would be beneficial for achieving a more stable heat release (especially limiting peak power).

Part of the heat release to the room takes place through the stove window(s). The window is very important for most wood stove owners, as the direct heat radiation through it contributes to both coziness and thermal comfort. Radiation through the stove window to the room will also play a role with respect to flattening (or not) the heat release profile during the combustion cycle. However, at the same time, limiting this radiation is important to ensure a high combustion temperature to secure low emissions of unburned compounds.

In the end, the most important parameters influencing the heat release profile are (1) the heat production (or combustion power) profile, which depends on the fuel properties and the wood stove design and operation, (2) the stove walls' thermal and physical properties, (3) flame/soot and glowing charcoal radiation through the stove window and conduction through the stove window, and, to a lesser extent, (4) radiation from internal wall surfaces through the stove window. From a thermal comfort point of view, the goal for an optimum wood stove design would be to achieve a heat release as stable as possible during a long period of time in order to prevent overheating in highly-insulated buildings (such as passive houses). At the same time, the stove efficiency should be increased and the emissions decreased compared to the wood stoves of today.

Regarding the control of the heat production profile (1), different measures could be applied, such as progressively activating or igniting the batch of wood logs, e.g. by igniting from the top of the batch instead from the bottom. Regarding stove walls (2), the thermal properties of the walls influence the heat transfer through the stove envelope, dictating the resulting surface temperature on the outer walls. This temperature is a major physical variable that influences the heat released to the room by convection and radiation. Using PCM enable new options to control both the heat storage and the heat released to the room, i.e. high specific heat storage capacity and the potential for relatively low and constant outer wall temperature for a significant part of the batch combustion cycle. Regarding sensible heat storage capacity, thermal inertia is key. Finally, the combustion process and its flame picture (3), as well as the flame and glowing charcoal location in relation the stove window, can be influenced and partly controlled. This again can contribute to a more controlled heat release to the room.

To assess the improvement potential of some of these possibilities, a simplified dynamic model of the stove envelope would be very useful to quickly investigate the influence of the envelope properties. Such a tool, Fuelsim Heat Transfer Module, has been developed at SINTEF Energy Research. In this work, it has been used to screen the influence of selected envelope properties and factors on the heat release profile from a wood stove to a room. Based on this, recommendations are given with respect to new developments of wood stoves adapted to future highly-insulated residential buildings.

2. Materials and their properties

The thermal properties, amount and placement of the materials used in stoves are essential influencing factors on the heat release profile. Table 1 lists thermal properties of typical materials used in wood stoves, as well as of two PCM candidates adapted to wood stoves.

As can be seen, there are large differences in density and specific heat between cast iron and plate steel on the one hand and soapstone on the other hand. The specific heat capacity per unit mass is about twice for soapstone, while the density is about twice for cast iron. Hence, the difference in thermal inertia, i.e. the heat storage capacity per Kelvin temperature rise and unit volume, is rather small. The thermal conductivity of soapstone though is much less (about 10 times less) than for cast iron and plate steel, which influences the thermal diffusivity (therefore, the material temperature and the temperature gradient across the material). Soapstone is thus a better insulation material than cast iron and plate steel, and contributes to higher temperatures in a combustion chamber. Skamol, as a representative for fire resistant insulation materials, is completely different, with a very low thermal conductivity and a low thermal inertia. It is typically used to insulate parts of the combustion chamber, especially in cast iron and plate steel stoves, in order to achieve higher temperatures and improved combustion.

The use of a PCM is one way to drastically modify the heat capacity and conductivity of a stove envelope with a limited mass and volume of material. Their density and conductivity are closer to an insulation material, while their specific heat is well above, as can be seen for *Erythritol* and *Sodium acetate trihydrate* in Table 1. In this paper,

Erythritol has been chosen as the PCM to be included in a stove, mainly due to its suitable phase change temperature. In reality, a number of factors should be considered when evaluating the suitability of a PCM for a specific application. A method for ranking and selection of PCM for wood stoves has been developed in [5].

Table 1: Properties of typical materials used in wood stoves and two PCM candidates [6] for wood stoves.

	Cast iron	Plate steel	Soapstone	Skamol, VI 100(600)	Sodium acetate trihydrate	Erythritol	
Density (solid)	7190	7870	2980	600	1420	1480	[kg/m ³]
Density (fluid)					1280	1300	[kg/m ³]
Specific heat (solid)	0.460	0.448	0.980	0.940	2.790	1.380	[kJ/kgK]
Specific heat (fluid)					3.000	2.760	[kJ/kgK]
Thermal inertia (solid)	3307	3526	2920	564	3962	2042	[kJ/m ³ K]
Thermal inertia (fluid)					3840	3588	[kJ/m ³ K]
Thermal conductivity (solid)	60	72	6.4	0.181	0.7	0.733	[W/mK]
Thermal conductivity (fluid)					0.4	0.326	[W/mK]
Phase change specific heat					260	339.8	[kJ/kg]
Phase change temperature					58	118	[°C]
Critical temperature					115	160	[°C]

3. Modelling approach and simulation matrix

A simplified thermal dynamic model of the stove envelope has been developed to investigate the influence of relevant properties and influencing factors. It enables to study a one-dimensional transient (or time-varying) heat transfer in a composite wall due to an imposed transient heat flux on the hot side of the wall (i.e. the combustion chamber side). This heat flux is based on the transient heat production profile from the combustion process. In the present work, this flux is pre-computed using another in-house simulation tool, Fuelsim-Transient, developed at SINTEF Energy Research to investigate the combustion process in wood stoves [7]. A part of this combustion heat, corresponding to the thermal efficiency of the stove, is then conducted through and partly stored in the composite wall. Dynamic simulations generates transient wall temperatures and a transient heat release profile to the room. By setting the material type and thickness of the different wall layers, as well as the stove thermal power, the resulting transient stove surface temperature and heat release profile can be evaluated. For a well-insulated combustion chamber, a larger fraction of the produced heat will be transferred to the room using a heat exchanger section, downstream before the flue gas goes into the stack. However, for the sake of simplicity, only one wall is used to represent the wood stove with a total mass and height equal to the real stove geometry.

Figure 1 shows a sketch of the composite wall. It consists of up to three layers with the possibility to include two radiation shields. For each layer i (1 to N) with width x_i , a uniform temperature of the layer T_i is computed as function of time t based on equation 1.

$$\frac{\partial E_i(t)}{\partial t} = k_i(T_i(t)) \frac{\partial^2 T_i(t)}{\partial x^2} \quad (1)$$

where k_i is the thermal conductivity of the layer material and, E_i , its internal energy (combining sensible and latent heat). If a PCM is used, a uniform temperature T_i in the PCM layer is assumed when at its phase change temperature. The temperature is kept constant until the entire phase change has been completed. Below the phase change temperature, PCM properties of the solid phase are used, while above the phase change temperature, properties of the liquid phase are used. Initial conditions $T_i(0)$ are set for all layer temperatures, e.g. the room temperature T_r . A time-varying heat flux is imposed on the inner part (i.e. $q_0(t)$ imposed) and at the outer part of the composite wall (i.e. $q_N(t)$ imposed). This last flux corresponds the heat emitted/released to the room, $q_c(t)$ (equation 2), computed assuming a constant room temperature T_r at 20°C and using the instantaneous stove surface temperature, $T_N(t)$. For the convective heat transfer, $q_{e,c}(t)$, temperature dependent correlations for the convective heat transfer coefficient $h_c(t)$ are used based on the stove typical height (L_{ref}). The heat release by radiation $q_{e,r}(t)$ is computed in a simplified way assuming that the stove is small compared to the room size: the flux is thus only a function of the stove surface emissivity (ϵ) and temperature (σ is the Stefan-Boltzmann constant). This way to

estimate $q_c(t)$ has been shown to be realistic in Georges et al. [3] using experimental data.

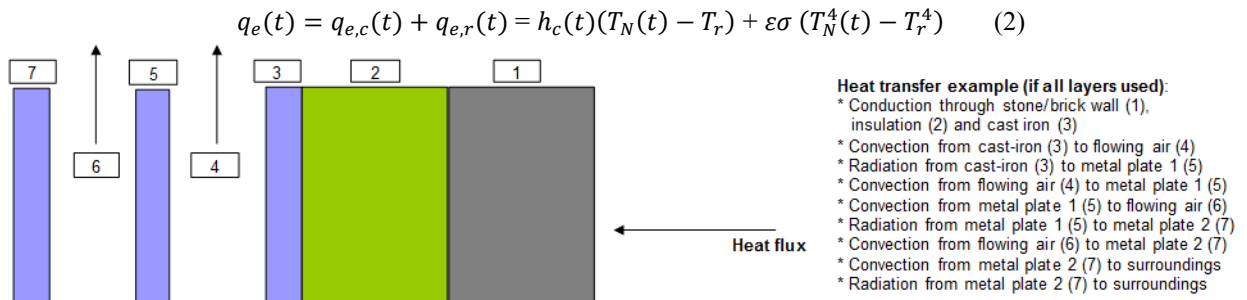


Figure 1: The composite wall in the dynamic model; radiation shields have not been used in this work.

The simulation matrix presented in this work is limited to study the effects of material choices and configurations on the transient heat release profile, e.g. the heat production profile has been kept constant. As cast iron stoves are more common than plate steel stoves and since both materials have similar properties, this study compares only cast iron and soapstone. Five cases with stoves of increasing weights have been studied in order to investigate the effect of increasing thermal inertia (Case 1 to 5). For these cases, the performance of cast iron and soapstone stoves have been compared as well as the influence of a PCM layer on the outside of the cast iron. The fraction of the heat imposed on the internal wall that is eventually stored in the wall at the end of the combustion cycle is one important performance index, for the heat storage capacity. Another performance index is the surface temperature of the outside wall at the end of the combustion cycle, and its subsequent decrease when the combustion process has ended, for the heat release rate.

4. Results and discussions

As shown in Figure 2 for a cast iron and soapstone stove of equal weight, the soapstone performs much better than cast iron for all cases but especially for lower weights. Case 5 is representative for a rather normal soapstone stove, the heat release profile using soapstone becomes very good with respect to thermal comfort, giving a low and rather constant heat release for a long period of time (over 2 hours). Case 1 is representative for a rather normal cast iron stove, the behavior using cast iron becomes very different, see also Figure 4 (left). A limited fraction of the heat (14%) is stored in the stove at the end of the combustion cycle.

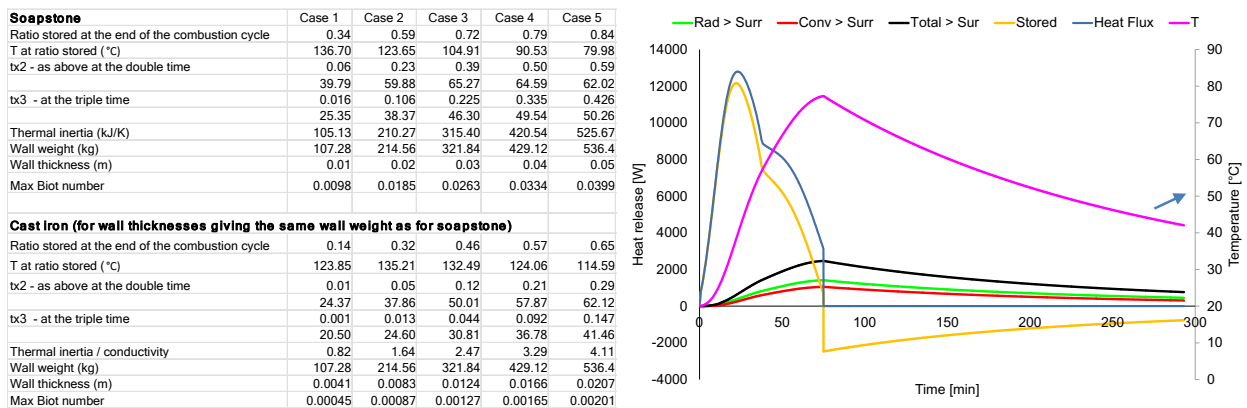


Figure 2: Comparison of cast iron and soapstone for equal weight stoves (left) for 8 kW mean net effect and 75 min combustion period, i.e. 10 kWh; Imposed heat flux, heat flows and wall temperature for Soapstone and Case 5 (right). Rad = Radiation; Conv = Convection; Sur = Surroundings; "Ratio stored at the end of the combustion cycle" is the fraction of heat transferred to the wall that is stored in the wall at the end of the combustion cycle; "T at ratio stored" is the outer wall temperature at the end of the combustion cycle

If the cast iron envelope is adjusted from an equal weight scenario to an equal volume scenario or an equal thermal inertia scenario compared to the soapstone, it can be seen in Figure 3 that the equal weight scenario gives the poorest and the equal volume scenario gives the best performance from a thermal comfort point of view. In the case of an imposed heat flux on an equal thermal inertia wall, cast iron gives almost identical behavior as soapstone, however, the wall mass is of course more than double.

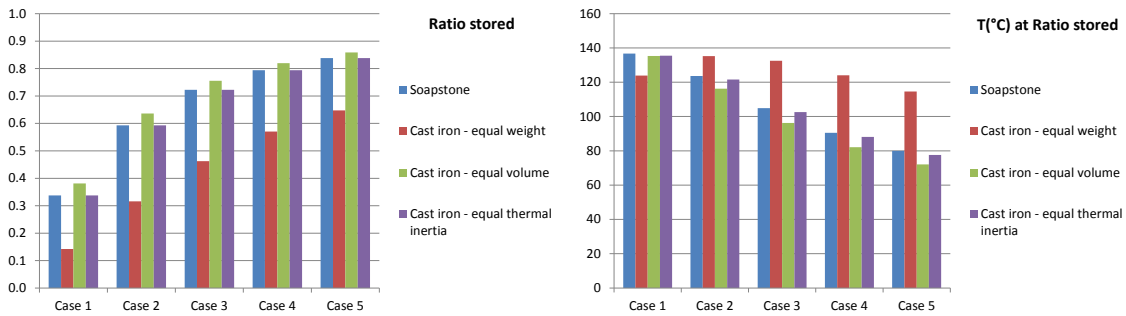


Figure 3: Comparison of cast iron and soapstone for Case 1-5.

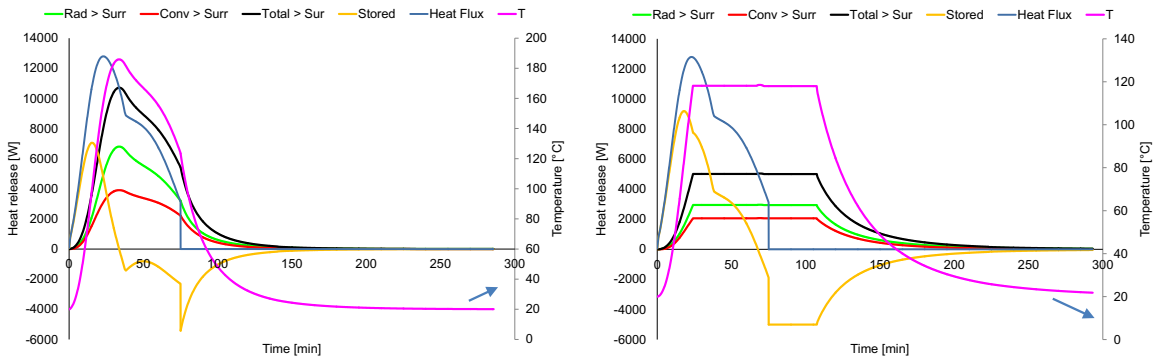


Figure 4: Imposed heat flux, heat flows and outer wall temperature of Case 1 for cast iron (left) and cast iron + PCM (right).

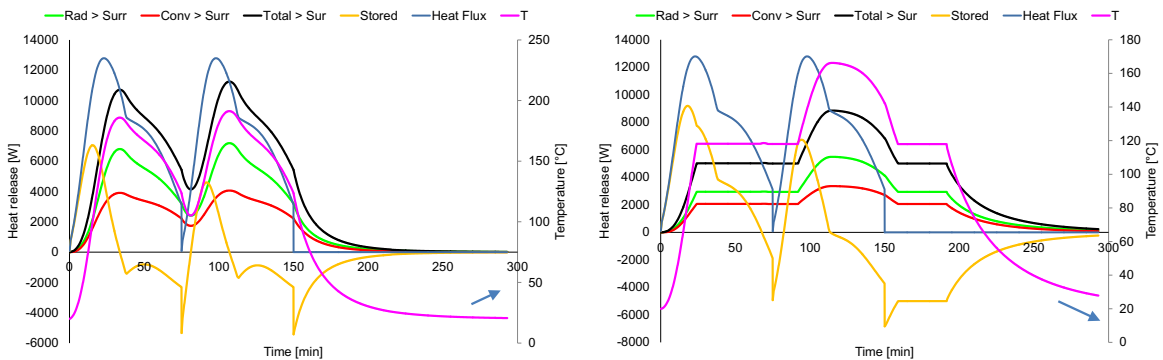


Figure 5: Imposed heat flux, heat flows and outer wall temperature of Case 1 for cast iron (left) and cast iron + PCM (right), both with two consecutive combustion cycles.

Adding the PCM, with a weight of 28 kg, to the cast iron stove of Case 1 significantly improves the performance for a single combustion cycle as can be seen in Figure 4 for a cycle with an average net effect of 8 kW for 75 min, i.e. a net heat production of 10 kWh have been used. 53% reduction in peak and 43% in average heat release is

achieved during the combustion cycle, giving an average heat release just below ~ 4 kW. The effect of adding PCM will decrease with increasing thermal inertia (i.e. Case 2 to 5).

As can be seen in Figure 5 for Case 1 with two consecutive combustion cycles, the second combustion cycle for cast iron without PCM produces a heat release profile rather similar to the first combustion cycle, with only a small increase in the peak heat release. However, if PCM is considered, the temperature during the second cycle increases well beyond the phase change temperature. In practice, this maximum temperature is slightly above the PCM critical temperature of 160°C , where above, irreversible damage to the PCM will occur. This will cause permanent damage to the PCM. Measures must be taken to ensure that this will never happen. A pause between the combustion cycles is a theoretical option, but maybe not from an optimum combustion process point of view, due to cooling of the combustion chamber. Then it could be better to decrease the amount of wood for the second combustion cycle. Wood stoves are in real life very complicated to operate manually and inherently hard to control. Hence, in real life, measures must be implemented for wood stoves with PCM to stop or greatly decrease the heat transfer to the PCM when its temperature increase significantly beyond the phase change temperature. The alternative is to ensure that the PCM capacity is large enough for the most extreme cases, which could become a rather costly option.

5. Conclusions

The use of wood stoves in highly-insulated buildings introduces requirements on their thermal performance. The average heat release from new wood stoves to the room should be decreased and its heat release profile should be flattened as well. Downscaling stoves and/or their heat release (kW) is key. As shown in this work, increasing the thermal inertia of the stoves, as done using soapstone, is one pathway. However, adding PCM to cast iron stoves significantly improves their heat storage performance as well and reduces the outer wall temperature, as long as the PCM don't (significantly) exceed its melting temperature. 53% reduction in peak and 43% in average heat release during the combustion cycle was demonstrated using Erythritol as PCM. The effect of PCM increases with decreasing cast iron stove weight, i.e. the benefits of PCM increase with decreasing cast iron thermal inertia. The developed numerical model of the heat transfer through composite walls makes it possible to compare and screen different composite wall material configurations in an efficient manner.

For a real condition where the stove is operated in various ways and for various durations, it becomes crucial to have a robust and flexible PCM system. The heat transfer through the PCM should be optimized to ensure maximum utilization of its heat storage capacity, while its critical temperature should never be exceeded (even in some part of it). Typically, a heat transfer enhancer would be needed to increase the conductivity and the temperature uniformity, which can be metal fins or foams inside the PCM layer.

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**Biography**

Dr. Øyvind Skreiberg (50) is Chief Scientist within stationary bioenergy at SINTEF in Trondheim, Norway, having 25 years of broad bioenergy experience, contributing to about 400 scientific publications, presentations and reports. His core research areas are wood stoves, biomass CHP, combustion, gasification, pyrolysis, torrefaction and carbonization. He has represented Norway since 1998 in IEA Task 32 Biomass combustion and co-firing.