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Transient Heat Production and Release Profiles for Wood Stoves

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Combustion of wood logs in wood stoves and fireplaces occurs through a so-called batch combustion process, i.e. it is a highly transient process where most parameters change during the combustion cycle. This results in periods with poor combustion conditions giving high emissions of unburnt compounds and a highly varying produced power throughout the combustion cycle. The power that is actually transferred to a room/building is also highly varying and depends additionally on both the heat storage capacity of the stove materials and their conductivity. Finally, the heat will be transferred to a room via radiation and convection from the outer stove surfaces, and a smaller part will be transferred through the stove window directly to the room. The primary goal would be to achieve a more stable heat release to the room/building, which can be done by improving either or both the combustion process and the heat storage and -transfer. By applying different materials, material configurations and designs it will be possible to flatten out the heat release profile to a room.
In this work different cases are analysed with regards to their influence on the heat release profile to a room. The results show the influence of improved combustion process control and using different materials including their configurations and give recommendations for material choices and localisations in wood stoves and fireplaces.

1. Introduction

The transient nature of combustion in wood stoves and fireplaces is a result of the batch loading principle of these units, i.e. the fuel is loaded as a batch, and then the batch is combusted for a period of time without additional fuel loading. The result is that the moisture content is evaporated at its maximum rate in the initial phase of the batch cycle, followed by devolatilization of the volatile content of the fuel, while the last phase will be the char burnout. This results in a low stove power in the beginning of the batch cycle due to moisture evaporation, increasing rapidly towards a maxima due to an accelerating devolatilization rate of the whole batch, and decreasing again as the char is combusted at a much lower rate. The high heating value of the char compensates somewhat for the latter effect. If loading a new batch before the current one has been completely combusted this new batch will go through the same transient process.
Hence, there is a need to control the combustion process better to lower the maximum devolatilization rate. This could be done by activating only a part of the batch at a time, approaching a more continuous combustion rate. However, still the moisture would be evaporated with a much higher rate initially, and therefore a constant stove power is not possible. However, with proper material choices and localisation, the heat release to a room can be flattened out further, approaching a more constant heat release for the main part of the combustion cycle. This is possible by using a so-called phase change material (PCM), which takes up heat at a constant temperature when it is heated due to phase change, and releases heat at the same temperature due to a reversed phase change when it is cooled down.
During a start-up cycle, i.e. starting with a cold stove, the situation is more severe than during re-loading. When re-loading an already hot stove, the stove is preheated and also heat from the combustion of remaining char will be available for supporting the drying process and, hence, the stove power is increased in this first part of the combustion cycle. The more frequent the re-loading, the more continuous the combustion process will become.

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In practise there are several possibilities that can be explored to flatten out the heat release profile from wood stoves and fireplaces: 1) Ensure that the whole batch is not activated at once, but rather progressively by e.g. igniting the batch from the top; 2) Having a combustion chamber design that allows for more controlled progressive activation of the batch, i.e. a more continuous fuel feeding; 3) Optimizing the division between direct radiation through the glass, the heat transfer through the combustion chamber walls and the heat transfer through the walls of the heat transfer section by changing the glass surface area and properties as well as the combustion chamber wall properties; 4) Extensive use of ordinary heat storage materials, e.g. soapstone, dampening the peak power by intermediate heat storage; 5) Use of PCM instead, to ensure heat release to a room at a constant temperature; 6) Combinations of the previous measures.

In this work the novelty lies in directly comparing these different possibilities. In all the cases the same fuel batch size, calculated according to the Norwegian standard (NS 3058, 1994), is assumed, i.e. fuel batch size effects are not evaluated here. In all cases the moisture content is assumed to be 20 wt% on wet fuel basis. The influence of the heat release profile on the thermal comfort in a room is not analysed here, however this has been studied in earlier works for some cases (Georges et al., 2013; Georges et al., 2014). In this work, the feasibility of material choices and localisation in wood stoves and fireplaces is discussed. By feasibility we mean technical feasibility, i.e. what can be done to improve the performance of these units with respect to efficiencies and thermal comfort.

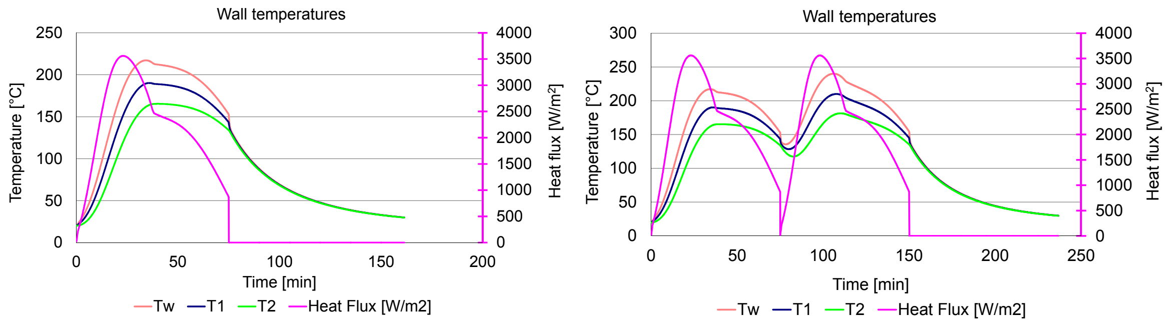
2. Case studies

Based on the previously listed possibilities, a number of cases (scenarios) are analysed with regards to their influence on the heat release profile to a room. For all cases both a cold and a hot (preheated) stove are analysed. The results are presented through material temperatures during the combustion cycle and for the following time period without heat production, i.e. only heat release. Both the heat production profiles and the heat release profiles from the stoves are also presented. In the evaluation, the *Fuelsim-Transient* software (Skreiberg, 2002) and a later developed *Fuelsim – Heat Transfer Module* have been used. The heat transfer modelling approach inside the stove envelope is described in Skreiberg and Georges (2017), where also the material properties used are listed. *Fuelsim-Transient* models the transient conversion of a batch of wood logs. The transient heat production profile is calculated from the transient fuel composition, i.e. the composition of the fuel burning as the combustion process progresses. *Fuelsim – Heat Transfer Module* uses the transient heat production profile as input to the modelling of the heat transfer inside the stove envelope.

2.1 Base case: 8 kW nominal power, 20 wt% moisture

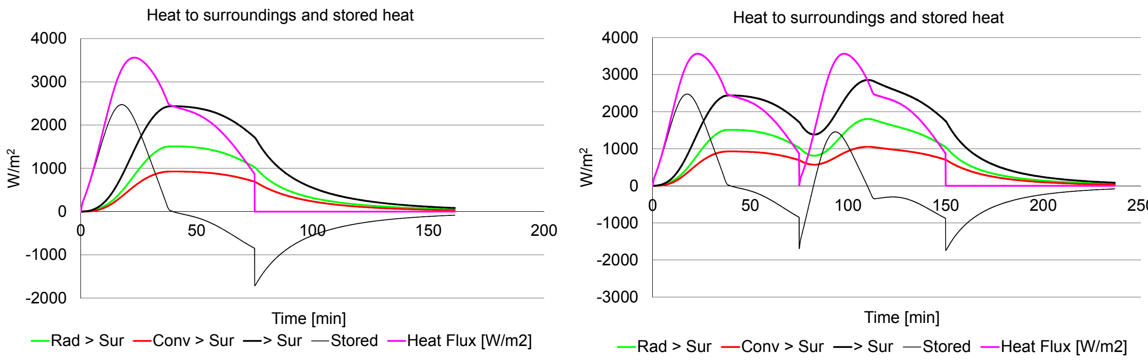
The base case heat production profile is a representative heat production profile for traditional stoves, i.e. with a typical and high heat power peak. To investigate the effect of this profile on the heat transfer through the stove walls and the final heat release profile, a traditional stove configuration was selected, where the combustion chamber is equipped with firebricks and the rest of the stove is made of cast iron. The effect of a glass is neglected and the heat production profile is forced through a single wall, representing all six walls of the stove and both the combustion chamber section and the heat exchanger section. In other words, the heat transfer is modelled by a one-dimensional heat transfer problem. The total outer surface area of the stove is 3.6 m^2 and its height is 1.2 m. The thickness of the firebrick is 2.5 cm and the cast iron 0.6 cm. The firebrick (Skamol V-1100(700)) and its higher insulating effect compared to cast iron is in the modelling approach spread out on the entire wall area, which is a simplification compared to a typical stove which has separate combustion chamber and heat exchanger sections. The thermal inertia of the stove becomes 80.5 kJ/K. The emissivity of all material surfaces are set to 0.9. Thermal conductivity, specific heat capacity and density of all the materials are given in Skreiberg and Georges (2017). The stove weight becomes 165 kg. The combustion chamber volume is 0.0275 m^3, which gives an ideal fuel loading according to NS 3058 (1994) of 3.085 kg. Assuming a batch heat production cycle length of 75 min and a stove efficiency of 85%, this gives a nominal power of 8 kW.

Figure 1 shows the heat production profile and the wall temperatures in the stove for a cold stove (the first heat production profile) and a hot stove (the identical following heat production profile) while Figure 2 shows the heat transfer to the surroundings and the stored heat. The calculation is stopped when the inner wall surface temperature Tw reaches 30°C.



(a) (b)

Figure 1: a) Base case heat production profile and wall temperatures for one combustion cycle. T1=Layer 1 (firebrick) temperature, T2=Layer 2 (cast iron) temperature, Tw=Inner wall surface temperature. b) for two combustion cycles.



(a) (b)

Figure 2: Base case heat to surroundings and stored heat for a) one combustion cycle and b) two combustion cycles. Rad > Sur = radiation to surroundings, Conv > Sur = convection to surroundings, > Sur = Rad + Conv to surroundings, Stored = stored heat.

2.2 Improved cases

Case 2: Modestly progressively activated batch (igniting from the top): Here the base case is modified through a more stable fuel composition, giving a flatter heat production profile. The heat production profile of Case 2 is compared with the base case profile in Figure 3.

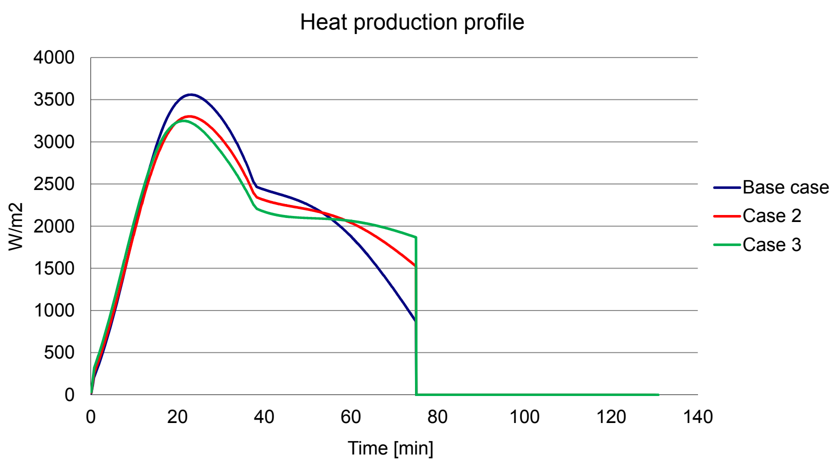


Figure 3: Heat production profile for Case 2 and 3, compared with the base case.

Case 3: Progressively activated batch (combustion chamber design): Here the base case is modified through a more stable fuel composition and an improved combustion chamber design, giving an even more flat heat production profile. The heat production profile of Case 3 is compared with the Case 2 profile in Figure 3.
Case 4: Heat transfer optimization between the heat transfer sections, i.e. combustion chamber walls and heat exchanger walls: Note that the total time has been kept equal to the base case, i.e. the simulation is not stopped when the inner wall surface temperature Tw reaches 30°C, but as a result at a higher temperature for the combustion chamber section and a lower temperature for the heat transfer section. The heat transport through the combustion chamber walls per unit area is set to three times less than through the heat exchanger walls. The *Fuelsim – Heat Transfer Module* was used also here.
Case 5: Extensive use of ordinary heat storage materials: Here soapstone is used as outer wall material instead of cast iron. The thickness of the soapstone is 3 cm. The stove weight becomes 331 kg.
Case 6: Use of PCM instead: Here erythritol (which must be encapsulated in practise) is used as outer wall material instead of cast iron. The thickness of the layer is 0.6 cm. The stove weight becomes only 41.6 kg.
Case 7: A selected combination of the above to achieve a more optimum case: Three wall materials are used, firebrick, soapstone and erythritol. Here erythritol is used as outer wall material. Soapstone is used as an intermediate wall material. The thickness of the soapstone layer is 1.5 cm (i.e. half compared to Case 5) and the erythritol layer 0.1 cm (i.e. one-sixth compared to Case 6). The stove weight becomes 176 kg. An option would be to change the order of the materials, i.e. switching layer 2 and 3, having the PCM in layer 2 and the soapstone in layer 3. In practise this has a rather small influence on the heat transfer to the room, and it becomes more important to focus on practicalities, i.e. in which layer it is most convenient and safe to place the PCM, with focus on the danger of overheating the material. This means in practise that the phase change layer should be the outer layer.
The resulting outer wall temperatures for the different cases are shown in Figure 4. The different cases result in significantly different outer wall temperatures and corresponding heat release profiles.

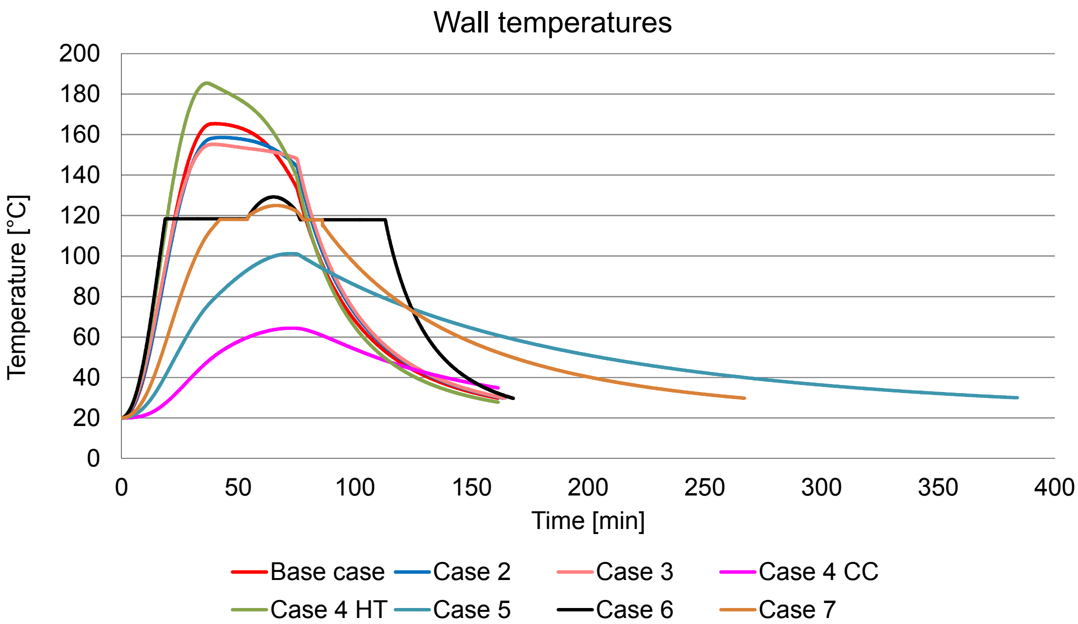


Figure 4: Comparison of outer wall temperatures for the different cases (For Case 4: CC=Combustion chamber section, HT=Heat transfer section).

3. Key performance indexes and results

To compare the results, the following comparison criteria are defined: 1) the ratio between the peak heat release and the peak heat production; 2) the ratio between the heat release mean power and the heat production mean power; 3) the heat release standard deviation in percent. Key input parameters and the performance indexes for the different cases are given in Table 1 for one combustion cycle and in Table 2 for two combustion cycles. Case 4 shows that dividing the stove in a combustion chamber section and a heat exchanger section do change the results somewhat compared to the base case, but not significantly with respect to drawing useful conclusions when comparing the different cases. There is also a considerable uncertainty with respect to the proper division of the heat production profile between the two sections.

Table 1: Key input parameters and performance indexes for the different cases (one combustion cycle)

	Base case	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Layer 1 weight (kg)	9.64	9.64	9.64	9.64	9.64	9.64	9.64
Layer 2 weight (kg)	155.30	155.30	155.30	155.30	321.84	31.97	160.92
Layer 3 weight (kg)	NA	NA	NA	NA	NA	NA	5.33
Total weight (kg)	164.95	164.95	164.95	164.95	331.48	41.61	175.89
Layer 1 thermal inertia (kJ/K)	9.06	9.06	9.06	9.06	9.06	9.06	9.06
Layer 2 thermal inertia (kJ/K)	71.44	71.44	71.44	71.44	315.40	44.12	157.70
Layer 3 thermal inertia (kJ/K)	NA	NA	NA	NA	NA	NA	7.35
Total thermal inertia (kJ/K)	80.50	80.50	80.50	80.50	324.47	53.18	174.12
Inner wall surface max temperature (°C)	217.16	206.02	201.18	185.56	138.71	202.67	169.98
Layer 1 max temperature (°C)	190.21	181.17	177.34	98.40	119.66	169.03	147.72
Layer 2 max temperature (°C)	165.38	158.57	155.19	185.41	101.22	129.18	129.10
Layer 3 max temperature (°C)	NA	NA	NA	NA	NA	NA	124.97
Total time (min)	161.40	163.65	164.40	161.40	383.93	167.93	267.00
Mean stove power (kW)	3.64	3.59	3.57	3.63	1.42	3.53	2.14
The ratio between the peak heat release and the peak heat production	0.68	0.69	0.67	0.66	0.30	0.45	0.43
The ratio between the heat release duration and the heat production duration	2.15	2.18	2.19	2.15	5.12	2.24	3.56
The heat release standard deviation in percent of mean heat release	87.99	85.54	83.80	83.95	76.73	57.47	84.38

Note: Phase change heat storage capacity is not included in the thermal inertia for the PCM

Table 2: Key input parameters and performance indexes for the different cases (two combustion cycles)

	Base case	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Inner wall surface max temperature (°C)	239.99	230.95	228.38	198.10	195.26	263.31	221.71
Layer 1 max temperature (°C)	210.01	202.82	200.74	124.47	164.52	232.98	192.18
Layer 2 max temperature (°C)	181.44	175.86	174.27	197.94	139.35	177.24	164.90
Layer 3 max temperature (°C)	NA	NA	NA	NA	NA	NA	158.75
Total time (min)	236.70	238.95	239.70	236.70	496.50	246.75	353.85
Mean stove power (kW)	5.02	4.97	4.95	5.01	2.31	4.83	3.31
The ratio between the peak heat release and the peak heat production	0.80	0.82	0.82	0.77	0.51	0.77	0.64
The ratio between the heat release duration and the heat production duration	1.58	1.59	1.60	1.58	3.31	1.65	2.36
The heat release standard deviation in percent of mean heat release	69.04	67.14	66.04	66.72	84.71	56.25	80.00

The base case being the reference, the changes/improvements compared to the base case for one combustion cycle can be summarised as follows:

Mean stove power: The nominal power is 8 kW, however the mean stove power will be lower since the stove will release stored heat for some time after the heat production has ended. For the base case (Case 1) the mean stove power is 3.64 kW. A more stable drying process and a closer to constant dry fuel composition reduce the mean stove power only slightly (Case 2 and 3). However, the heat storage stove with soapstone (Case 5) reduces the mean stove power to 1.42 kW, while the stove with PCM (Case 6) reduces it only to 3.53 kW. The stove with both soapstone and PCM (Case 7) reduces it to 2.14 kW. The heat storage capacity of the stove is the main factor influencing the mean stove power. The ratio between the heat release duration and the heat production duration mirrors the mean stove power results. The ratio between the peak heat release and the peak heat production also mirrors the mean stove power results, except for the stove with PCM, which performs almost as good as the stove with both soapstone and PCM. The heat release standard deviation in percent of mean heat release is slightly improved by a more stable drying process and a closer to constant dry fuel composition. The soapstone stove is also only slightly better than the base case stove, while the PCM stove is by far the best. Combining soapstone and PCM actually here performs only slightly better than the base case stove. Combining cast iron and PCM, as shown in Skreiberg and Georges (2017), then becomes a better option.

Outer wall temperature: The max outer wall temperature is 165.38°C in the base case (Case 1). A more stable drying process and a closer to constant dry fuel composition (Case 2 and 3) reduces it somewhat. The lowest temperature of 101.22°C is achieved for the heat storage stove (Case 5), while the PCM stove (Case 6) has a somewhat higher temperature, which is close to the temperature for the stove with both heat storage material and PCM (Case 7).

Sensitivity analysis: Key input parameters have been varied for the different cases to evaluate the effect with respect to: 1) the amount of cast iron used in the base case, Case 2 and Case 3, where an increasing amount reduces the mean stove power and the outer wall temperature; 2) the amount of soapstone used in Case 5, where an increasing amount reduces the mean stove power and the outer wall temperature; 3) the amount of PCM used in Case 6 and Case 7 where a smaller effect of the additional mass can be seen and the effect is mainly due to the phase change capacity of the PCM, i.e. if the heat transported to this layer is enough to complete the phase change or not. If the phase change capacity is too low, the PCM temperature will continue to increase in the liquid phase, with the risk of overheating the material.

Cold or preheated stove (one or two combustion cycles): The base case being the reference, the changes/improvements compared to the base case for two combustion cycles can be summarised as follows, through a comparison with one combustion cycle:
1) Mean stove power increases in all cases due to the preheating and the following combustion cycle and only one cool down cycle.
2) The ratio between the heat release duration and the heat production duration mirrors the mean stove power results, and becomes lower than for one combustion cycle.
3) The ratio between the peak heat release and the peak heat production increases since the peak heat release increases due to the preheating while the peak heat production remains constant.
4) The heat release standard deviation in percent of mean heat release improves in all cases except for the heat storage stove (Case 5).
5) The outer wall temperature increases in all cases due to the preheating and the following combustion cycle.

4. Conclusions

Based on the key input parameters and performance indexes for the different cases a number of conclusions can be drawn. The mean stove power is always lower than the nominal heat production power. Preheating of the stove influences the stove performance towards higher mean stove power and higher outer wall temperatures. Improving the combustion process control by igniting from the top or further combustion chamber design induced control improvements reduce the mean stove power.
A heat storage stove with a high thermal inertia prolongs the cool down period very much and, hence, reduces the mean stove power. A PCM stove prolongs the cool down process to a lesser extent, but results in, by far, the most constant heat release to a room. The phase change temperature will dictate the outer wall temperature and influence the duration of the cool down process, however, if too little PCM is used overheating is a risk, with degradation of the PCM as a consequence.
A combination of a heat storage stove and a PCM stove is not necessarily very beneficial. The amount of each material need to be carefully selected based on the expected use pattern of the stove. Even though in this work, the heat production transferred to the stove walls has been kept constant, the efficiency of use for the heat released to a room will increase if the room does not get overheated. Hence, for low energy or passive houses overheating must be avoided, i.e. the heat release profile to a room should be as flat as possible.
In reality, the stove configuration will influence also the heat production transferred to the stove walls, and hence the thermal efficiency of the stove. Again the most stable combustion conditions will potentially improve the thermal efficiency. However, a too high heat production in combination with too low heat storage capacity of the stove will decrease the thermal efficiency, due to an increased chimney inlet temperature.
The optimum stove can be said to be a stove which satisfies the thermal comfort demands of the user and gives the highest possible thermal efficiency and the lowest possible emissions. Regarding the latter, increased combustion process control is very important for stoves with limited heat storage capacity, while stoves with a high heat storage capacity, using traditional heat storage materials or PCM, can achieve low emissions through a short and intense heat production cycle, followed by a long heat release period.
In further work, evaluating in more detail the practical aspects of implementing PCM in wood stoves as well as investigating the cost aspect of the different stove configurations would be interesting.

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