

On the proper integration of wood stoves in passive houses: investigation using detailed dynamic simulations

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Abstract

Wood stoves are attractive for the space-heating (SH) of passive houses. Nevertheless, there are still questions about their integration. Firstly, the power oversizing of the current stoves and their long operating time may lead to unacceptable overheating. Secondly, it is also unclear how one stove can ensure the thermal comfort in the entire building. The paper investigates these aspects using detailed dynamic simulations (TRNSYS) applied to a detached house in Belgium. An 8 kW stove is assumed to be representative of the lowest available powers in the market. Results confirm that a large power modulation is important to prevent overheating. Opening the internal doors, a high building thermal mass and a heat emission dominated by radiation also reduce the overheating risk, but to a smaller extent. Besides, a single stove cannot enforce the thermal comfort during design weather conditions:

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a peak-load system is then needed. Using more standard conditions, a Typical Meteorological Year (TMY), the stove can mainly perform the SH but it then requires the internal doors inside the building to be opened. The temperature distribution between rooms is in fact dominated by the architectural properties. Finally, the emission and distribution efficiency of the stove is also investigated.

Keywords: Wood stove, Passive house, Renewable energy integration

Nomenclature

C_d Discharge coefficient of a large opening [-]

P_c Combustion power of the stove [W]

P_d Net power delivered to the stove envelope [W]

P_e Total power emitted by the stove to a thermal zone [W]

$P_{c,min}$ Minimal combustion power of the stove [W]

$P_{c,n}$ Nominal combustion power of the stove [W]

P_e^c Convective power emitted by the stove [W]

P_e^r Radiative power emitted by the stove [W]

τ_{min} Minimal imposed cycle length [min]

t_c Power fraction emitted by the stove in form of convection [-]

T_e Stove surface temperature [°C]

T_s Sensible air temperature [°C]

$T_{op,5\%}$ 5% percentile T_{op} during the heating season [°C]

$T_{op,95\%}$ 95% percentile T_{op} during the heating season [°C]

$T_{op,max}$ Maximal T_{op} during the heating season [°C]

$T_{op,min}$ Minimal T_{op} during the heating season [°C]

T_{op} Operative temperature [°C]

T_{set} Set-point air temperature for the space-heating [°C]

TMY Typical Meteorological Year

1. Introduction

Wood stoves are an attractive solution for the space-heating (SH) of passive houses as they can combine good *environmental* and *economic* performance.

Using well-insulated envelopes, the energy needs are relatively low so that energy-consumption costs during operation are thus low. In terms of payback time, savings on these energy costs counterbalance more slowly the extra-investment that must often be accepted to afford a more energy-efficient heating system. Particularly for a passive house, it can be shown that selecting a heating system with a low investment cost is a necessary condition to reach cost effectiveness [1]. This low investment is possible using a wood stove. Furthermore, the minimization of the investment in the SH system underlies also the definition of the passive house [2].

In terms of environmental performance, wood stoves use biomass so that they have the potential to be environmental friendly : they can emit relatively small amounts of greenhouse gases (GHG). Furthermore, the state-of-the-art wood stoves present rather high energy efficiency (e.g. 85%). This is also an important factor to limit the amount of wood to be extracted from forests. Nevertheless, best techniques to limit emissions of small particles should be implemented to prevent the pollution of the outside air (e.g. using filters).

Finally, in terms of safety and indoor air quality (IAQ), the last decade has seen the emergence of airtight stoves equipped with an independent supply for the combustion air and the flue gas removal. This improvement makes possible the integration of wood stoves in airtight envelope equipped with a balanced mechanical ventilation.

1.1. Research context and questions

As explained, the SH of a passive house using a wood stove can be an attractive solution. Nevertheless, this conclusion is only correct if a set of conditions are fulfilled. These conditions are mainly linked to the correct *integration* of wood stoves in super-insulated envelopes.

Firstly, to maintain cost effectiveness, a single wood stove should cover the main part of the SH needs during the heating season : the wood stove should be the main SH system. In other words, the stove should not only be installed for visual or thermal coziness. In fact, a peak-load SH system can be added but it should not increase the investment significantly. For example, this can be done easily using inexpensive electric heaters. This first condition is rather severe from a thermal comfort point of view : a single heat emitter (i.e. the wood stove) should be able to enforce the thermal comfort

in the entire passive envelope. As a consequence, rooms that are far from the stove could experience unacceptable low temperatures during the winter. The first question (Q1) of the paper is then to investigate how a single heat source located in one thermal zone is able to mainly perform the SH in a passive house.

Secondly, many heating systems face the well-known problem of the *power oversizing* when implemented in a passive house. By definition of the passive house, the nominal power of losses should be limited to 10 W/m^2 in order to enable air heating [2]. For a single-family house, it typically leads to a total power of roughly 2 kW. Many SH technologies cannot reduce the nominal power ($P_{c,n}$) down to ~ 2 kW. For instance, the minimal $P_{c,n}$ for wood stoves often encountered in the market is 6-8 kW (see e.g. [3]). The oversizing of the heating system compared to the buildings needs is then large even considering stove *power modulations* of 30-50% of $P_{c,n}$: the heat losses of ~ 2 kW are only found in the coldest days so that a power lower than 1 kW is most likely to appear during everyday operation. In practice, the reality is even more severe. Wood stoves, as many other heating systems, need to operate with long production cycles in order to reach their best performance, in terms of energy efficiency as well as emissions of pollutants. In the measurements of Persson et al. [4], a start-up time of 0.6 h is reported before the tested pellet stoves deliver their $P_{c,n}$. The wood-log combustion should rather be considered as a batch process where each batch has a length of ~ 45 min or more. The second question (Q2) of the paper is to investigate how an oversized wood stove can operate with long production cycles in a passive house without generating overheating.

Of course, different technologies based on a wood stove can be implemented in a passive house. In particular, *hydro-stoves* are equipped with a heat exchanger to produce hot water. The main part of the combustion heat is recovered by this exchanger while the remaining is directly emitted into the room (e.g. with a proportion of 80 to 20%, respectively). It has a triple advantage. Firstly, the power released into the room is significantly decreased so that it prevents overheating. Secondly, the generated hot water can be stored in a storage tank and this energy can subsequently feed a hydronic SH system (e.g. equipped with radiators). This last strategy is more secure to guarantee an acceptable thermal comfort in all the thermal zones. Finally, the hydro-stove can contribute to the production of domestic hot water (DHW). As a conclusion, the hydro-stove is already an answer to the problems raised by questions Q1 and Q2. As the article still discusses these two questions, it does not mean that the hydro-stove technology is discarded here. In fact, the paper only investigates the limits of the integration of a wood stove in a passive envelope, addressing the questions of the overheating and the SH distribution using a single heat source.

In terms of energy efficiency, the potential overheatings tend to increase the energy consumption. On the contrary, the simplification into one heat emitter for the entire envelope tends to reduce the energy consumption as the thermal comfort is not enforced strictly in each room : the temperature in thermal zones without a heat emitter will naturally have a lower temperature. In the remainder of this article, this phenomenon will be termed *temperature zoning*. As a consequence, it is worth investigating the resulting energy efficiency of a wood stove for the SH distribution. This is the last question of

the paper (Q3). The efficiency of the generation sub-system (e.g. the energy conversion within the stove) is not addressed.

1.2. Outcome of the paper and other existing contributions

The present article investigates the wood stove integration using detailed dynamic simulations. Simulations are performed on a typical detached house geometry that is representative of the Belgian context. The relative influence of the stove and the building architectonic properties on the thermal comfort and the energy efficiency is determined using parametric studies.

1.2.1. Stove properties

The stove properties have obviously a large influence on the thermal comfort. The overheating problem is directly linked to the stove nominal combustion power ($P_{c,n}$), to the stove thermal mass (that can store the heat delivered by the combustion before this energy is progressively released to the building zone), and to the power modulation capacity of the stove (that reflects the ability of a stove to adapt its combustion power as a function of the building needs). The influence of the stove control has been clearly shown in the simulations of Persson et al. [5] using pellet stoves. It was proved that the power modulation is an important parameter to reduce the number of start/stop phases and, therefore, the emissions of pollutants. Nevertheless, this work was not performed in the specific context of passive houses where the risk of overheating, or short cycles, is higher.

1.2.2. Building properties

The building properties can have a double impact. Firstly, the thermal mass of the building can reduce the overheating : with a higher thermal

mass, the walls temperature will rise more slowly for a given radiant heat flux emitted by the stove. Secondly, in light structures (as wooden structures), partition walls inside the building are also filled with thermal insulation. This is usually done to guarantee acoustic insulation between rooms. For convenience, this thermal insulation located in partition walls will here be termed *internal insulation*. The level of internal insulation can be very different between heavy concrete and light wooden structures. This insulation will prevent the heat from diffusing freely from the zone where the stove is placed to the neighboring rooms. This effect was clearly demonstrated by Pfluger in his contribution to the Passive House Institute (PHI) report [6]. In order to reduce the temperature zoning, the influence of opening the internal doors of the building can also be investigated. This was also done by Feist et al. [2] as well as in the PHI report [6]. The natural convection between rooms was shown to be very efficient to diffuse heat within the envelope.

1.2.3. Originality and existing contributions

In the field of the stove integration in passive houses, an important contribution is the work of Pfluger reported in [6]. This work has similarities with the present contribution in terms of methodology, objectives and conclusions. Both resort to detailed dynamic simulations to investigate how the stove and building properties influence the overheating and the heat distribution. Furthermore, both contributions aim at giving guidelines for the proper integration of wood stoves in passive houses.

From a larger point of view, field measurements of Carvalho et al. [7] and Jensen et al. [8] showed the need to develop a better knowledge about the stove integration in well-insulated buildings (e.g. about the overheating

risk).

Let us also mention that preliminary developments for the present study have already been communicated at scientific conferences [9, 10].

2. Methodology

2.1. Building model

The general simulation procedure is first explained, while the specific building typology used for the present results is introduced afterwards.

2.1.1. Building modeling procedure

The building is modeled using the multi-zone building model of TRNSYS (i.e. Type 56 [11]). In order to investigate the influence of the heat diffusion in the envelope through natural convection, the airflow rates between rooms are computed using a ventilation network model. This is done using the TRNFLOW [12] module based on the COMIS library. The opening of the internal doors could be a very efficient way to homogenize heat within the entire envelope. Doors are modeled using a *large opening* approximation (see e.g. Etheridge et al. [13]). A discharge coefficient (C_d) then needs to be introduced in order to tune the model to a specific flow physics (i.e. here cross-flows through internal doors). This coefficient is known to be case dependant. Following the review performed by Heiselberg [14] based on published experimental results, a range of C_d from 0.4 to 0.8 is considered in the paper (a standard value of 0.65 is used by default if the C_d is not explicitly specified). The building has a balanced whole-house mechanical ventilation equipped with a heat recovery unit. Its thermal efficiency is here

assumed to be 85%. The constant-air-volume (CAV) ventilation operates a cascade-flow : the fresh air is injected in the living room and bedrooms and is extracted in *wet rooms* (e.g. bathroom, laundry, toilets). Standard hygienic flow rates [15] are imposed. For the sake of clarity, the heat exchanger bypass is not activated during the heating season if an overheating takes place within the building envelope. Furthermore, no pre-heating of the fresh air after the heat recovery unit is considered. Solar protections are activated during the heating period but only for high solar radiation levels. Synthetic time-varying internal gains are applied to the building with a mean value of 2.1 W/m^2 in good accordance with the passive house standard (see e.g. [16]).

2.1.2. The benchmark passive house

A fixed detached single-family house geometry is used for all the simulation results presented here. It is a typical Belgian two-storey's building that was developed in the investigation of Massart et al. [17]. Belgium has been selected because its climate is quite comparable to countries where the passive standard have been first established (i.e. Germany, Switzerland and Austria). The benchmark house has a net heated surface of 152 m^2 . The envelope presents a protected volume of 420 m^3 , 360 m^2 of opaque surfaces and 35 m^2 of windows. The house and its internal organization are shown in Figure 1 : the building is divided into 10 thermal zones. The living room where the wood stove is placed faces the south. This can be seen as the most severe situation in terms of thermal comfort (i.e. risk of overheating).

While the building geometry is kept unchanged between simulations, five distinct construction modes corresponding to five levels of thermal inertia are considered : from *very-heavy* to *very-light* inertia. A summary of the main

building properties is given in Table 1. The insulation level of the envelope is strictly equivalent for the five cases. It has been established in order to comply with the passive house standard. In the present work, a set-point temperature (T_{set}) of 20°C is considered for the SH system. The net SH needs evaluated using the PHPP evaluation package [16] and the climate of Uccle (i.e. city near Brussels) is estimated to be 15 kWh/m².year, while the total heat losses are 2.4 kW in design weather conditions (i.e. -10°C). Nonetheless, the construction modes have a strong influence on the internal insulation. An important point to notice is that a lower thermal mass leads to a higher internal insulation. This will have a significant impact on results.

2.2. Stove model

The objective of the article is not to report in details about the stove model. Extended explanations can be found in [18]. Nevertheless, the major model features needed for a good physical understanding of the results are introduced. The general modeling procedure is first explained while the elements specific to pellets and logs are developed afterwards.

The overall procedure is shown in Figure 2. In the room where the stove is placed, the sensible air temperature (T_s) is first computed by the building model and then sent to the stove control. If activated, this control can adapt the stove combustion power, P_c . The fraction of P_c delivered to the stove envelope, termed P_d , is computed using the stove generation efficiency. This envelope has a given composition : it may contain several layers presenting different thermal conductivities and heat capacities. In practice, part of the combustion power can be directly transferred from the combustion chamber to the room through a window. Unless stated otherwise, this last effect is

not taken into account in the present study. A specific module of the stove model computes the heat transfer inside its envelope as a function of time (see Figure 2). This is done here assuming one-dimensional heat transfer. The final result is the temperature of the external surface of the stove, T_e . Then, T_e and T_s are used to compute the power emitted by the stove through convection (P_e^c) and radiation (P_e^r) : P_e^c is evaluated using correlations for isothermal plates [19], P_e^r is evaluated analytically assuming that the stove is very small compared to the room dimensions [20]. Finally, these two powers are considered as gains that are applied to the building model : P_e^c is directly injected to the air node while P_e^r is distributed among the room walls as a function of the view factors. This overall procedure can be seen as a *loosely-coupled* approach where the stove geometry is not physically present in the building model but is rather considered as an internal gain injected into the building. For each time step, TRNSYS iterates several times on this overall loop until a global convergence is reached.

In order to give a SH system of reference, a brief definition of the *perfect heating* is given : the perfect heating can be considered as a pure convective heating that delivers instantaneously, or more precisely in one time step, the exact amount of energy to enforce the set-point temperature (T_{set}) within a room.

2.2.1. Pellet stove model

The dynamics of pellets combustion is faster than the stove and the building characteristic time scales so that the combustion process in pellet stoves can be assumed instantaneous [4]. The P_c is here modulated using a PID controller (i.e. Proportional + Integral + Derivative control). The limita-

tions of the pellet stove are introduced progressively into this PID controller, see Figure 3 :

- If the P_c can be modulated continuously from 0 to $P_{c,n}$, the PID controller is able to track the T_{set} and the stove operates continuously to counterbalance the envelope losses (see Scenario 1 in Figure 3).
- State-of-the-art pellet stoves can modulate up to $\sim 30\%$ of $P_{c,n}$. This limitation in terms of power modulation is mimicked by a saturation of the PID command to a lower limit. If the zone thermal losses are lower than the minimal combustion power ($P_{c,min}$), the stove starts to cycle between a start and a stop temperature, here taken as 20°C and 22°C respectively (see Scenario 2 in Figure 3). In this case, the length of the production cycle of the stove is determined *implicitly* by the gap between the start and stop temperatures, the building inertia and the level of its thermal losses.
- As the length of the production cycle is a main physical parameter of the present study, a constraint on the minimal cycle length is also introduced *explicitly* in the controller. The stove is only stopped if the stop temperature is reached *and* if the stove has operated at least during a given period, the imposed minimal cycle length, τ_{min} (see Scenario 3 in Figure 3). In this case, T_s sometimes exceeds the stop temperature of the stove control.

2.2.2. Log stove model

The combustion of logs needs to be treated as a batch process where the combustion of wood is decomposed in several phases [21]. State-of-the-art

log stoves can modulate up to 50% of $P_{c,n}$. It is here considered that this power modulation is not adapted as a function of the room needs, but rather as a choice of the user (e.g. by adjusting the air intakes of the combustion chamber) : the power modulation level is selected a priori and is not changed during operation. As small variations of T_s have a limited impact on P_c , the combustion model can be decoupled during simulation. Another software specific to wood logs is first applied [22]. Its combustion model based on experimental data enables to generate the time profile of P_c . Considering the log stove control in TRNSYS, one batch combustion starts each time T_s falls below 20°C (i.e. the start temperature).

2.2.3. Generic stove analysis

The stove models can also be analyzed at the limit of very small stove thermal masses. In other words, the thermal comfort can be investigated assuming that the damping effect of the stove mass is negligible compared to the building dynamics. Of course, it is a significant limitation but it gives the opportunity to simplify the problem to a large extent. As the stove mass is neglected, the power delivered by the combustion to the stove envelope (P_d) is assumed to be equal to the heat emitted to the room (P_e). The temperature of the stove envelope (T_e) should not be computed anymore if the ratio between convection and radiation, t_c , is taken as a free parameter of the analysis :

$$t_c = \frac{P_e^c}{P_e^c + P_e^r}. \quad (1)$$

In this context, a lot of physical parameters are not necessary anymore and are just hidden behind t_c : the stove dimensions, its envelope constitution and surface emissivity, the presence of radiation shields or the fraction of glazing

in the stove envelope. The main idea is to investigate the influence of t_c on the thermal comfort and to determine the value that should be promoted when developing or installing a new stove.

2.2.4. Thermal comfort assessment and overall model limitations

The present work rates the global thermal comfort assuming that the occupant is far enough from the stove for the radiation asymmetry to be neglected, and where the effect of the direct radiation from the combustion chamber is also negligible. The thermal comfort is evaluated by monitoring the operative temperature, T_{op} . Extended explanations motivating this choice can be found in [18]. The maximal acceptable T_{op} is here taken to be 24.5°C. Using the EN ISO 7730 [23], this is the limit for a PMV < 0.5 with a *clo* and a *met* of 1.0 (with a relative air speed < 0.1 m/s). By default, instantaneous values of T_{op} are reported in the article. Nevertheless, the 5% and 95% percentile of T_{op} during the heating season were also systematically analyzed (termed $T_{op,5\%}$ and $T_{op,95\%}$, respectively); they are only mentioned in the article when they provide meaningful complementary information.

3. Results in design weather conditions

The thermal comfort is first investigated in strict design conditions : a constant outdoor design temperature is applied (here -10°C) and no solar or internal gains are considered. The thermal comfort is analyzed when a perfect heating is only performed in the living room and when the temperature of other rooms is free-floating. In this way, it shows how the heat flows in the building in severe weather conditions. Basically, internal doors are closed and, at simulation time 0, all the internal doors are opened. Results are

shown in Figure 4 for different wall compositions and two different values of C_d .

When internal doors are closed ($t < 0h$), the coldest bedroom, zone 8 in Figure 1, presents a temperature that depends on the building construction mode, see Figure 4. At first sight, it may look strange as all the construction modes analyzed here use an envelope with the same insulation level (see Table 1). In fact, results are different because the internal insulation levels are different : the lighter the structure, the higher the internal thermal insulation. As expected, this internal insulation gives a strong temperature zoning. With closed internal doors, results also tell us that the heat is mainly transmitted from the living room to other zones by conduction through walls.

When internal doors are open ($t > 0h$), the temperature in the coldest bedroom first increases quickly and then follows a slower progression. In fact, the temperature difference between the living room and other rooms generates a strong natural convection inside the building. Firstly, the final steady-state temperature is ranging from 14.5° to 16°C following the C_d considered. A temperature magnitude that is well above the previous temperatures found with closed doors. Secondly, the final steady-state temperature is almost equivalent between the constructive modes considered. With open internal doors, it shows that the prevailing heat diffusion process in the building is the natural convection.

Even though the effect of the natural convection is strong, opening the internal doors is not enough to ensure the thermal comfort in design conditions. This conclusion is independent on the C_d considered for internal doors. As a consequence, an additional heat emission sub-system should be added

as a peak-load heating. For example, an electric heating coil can be placed in the main ventilation duct.

Nevertheless, these design outdoor conditions appear very seldom during a year. Furthermore, in a passive house, the performance of the envelope is such that the characteristic time constant of the building is relatively long (here between 74 and 243 h using EN 13790 [24]). It is then not sure that a cold wave will last long enough for the building temperature to reach such steady-state regimes. In addition, the coldest days are often related to a clear sky so that it is also very conservative to neglect solar gains in the analysis. This last effect is well explained in Feist et al. [2]. Finally, internal gains are also not negligible. As a consequence, Section 4 investigates the stove SH performance using more "standard" operating conditions.

4. Thermal comfort in TMY weather conditions

The SH is now investigated with internal and solar gains for a Typical Meteorological Year (TMY) (generated by the Meteonorm database). In order to simplify the analysis, the parameters of the stoves have been adapted in order to get a nominal P_d of 8 kW delivered by the combustion to the stove thermal mass. In this way, it leaves the question of the generation efficiency apart and evaluates solutions with a comparable amount of energy delivered to the room. In practice, the nominal power of the stove, $P_{c,n}$, is then slightly higher but is here left undetermined (e.g. 9.4 kW assuming a 85 % efficiency). The oversizing of the stove is thus ~ 3.5 compared to the nominal power of the envelope losses. Furthermore, 8 kW is well representative of the minimal power of existing stoves currently available on the market (see e.g. [3]). All-

year simulations are run with a time step of 3 min for closed doors and 1 min for open doors. A parametric study is performed where one simulation is done for each set of the following parameters : the building construction mode, the stove power modulation level, the imposed cycle length and the opening of the internal doors. Nevertheless, given the large set of data investigated, results are only reported in graphs for the combinations of parameters that gives significant difference in behaviour. For the combinations not reported, results can be assumed similar.

4.1. Generic pellet stove without inertia

The performance of two generic pellet stoves is compared. The first stove has no power modulation (i.e. on-off stove) while the second can modulate up to 30 % of $P_{c,n}$ (i.e. $P_{c,min} = P_{c,n}$ and $0.3 P_{c,n}$, respectively).

The minimal operative temperature ($T_{op,min}$) found during the heating season in the building is first analyzed in Figure 5. For comparison, the perfect heating applied in the living room using a set-point temperature of 21°C is shown on the ordinate axis : this temperature level is the mean value between the start and stop temperatures of the pellet stove (i.e. 20°C and 22°C, respectively). $T_{op,min}$ is almost independent of the stove properties and very close to the temperature found using the perfect heating : neither t_c , the cycle length or the power modulation affect $T_{op,min}$ significantly. In fact, $T_{op,min}$ is mainly influenced by the building architectonic properties.

For closed internal doors, the temperature zoning is strongly influenced by the construction mode. For the very-heavy building, $T_{op,min}$ is approximately 16°C, a temperature that could already be accepted by some users in a bedroom. On the contrary, light construction modes lead to unacceptable $T_{op,min}$

during the heating season. Although unacceptable, these temperature levels are well above the temperatures found in design weather conditions (cfr. Section 3). It clearly confirms that strict design conditions are particularly severe for the analysis of the SH in a passive house.

Opening the internal doors has a strong influence on $T_{op,min}$. Again, the diffusion of heat inside the building envelope is mainly dominated by natural convection. As a consequence, the influence of the construction mode on $T_{op,min}$ almost disappears : all the curves collapse around $\sim 18^\circ\text{C}$. By definition, the minimal temperature only appears one time during a heating season so that the 5% percentile of the operative temperature, $T_{op,5\%}$, can complement the analysis. In fact, T_{op} in the coldest bedroom falls below $\sim 19^\circ\text{C}$ only 5% of the time, a temperature that is very close to the T_{set} applied to the living room (i.e. $20^\circ\text{C}/22^\circ\text{C}$).

As a conclusion, during a TMY, the stove is able to enforce the thermal comfort in the entire envelope as long as internal doors can be opened. If needed, the T_{set} in the living room can be slightly increased to guarantee a better thermal comfort in bedrooms. Nevertheless, several reasons may lead an occupant to close the internal doors : an obvious motivation is intimacy. The thermal comfort analysis as a function of the door opening frequency is not performed in the present work.

The maximal operative temperature found in the living room during the heating season, $T_{op,max}$, is reported in Figures 6 and 7. In comparison, the perfect heating applied to the living room using a T_{set} of 20°C is also reported on the ordinate axis. Using the perfect heating, it is worth noticing that solar and internal gains already produce overheating. As expected, the lower the

building thermal mass, the higher the overheating. Using the perfect heating, $T_{op,max}$ is mainly influenced by the building properties and the solar shading strategy. As far as the generic pellet stove is concerned, results using a pure convective source converge to the perfect heating performance at the limit of very short production cycles.

For long production cycles, the 30% power modulation turns out to be the most efficient way to reduce the overheating. In fact, except for the case with a pure convective source ($t_c = 1$) and closed doors, $T_{op,max}$ is always acceptable even with production cycles of 90 min. For instance, if the source is mainly radiative ($t_c = 0$), $T_{op,max}$ is almost independent of the cycle length and slightly higher than values found using the perfect heating. On the contrary, the stove without modulation essentially leads to unacceptable overheating. Starting from the less favorable case reported in Figure 6(a), one clearly notices that a heavy thermal mass, an emission dominated by radiation and the opening of internal doors have a benefic influence on the thermal comfort. Nevertheless, if applied separately, none of these three actions is able to limit the overheating sufficiently. Only the combined action of the three parameters is able to maintain $T_{op,max}$ lower than 24.5°C for an on-off stove with long production cycles, see Figure 7(b).

In order to get a better insight into the proper influence of the power oversizing, the overheating using a 2 kW stove was also investigated. The stove power is then comparable to the nominal power of the envelope losses. Results, not reported here, demonstrate that the thermal comfort is significantly better than using a 8 kW stove. In most situations, the overheating is totally under control even for cycles of 90 min. The only exception is a

on-off stove using convection ($t_c = 1$) in combination with a light building construction and closed internal doors.

4.2. Generic log stove without inertia

The performance of two generic log stoves is compared. The first stove has no power modulation while the second can modulate up to 50 % of $P_{c,n}$ (i.e. $P_{c,min} = P_{c,n}$ and $0.5 P_{c,n}$, respectively). Two different batch loads are considered : one with a batch that delivers 10 kWh to the stove envelope and the second delivers 20 kWh. As a consequence, the stove without power modulation will operate at a mean power of 8 kW during 1.25 h for the first batch and 2.5 h for the second batch; the stove with 50 % power modulation will operate at a mean power of 4 kW during 2.5 h and 5 h, respectively (see P_d in Figure 8).

As for the pellet stove, the minimal operative temperature ($T_{op,min}$) during the heating season is found to be independent of the stove properties and very close to the perfect heating. Results are thus not reported in the article as they do not provide any meaningful additional information.

Compared to pellets, the combustion cycle lengths of logs are significantly longer so that the overheating risk is more severe. Results, reported in Table 2, show that the trends are equivalent to the pellets generic stove but with more pronounced overheatings. Without power modulation, no strategy is able to maintain $T_{op,max}$ below 24.5°C. In this case, best performance is obtained with a pure radiative source, a very-heavy building and open doors. Then, $T_{op,max}$ can only be limited to 26°C. The power modulation is less efficient than using the pellet generic stove : the modulation is here limited to 50% while some current pellet stoves can downsize their power to

30% of $P_{c,n}$. The integration is still possible but the power modulation in itself is not sufficient anymore to prevent the overheating in the living room. One should complement it with at least two of the three following strategies in order to limit $T_{op,max}$ to 24.5°C : a radiative heat source, the opening of the internal door and a heavy building thermal mass.

4.3. Typical stove with inertia : 50 and 150 kJ/K

The influence of the stove thermal mass is now investigated so that a specific stove design should then be considered. The geometry is inspired from typical existing products developed for passive or low-energy houses. It is modeled by a box of 0.6 m x 0.6 m x 1.2 m where the combustion power and wall composition is uniformly distributed. Following the manufacturer data [3, 25] and pellet stoves parameters communicated in Persson et al. [4], two levels of thermal mass are considered. The first level of 50 kJ/K is representative of a pellet stove without particular energy storage, while the second level of 150 kJ/K is representative of a stove with a specific thermal storage (e.g. 100 kg of natural stone). These stove envelopes are not equipped with radiation shields or designed to improve convection. The heat is thus assumed to be only emitted by the external surface of the stove. This surface temperature will typically rise up to $\sim 200^\circ\text{C}$ during operation so that the convective part is rather constant and ranges between 0.35 and 0.45 (i.e. t_c in $[0.35; 0.45]$). The radiative part is thus dominant but a non-negligible convective contribution is present.

Results for pellets, shown in Figure 9, only consider closed internal doors but the conclusions are also valid for open doors. The reference case without thermal mass is shown in Figure 9(a) where a constant t_c of 0.35 is imposed.

Compared to the reference case, the effect of the stove thermal mass is then explicit, see Figures 9(b) and 9(c). The thermal mass is able to store the energy of short cycles so that the $T_{op,max}$ is significantly decreased. With increasing cycles lengths, the stove thermal mass is progressively saturated and $T_{op,max}$ converges gradually to the values obtained without thermal mass. The stove with 30 % modulation was already performing well in the case without thermal mass so that it is more interesting to check whether the stove thermal mass makes the integration of the on-off stove easier. As long as cycles longer than 60 min are concerned, the 50 kJ/K thermal mass should not be expected to reduce the overheating and the conclusion developed for the generic stove without thermal mass still apply. For the 150 kJ/K, $T_{op,max}$ is reduced by a few degrees and may be a part of the solution to operate an on-off stove without generating unacceptable overheating. In general, the presence of the 150 kJ/K thermal mass is not sufficient to guarantee the thermal comfort using an on-off pellet stove.

Results for logs are not reproduced here. Nevertheless, as the production cycles are longer for logs than for pellets, these results demonstrate that the effect of a thermal mass up to ~ 150 kJ/K is almost negligible on $T_{op,max}$.

Finally, this analysis also proves that the investigations using a generic stove without mass are representative.

4.4. Sensitivity analysis : C_d and heating intermittence

Firstly, previous results were obtained using the default C_d value of 0.65. In theory, the overheating and the diffusion of heat in the building are both affected by C_d . Nevertheless, a sensitivity analysis showed that $T_{op,max}$ and $T_{op,min}$ can only vary up to $\sim 1^\circ\text{C}$ for C_d ranging from 0.4 to 0.8. Secondly,

it was systematically assumed that a constant heating was applied. A daily SH intermittence was also tested. It did not show significant difference in $T_{op,min}$. This is mainly due to the long characteristic time constant of passive envelopes [24].

5. Energy efficiency in TMY weather conditions

The SH energy needs are now investigated. The reference case is here taken as the uniform perfect heating applied to *all the building zones*. In fact, simulations showed that the 50 and 150 kJ/K stove thermal masses do not modify the SH needs significantly compared to the generic stove. They also showed that the SH needs are almost independent of the convection/radiation ratio, t_c , for long production cycles. As a consequence, only results for the generic stove using convection are reported. For the sake of the clarity, the pellet stove is first analyzed, see Figures 10.

For closed doors, the thermal comfort analysis has shown that a strong temperature zoning takes place. As a consequence, the SH needs are lower than using the uniform perfect heating and the difference increases with higher internal insulation. The reduction in consumption can be important but at the cost of a lower thermal comfort outside the living room. Like for the minimal temperature in the building, $T_{op,min}$, the stove imperfections do not alter drastically the energy efficiency. Nevertheless, the SH needs increase slowly with the cycle length. In fact, long production cycles can lead to a large overheating in the living-room that directly increases the envelope thermal losses. As a consequence, the higher the overheating, the higher the increase of the SH needs with the cycle length.

For open doors, the analysis of the thermal comfort has shown that the natural convection produces an efficient temperature homogenization in the passive house : the difference in temperature between thermal zones is limited. Indeed, for short production cycles where there is no significant overheating in the living room, the SH needs using a pellet stove is very close to the perfect heating, as shown in Figure 10(b). Like for closed door, the stove imperfection does not alter drastically the SH needs. They also increases progressively with the cycle length as previously explained for closed doors.

The analysis of the thermal comfort using a log stove illustrated that it has a rather similar behavior as using the pellet stove, but where the overheating is amplified by the use of longer production cycles. This trend can also be observed for the energy efficiency, see Table 3. For closed doors, the length of the cycles increases the SH needs in a way that the benefit of the thermal zoning can sometimes be lost (e.g. for the heavy building construction modes). This is more severe with open doors, where the SH needs using a stove can be up to 25 % higher than the uniform perfect heating (e.g. with a delivered energy of 20 kWh by cycle).

6. Discussion and conclusions

Wood stoves are an attractive solution to perform the space-heating (SH) of passive houses. Nevertheless, important issues regarding the integration of wood stoves in passive houses are still open. The article investigates this integration using detailed dynamic simulations on a benchmark detached house typology and using the Belgian context.

The first question (Q1) was to investigate whether a single heat source

located in one thermal zone is able to mainly perform the SH in a passive house. On the one hand, simulation results showed that it is not possible in steady-state design weather conditions. In these extreme conditions (or during a cold wave), the wood stove should be complemented by a peak-load heat emitter in order to maintain an acceptable thermal comfort in the entire building. On the other hand, more standard operating conditions were considered. It was done using a Typical Meteorological Year (TMY) and by integrating the internal gains in the building model. During a TMY, the stove is able to enforce the thermal comfort in the entire envelope if the internal doors can be opened. Depending on the discharge coefficient of doors (C_d) and the level of internal insulation, the minimal temperature during the heating period was found to range between 16°C and 18.5°C. The thermal comfort is most of the time acceptable and can even be improved if the set-point temperature can be temporarily increased in the living room. In practice, the internal doors cannot always be opened. Nevertheless, the influence of the opening frequency was not investigated. Finally, all the simulations showed that the temperature homogenization in the building envelope strongly depends on the architectonic properties.

The second question (Q2) was to investigate whether an oversized wood stove can operate on long production cycles in a passive house without generating overheating. A typical stove power of 8 kW was taken. It corresponds to a oversizing of ~ 3.5 compared to the nominal power of the building losses. For the benchmark passive house and a TMY, simulations showed that results strongly depend on the stove properties. Architectonic properties, as the building thermal mass and the doors opening, can improve the thermal

comfort but to a lower extent. For the pellet stoves, a 30% power modulation proved to be a very efficient way to prevent the overheating. In many cases, it is a sufficient condition to guarantee the thermal comfort in the living room. If a pellet stove is not able to perform a large power modulation, its integration is still possible if a set of measures is taken : a heat that is mainly emitted by radiation, a large building thermal mass and the opening of internal doors. Log stoves are characterized by longer cycle length than pellet stoves. In this case, a 50% power modulation is a necessary condition for the integration but it is not a sufficient condition anymore. In fact, this technology should be complemented with a set of measures to prevent large overheating (the same as for the on-off pellet stove). For both pellet and log stoves, their thermal inertia can reduce the overheating. Simulation showed that only thermal inertia higher than ~ 150 kJ/K could contribute significantly to the overheating reduction. It corresponds to stoves that have specific heat storage elements in their envelope. As results still depend on the building geometry, the present study at least suggests the need to reduce the minimal nominal power of stoves ($P_{c,n} < 8$ kW), to promote their power modulation ($P_{c,min} < 0.5P_{c,n}$) and large heat storage capacities in their envelope ($\gtrsim 150$ kJ/K). Another alternative is to promote *hydro-stoves*.

The last question (Q3) was to investigate the heat emission efficiency of wood stoves. From the simulation results using a TMY, two factors mainly determine this efficiency : the temperature zoning in the building and the overheating in the living room. The dominating parameter is the temperature zoning which can lead to a significant reduction of the energy needs compared to an uniform temperature applied in the whole building : this

is done at the expense of a lower thermal comfort. On the contrary, the overheating increases the needs. In fact, the emission efficiency deteriorates progressively with increasing cycle lengths. In general, the overheating induced by the stove limitations does not increase the energy needs drastically : the maximal energy increase induced by the cycle length was here found to be 2 kWh/m².year.

Although simple, the low-resolution modeling approach used in this work is able to give an insight into the whole-year thermal comfort. It should be accurate enough to detect unacceptable strategies for the stove integration [18]. Furthermore, it enables to investigate the proper influence of the large set of physical parameters involved in the problem, and this, at a reasonable computational cost. Nevertheless, limitations of the present study are essentially linked to this modeling approach. The objective of the article was also to detect the interesting or critical configurations. These selected cases can be further assessed using more advanced simulation techniques (e.g. local thermal comfort using CFD and a bio-heat model) or by the way of measurements.

7. Acknowledgements

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- [1] L. Georges, C. Massart, G. V. Moeseke, A. De Herde, Environmental and economic performance of heating systems for energy-efficient dwellings : case of passive and low-energy single-family houses, *Energy Policy* (40) (2012) 452–464.
- [2] W. Feist, J. Schnieders, V. Dorer, A. Haas, Re-inventing air heating : convenient and comfortable within the frame of the Passive House concept, *Energy and Buildings* (37) (2005) 1186–1203.
- [3] Ø. Skreiberg, M. Seljeskog, E. Karlsvik, Environmental and energetic performance history and further improvement potential for wood stoves, in: *Proceedings of the 20th European Biomass Conference and Exhibition*, Milan, 2012, pp. 1305–1310.
- [4] T. Perrson, F. Fiedler, S. Nordlander, C. Bales, J. Paavilainen, Validation of a dynamic model for wood pellet boilers and stoves, *Applied Energy* (86) (2009) 645–656.
- [5] T. Perrson, S. Nordlander, M. Rönnelid, Electrical savings by use of wood pellet stoves and solar heating systems in electrically heated single-family houses, *Energy and Buildings* (37) (2005) 920–929.
- [6] W. Feist, W. Hasper, H. Krause, J. Nitsch, R. Pfluger, R.-P. Strauß, Protokolland nr. 36 : heizung mit biobrennstoffen für passivhäuser, Tech. rep., Passiv Haus Institut, Darmstadt (December 2007).
- [7] R. Carvalho, O. Jensen, L. Tarelho, A. Afshari, N. Bergsøe, J. Andersen, Energy performance of Portuguese and Danish wood-burning stoves, in:

- Proceedings of the World Renewable Energy Congress 2011, Sweden, 2011.
- [8] O. Jensen, A. Afshari, N. Bergsøe, R. Carvalho, Field study of energy performance of wood-burning stoves, in: Proceedings of the World Renewable Energy Congress 2011, Sweden, 2011.
- [9] L. Georges, C. Massart, Investigation of the space-heating strategies in very low-energy houses using dynamic simulations : case of decentralized wood stoves approaches, in: Proceedings of the 27th Plea conference, Louvain-la-Neuve, 2011, pp. 609–614.
- [10] L. Georges, C. Massart, A. De Herde, V. Novakovic, Investigation of the space-heating using wood stoves in very low-energy houses, in: Proceedings of the CISBAT conference, Lausanne, 2011, pp. 745–750.
- [11] TRNSYS a transient system simulation program, volumes 1 to 8 (2011).
- [12] TRNFLOW a module of an air flow network for coupled simulation with TYPE 56 (multi-zone building of TRNSYS), version 1.4. (2009).
- [13] D. Etheridge, M. Sandberg, Building ventilation : theory and measurements, 1996.
- [14] P. Heiselberg, Modelling of natural and hybrid ventilation, Tech. rep., Aalborg University, lecture notes no. 004 (2006).
- [15] Bureau de normalisation NBN, Norme belge NBN D50-001 : dispositifs de ventilation dans les bâtiments d’habitation (1991).

- [16] W. Feist, R. Pfluger, B. Kaufmann, J. Schnieders, O. Kah, Passive House Planning Package 2007, Passiv Haus Institut, Darmstadt (June 2007).
- [17] C. Massart, A. De Herde, Conception de maisons neuves durables, Louvain-la-Neuve, 2011.
- [18] L. Georges, V. Novakovic, On the integration of wood stoves for the space-heating of passive houses : assessment using dynamic simulation, in: Proceedings of the first BSO conference, Loughborough, 2012, pp. 745–750.
- [19] S. Churchill, H. Chu, Correlating equations for laminar and turbulent free convection from a vertical plate, International Journal of Heat and Mass Transfer (18) (1975) 1323–1329.
- [20] F. Incropera, D. Dewitt, T. Bergman, A. Lavine, Fundamental of Heat and Mass Transfer, sixth Edition, John Wiley and Sons, 2007, p. 833.
- [21] J. Saastamoinen, P. Tuomaala, T. Paloposki, K. Klobut, Simplified dynamic model for heat input and output of heat storing stoves, Applied Thermal Engineering (25) (2005) 2878–2890.
- [22] Ø. Skreiberg, Post-doc report, part 3, *Fuelsim-Transient* : a mass, volume and energy balance spreadsheet for batch combustion applications, Tech. Rep. Rapport ITEV 2002:03, NTNU, Trondheim (2002).
- [23] European Committee for Standardization, European standard EN ISO 7730 : ergonomics of the thermal environment (analytical determination and interpretation of thermal comfort using calculation of PMV and PPD indices and local comfort criteria) (2005).

- [24] European Committee for Standardization, European standard EN ISO 13790 : energy performance of buildings, calculation fo energy use for space-heating and cooling (2008).
- [25] RIKA, Stove manufacturer website (June 2012).
URL <http://www.rika.at/en/B2C/>

Figure 1 : Sketches of the ground and first floors : kitchen coupled to the living-room (zone 1), corridor with an open staircase (zone 2), laundry (zone 3), office (zone 4), four bedrooms (zones 5 to 8) and a bathroom (zones 9-10). The south direction is pointing upwards.

Figure 2 : Block diagram illustrating the coupling of the stove SH model with one thermal zone : stove and building models are colored in orange and grey, respectively.

Figure 3 : Illustration of the pellet stove control : the limitations of power modulation (Scenario 2) and enforced minimal cycle length (Scenario 3) are compared to the case without these limitations (Scenario 1).

Figure 4 : Effect of the door opening at $t = 0\text{h}$ on T_{op} in the coldest bedroom during design outdoor conditions (i.e. -10°C) : results are shown for three construction modes and two values of discharge coefficient C_d (0.4 and 0.8).

Figure 5 : $T_{op,min}$ as a function of τ_{min} for the 8 kW generic pellet stove : the stove with a 30% power modulation is in solid line while the on-off stove is in dash-dotted lines. The perfect heating which is only applied to the living room with T_{set} of 21°C is superimposed on the ordinate axis.

Figure 6 : $T_{op,max}$ as a function of τ_{min} for the 8 kW generic pellet stove and closed internal doors : the stove with a 30% power modulation is in solid line while the on-off stove is in dash-dotted lines. The perfect heating which is only applied to the living room with T_{set} of 20°C is superimposed to the ordinate axis.

Figure 7 : $T_{op,max}$ as a function of τ_{min} for the 8 kW generic pellet stove and open internal doors : the stove with a 30% power modulation is in solid line while the on-off stove is in dash-dotted lines. The perfect heating which is only applied to the living room with T_{set} of 20°C is superimposed to the ordinate axis.

Figure 8 : Combustion power, P_c , as a function of time for the 8 kW log stove [22] : the stove operated at 50 % of $P_{c,n}$ is shown in solid line while dash-dotted lines are representative of a on-off stove; the batches of 10 and 20 kWh are colored in black and grey, respectively.

Figure 9 : $T_{op,max}$ as a function of τ_{min} for a typical 8 kW pellet stove : the stove with a 30% power modulation is in solid line while the on-off stove is in dash-dotted lines. The perfect heating which is only applied to the living room with T_{set} of 20°C is superimposed on the ordinate axis.

Figure 10 : SH needs as a function of τ_{min} for the 8 kW generic pellet stove : the stove with a 30% power modulation is in solid line while the

on-off stove is in dash-dotted lines. The uniform perfect heating which is here applied all the building zones with T_{set} of 20°C is superimposed on the ordinate axis.

Table 1: Construction modes of the benchmark detached passive house [17] : overall building thermal inertia (using EN 13790 [24]), constitution of walls and their thermal transmittance.

Construction mode	Thermal inertia (MJ/K)	Envelope thermal insulation (W/m ² .K)				Internal thermal insulation (W/m ² .K)		
		External wall	Ground slab	Roof	Glazing/Window	Floor/ceiling	Partition wall	Bearing wall
Masonry	Very-heavy (79)	CS+EPS (0.11)	C+EPS(d) (0.15)	WS+WF (0.11)	TGW (0.8)	C (1.6)	CS (3.0)	CS (2.6)
heavy	Heavy (42)	WS+GW (0.11)	C+EPS(d) (0.15)	WS+GW (0.11)	TGW (0.8)	C (1.6)	WS+MW (0.36)	CS (2.6)
Mixed wood-masonry	Medium (37)	WS+WF (0.11)	C+EPS(u) (0.15)	WS+WF (0.11)	TGW (0.8)	WS+WF (0.23)	WS+MW (0.36)	CS (2.6)
Wooden	Light (24)	CC+EPS (0.11)	C+EPS(u) (0.15)	WS+GW (0.11)	TGW (0.8)	WS+GW (0.21)	WS+GW (0.36)	CC (2.0)
Masonry	Very-light (19)	WS+GW (0.11)	C+EPS(u) (0.15)	WS+GW (0.11)	TGW (0.8)	WS+GW (0.21)	WS+GW (0.36)	WS+GW (0.25)
Wooden								

CS stands for calcium-silicate blocks, CC for cellular-concrete blocks, C for concrete, WS for wooden structure, TGW for triple-glazing window, GW for glass wool, WF for wood fiber, MW for mineral wool, EPS(d) and EPS(u) correspond to the EPS placed down and up of the concrete slab, respectively.

Table 2: $T_{op,max}$ for the 8 kW generic log stove [°C] with values $\geq 24.5^\circ\text{C}$ in bold.

Doors	Closed						Open									
	100% $P_{c,n}$		10 kWh		20 kWh		50% $P_{c,n}$		10 kWh		20 kWh		50% $P_{c,n}$			
$P_{c,min}$	20 kWh	2.5 h	1.25 h	1.25 h	5 h	5 h	10 kWh	2.5 h	2.5 h	1.25 h	1.25 h	20 kWh	5 h	5 h	10 kWh	2.5 h
Cycle length	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0
t_c	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0
Very-heavy	35.4	26.8	33.6	26.3	29.5	24.9	28.8	23.9	29.6	25.6	28.5	25.7	26.1	24.3	25.7	23.2
Heavy	37.0	28.8	35.0	28.0	30.5	26.4	29.6	26.2	30.6	27.0	29.5	27.1	26.7	24.8	26.2	24.4
Medium	39.4	31.2	36.8	28.9	32.7	27.9	30.8	25.9	31.6	28.7	30.1	28.8	27.9	26.4	27.0	24.8
Light	41.0	32.3	37.5	30.0	33.5	30.1	31.4	26.7	32.1	29.6	30.3	29.2	28.7	26.9	26.9	25.5
Very-light	45.4	37.4	40.9	33.6	38.3	32.7	33.7	29.0	34.2	32.1	31.8	30.6	29.0	29.2	27.7	27.4

Table 3: SH needs in [kWh/m².year] for the 8 kW generic log stove using $t_c = 1$ (i.e. pure convective).

Doors	Closed				Open			
$P_{c,min}$	100% $P_{c,n}$		50% $P_{c,n}$		100% $P_{c,n}$		50% $P_{c,n}$	
Load	20 kWh	10 kWh	20 kWh	10 kWh	20 kWh	10 kWh	20 kWh	10 kWh
Cycle length	2.5 h	1.25 h	5 h	2.5 h	2.5 h	1.25 h	5 h	2.5 h
Very-heavy	7.2	6.8	7.1	6.8	8.1	7.8	8.0	7.8
Heavy	8.0	7.3	7.7	7.2	9.0	8.3	8.7	8.3
Medium	6.6	6.0	6.4	6.1	8.8	8.2	8.6	8.2
Light	7.1	6.1	6.9	6.2	9.6	8.5	9.1	8.6
Very-light	6.3	5.1	6.2	5.1	10.1	8.8	9.8	8.6



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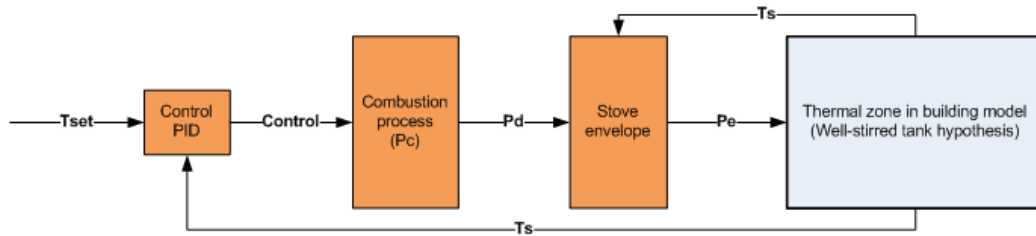


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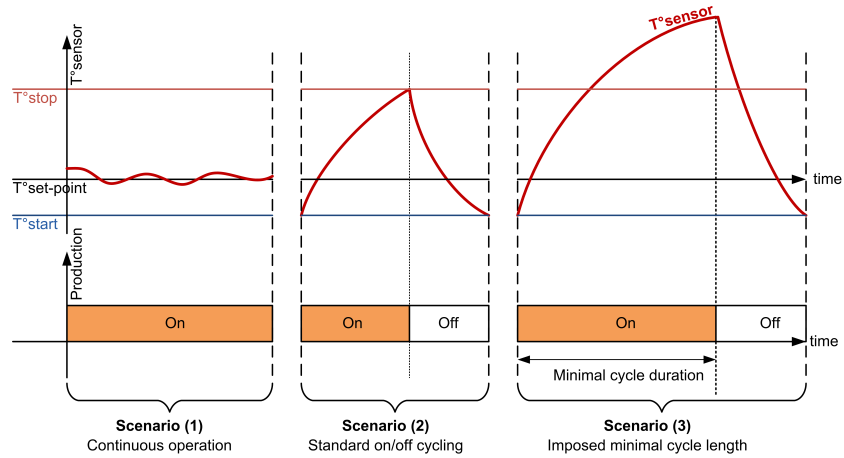


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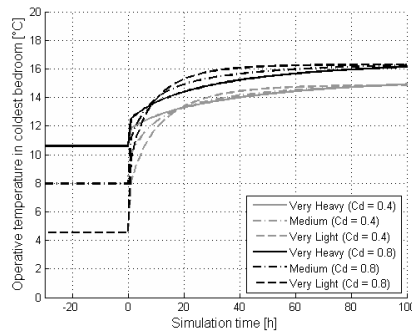
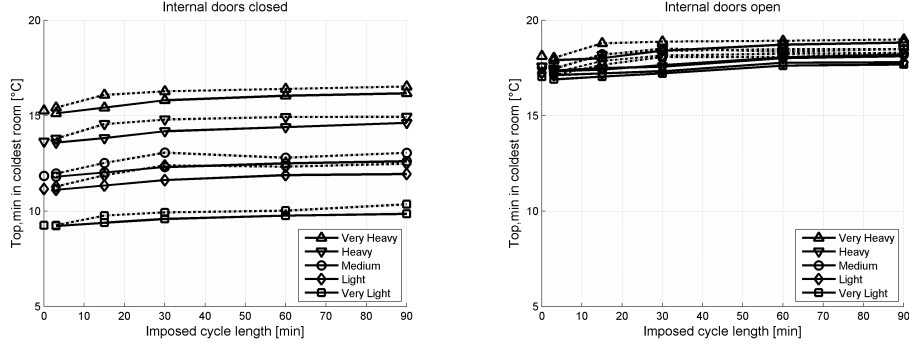
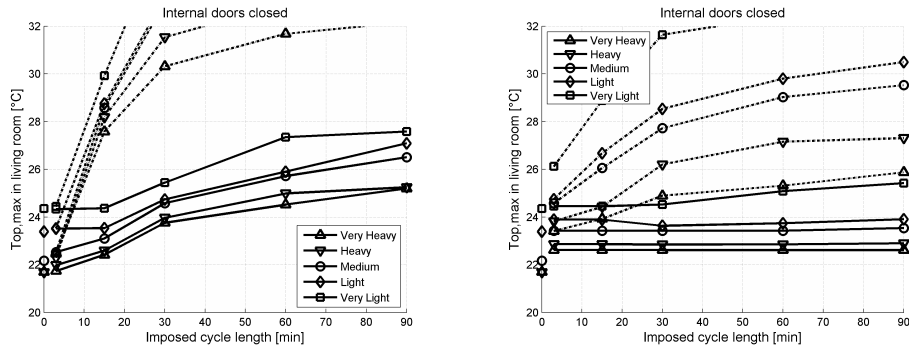


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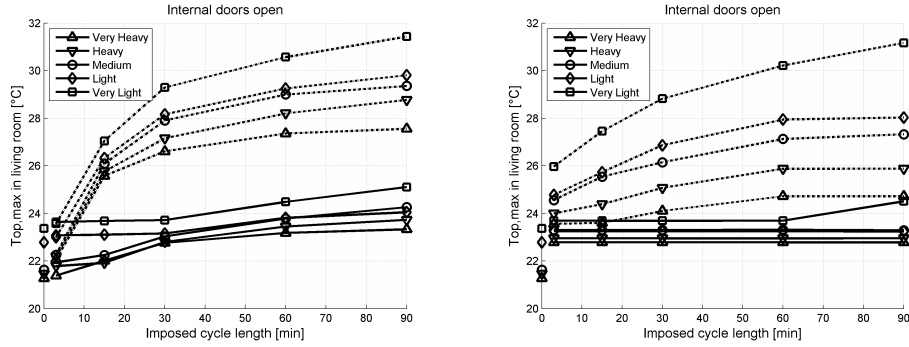
(a) Pure convective ($t_c = 1$), closed doors (b) Pure convective ($t_c = 1$), open doors

Figure 5: $T_{op,min}$ as a function of τ_{min} for the 8 kW generic pellet stove : the stove with a 30% power modulation is in solid line while the on-off stove is in dash-dotted lines. The perfect heating which is only applied to the living room with T_{set} of 21°C is superimposed on the ordinate axis.



(a) Pure convective ($t_c = 1$), closed doors (b) Pure radiative ($t_c = 0$), closed doors

Figure 6: $T_{op,max}$ as a function of τ_{min} for the 8 kW generic pellet stove and closed internal doors : the stove with a 30% power modulation is in solid line while the on-off stove is in dash-dotted lines. The perfect heating which is only applied to the living room with T_{set} of 20°C is superimposed to the ordinate axis.



(a) Pure convective ($t_c = 1$), open doors (b) Pure radiative ($t_c = 0$), open doors

Figure 7: $T_{op,max}$ as a function of τ_{min} for the 8 kW generic pellet stove and open internal doors : the stove with a 30% power modulation is in solid line while the on-off stove is in dash-dotted lines. The perfect heating which is only applied to the living room with T_{set} of 20°C is superimposed to the ordinate axis.

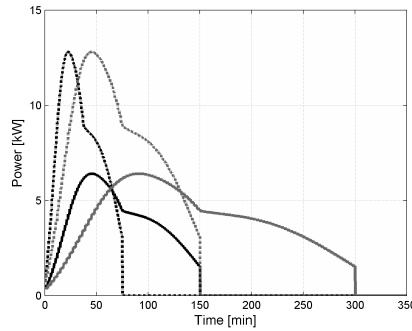
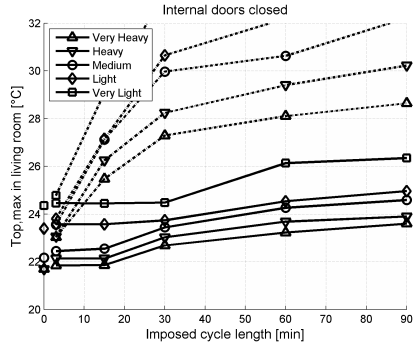
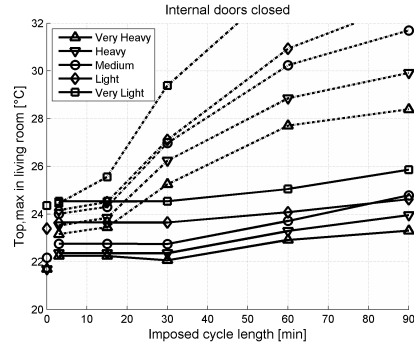


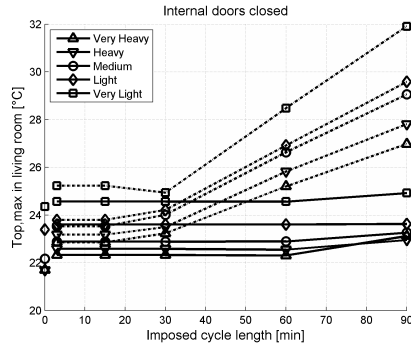
Figure 8: Combustion power, P_c , as a function of time for the 8 kW log stove [22] : the stove operated at 50 % of $P_{c,n}$ is shown in solid line while dash-dotted lines are representative of a on-off stove; the batches of 10 and 20 kWh are colored in black and grey, respectively.



(a) 0 kJ/K ($t_c = 0.35$), closed doors

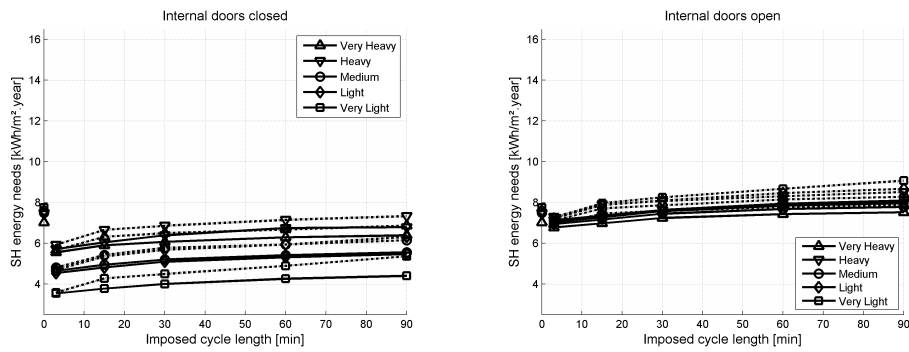


(b) 50 kJ/K, closed doors



(c) 150 kJ/K, closed doors

Figure 9: $T_{op,max}$ as a function of τ_{min} for a typical 8 kW pellet stove : the stove with a 30% power modulation is in solid line while the on-off stove is in dash-dotted lines. The perfect heating which is only applied to the living room with T_{set} of 20°C is superimposed on the ordinate axis.



(a) Pure convective ($t_c = 1$), closed doors (b) Pure convective ($t_c = 1$), open doors

Figure 10: SH needs as a function of τ_{min} for the 8 kW generic pellet stove : the stove with a 30% power modulation is in solid line while the on-off stove is in dash-dotted lines. The uniform perfect heating which is here applied all the building zones with T_{set} of 20°C is superimposed on the ordinate axis.