On the proper integration of wood stoves in passive houses under cold climates

Laurent Georges[a,*], Øyvind Skreiberg[b], Vojislav Novakovic[a]

[a]*Department of Energy and Process Engineering,*
Norwegian University of Science and Technology (NTNU),
Kolbjørn Hejes vei 1B, 7491 Trondheim, Norway
[b]*Department of Thermal Energy,*
SINTEF Energy Research,
Kolbjørn Hejes vei 1A, 7465 Trondheim, Norway

Abstract

The space-heating (SH) of residential buildings using a wood stove is an attractive solution. The way to properly integrate stoves in passive houses (PH) is still in question: current nominal powers are generally oversized compared to the PH needs (i.e. overheating risk) and it is not well understood how one stove can contribute to the SH of the entire building during a heating season. This question has already been addressed for the temperate climate of Belgium in a previous paper. The present work investigates cold climates also using a larger range of stove parameters. This is done using detailed dynamic simulations (TRNSYS) on a typical Norwegian single-family house typology. Using a large sensitivity analysis, recommendations to prevent overheating are given with a distinction between pellet and log stoves. Results also show that the overheating risk is somehow comparable between cold climates. On

---

[*] Corresponding author

Email addresses: `laurent.georges@ntnu.no` (Laurent Georges), `oyvind.skreiberg@sintef.no` (Øyvind Skreiberg), `vojislav.novakovic@ntnu.no` (Vojislav Novakovic)

Preprint submitted to Energy and Buildings *December 2, 2013*

the contrary, the ability of one stove to ensure alone the thermal comfort strongly depends on the local climate. For the milder climates, the stove can cover a significant part of the SH while, for colder climates, the stove should only be considered as a part of the total SH emission system.

Keywords: Wood stove, Passive house, Cold climate, Renewable energy integration

---

Nomenclature

A_{fl} Heated area [m^2]

C_d Discharge coefficient of a large opening [-]

CTMY Coldest hours of the heating season based on a TMY

HDD$_{18}$ Heating degree-days based on a Θ of 18°C

I_{th} Stove thermal mass [kJ/K]

$I_{tot,rad}$ Mean total radiation on a horizontal surface [W/m^2]

P_c Combustion power of the stove [W]

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

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

P_d Net power delivered to the stove envelope [W]

$P_{d,n}$ Nominal net power delivered to the stove envelope [W]

P_e Power emitted by the stove into the room [W]

$P_{SH,n}$ Net space-heating power in SDC [W/m^2]

Q_d Batch load (i.e. energy to the stove envelope per batch) [kWh/batch]

Q_{max} Maximal allowed value for the annual net SH needs [kWh/m^2.year]

SDC Standard Design Conditions with $\Theta_{SH,dim}$ and no gains

τ Combustion cycle length [min]

τ_{min} Minimal imposed cycle length [min]

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

$T_{op,5\%}$ 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_s Sensible air temperature [°C]

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

TMY Typical Meteorological Year

Θ Outdoor air temperature [°C]

Θ_{ym} Annual mean outdoor temperature [°C]

$\Theta_{SH,dim}$ Design outdoor temperature [°C]

WTMY Warmest hours of the heating season based on a TMY

1. Introduction

On the one hand, wood is a very important renewable energy source. Today, wood and its waste accounts for almost 50% of the EU-27 renewable energy production [1]. In some European countries with cold climate, the share of bioenergy is much higher than 50% and wood logs account for a considerable part of this [2, 3]. In the future, renewables should cover 20% of the final energy consumption in Europe by 2020 and a large part by 2050 [4]. For example, the goal in Norway is to double the use of bioenergy from 2008 to 2020 [5], and wood logs used in stoves is expected to account for 50% of this increase. Hence, there is no doubt about the expected importance of bioenergy amongst the renewable energy sources, nor the importance of wood logs for renewable energy production. On the other hand, energy consumption of buildings in developed countries comprises 20–40% of total energy use [6] so that its reduction has become a major concern, as illustrated by the European Performance of Buildings Directive [7]. A common strategy is to reduce the space-heating (SH) needs by a better insulation of the building envelope. Among building concepts that have emerged, the passive house (PH) is based on a super-insulated building envelope [8]. Furthermore, the concept of *Zero Energy Building* (ZEB) has also been increasingly popular. In many research developments, the PH standard is often considered as a minimal performance requirement for ZEB envelopes.

The SH of passive houses using wood stoves is thus a strategic area. Furthermore, this solution can be cost effective [9] and state-of-the-art stove technologies present acceptable energy efficiency (e.g. 85 %). This heating strategy has also positive aesthetic aspects as well as can provide thermal coziness. New airtight stoves equipped with an independent supply for the combustion air and flue gas removal are now developed so that it enables to maintain an acceptable indoor air quality (IAQ) in airtight building envelopes [10]. In fact, the integration of wood stoves in passive houses presents some challenges. These challenges have already been investigated for the Belgian context in previous communications from the authors [11, 12]. Belgium is characterized by a temperate climate and a PH definition comparable to Germany. Besides, analysis using a similar methodology and conclusions can be found for the German context [10, 8].

Firstly, there is a real overheating risk in the room where the stove is placed. Current wood stoves have a minimal nominal power, $P_{c,n}$[1], of about 8 kW while the nominal power of the losses in passive houses during design conditions is much lower (roughly 3 kW for Oslo): current stoves are thus much oversized compared to the instantaneous envelope needs. Furthermore, wood stoves are characterized with rather long combustion cycles, typically more than 45 min for a log stove [13], while a pellet stove typically has a 30 min start-up period [14]. These long cycles should be promoted in order to get the best energy efficiency and to reduce the emission of pollutants that are dominant during the start and stop phases. In addition, the power modulation of the state-of-the-art stoves is limited: the minimal combustion power ($P_{c,min}$) with a pellet stove is typically 30 % of $P_{c,n}$ and 50 % for log stoves.

---

[1] Different definitions of the *nominal* power exist. By convention, it is here taken as the maximal power of the stove.

As a result, there is thus a strong overheating risk to operate an oversized wood stove on a long production cycle in a passive house. This phenomenon was observed experimentally in field measurements [15, 16] within Danish low-energy houses. Let us mention that the expression *on-off* stove refers to a stove that can only operate at nominal load $P_{c,n}$. It therefore can be applied consistently to pellet stoves. On the contrary, the combustion power of wood logs in a batch is by nature unsteady so that the expression *on-off* stove may be misleading. In this case, we rather refer to a log stove *without power modulation* : the time-averaged combustion power of one batch is then equal to $P_{c,n}$.

Investigations for the Belgian context [12] were performed for wood stoves without large heat storage. It was shown that the integration of a 8 kW pellet stove does not generate severe overheating if the stove has a 30 % power modulation. If the pellet stove cannot modulate (i.e. an on-off stove), the integration is still possible but some architectonic measures should be taken to limit the overheating (i.e. high building thermal mass and opening of the doors inside the building). As regards log stoves, their combustion cycles are usually longer so that a 50 % power modulation is a necessary but not sufficient condition to prevent overheating. It should be complemented with some additional architectonic measures to prevent the overheating (as for the on-off pellet stove). From these investigations, general recommendations were that stove manufacturers should develop solutions with a $P_{c,n} < 8$ kW, a large power modulation ($P_{c,min} < 0.5 P_{c,n}$) and/or a large thermal mass ($I_{th} \gg 150$ kJ/K).

Secondly, the wood stove could mainly cover the SH needs if the heat delivered by the stove can diffuse efficiently inside the entire building envelope. Somehow, it is in line with the original philosophy of the passive house [8] where the SH distribution system should be simplified as much as possible, a wood stove being a potential basis for this simplification. Investigations in the Belgian context have shown that one stove cannot alone ensure the thermal comfort in strict design conditions (SDC), i.e. during a cold wave. However, the stove may cover a significant part of the heating load during a Typical Meteorological Year (TMY) if the building occupants can accept a lower operative temperature (T_{op}) in bedrooms and often leave the internal doors of the building open.

In fact, the implementation of a so-called *hydro-stove* equipped with a hot-water heat exchanger is already a solution to the heat distribution and to prevent the overheating problem: a large part of the power released by the combustion is indeed recovered and can be fed into a hydronic system equipped with radiators (see e.g. [17, 18]). Nevertheless, the present work aims at investigating the limits of the integration of stoves using the standard approach where all the heat is directly released into the room. Furthermore, only stoves corresponding to state-of-the-art products already available on the market are investigated. It is still assumed that the stove envelope has no large dedicated heat storage (i.e. $I_{th} \leq 150$ kJ/K).

The first objective of the present article is to extend results to cold climates. Basically developed for temperate climates as Germany, the PH concept has then been exported to Nordic countries as Denmark, Norway, Sweden as well as to cold climates like Canada and Estonia. Sometimes, the PH standard has been adapted to local conditions, such as the climate (e.g.

Norway [19] and Sweden [20]). The integration of wood stoves should therefore be assessed in the specific context of cold climates. Preliminary results for Norway were communicated in a conference [21]. The second objective of the article is to investigate a larger range of stove properties, such as the $P_{c,n}$ and the power modulation. A large parametric study is done on both the stove and building properties so that conclusions are general and representative for many countries. Even though a total of $\sim$4000 simulations has been performed, the number of investigated test cases had nonetheless to be restricted. This research effort aims at developing a conceptual and theoretical background for the stove integration inside super-insulated building envelopes. This is done using detailed dynamic simulations in order to investigate the whole-year thermal comfort at an acceptable computational cost. This framework can subsequently serve as a basis for field measurements or more detailed simulations (e.g. Computational Fluid Dynamics, CFD).

2. Methodology

The thermal comfort is investigated using detailed dynamic simulations (here using TNRSYS [22]) on a detached single-family house. For the sake of consistency, the simulation methodology is kept equivalent to the investigations for the Belgian context. Only the most important aspects of the simulation procedure are introduced here as well as elements specific to cold climates. The interested reader is invited to consult the following communications [11, 12] in order to get an extended knowledge of the methodology and modeling.

2.1. Building model and parameters

The multi-zone building model of TRNSYS (i.e. the Type 56) is used [22]. In order to investigate natural convection inside the envelope, the airflow rates between rooms are computed using a ventilation network model (here using TNRFLOW [23]): in passive houses, the opening of the internal doors is indeed an efficient way to homogenize the temperature within the entire envelope [10, 8]. Doors are modeled using a large opening approximation introducing a discharge coefficient (C_d) in order to tune the model to a specific flow physics. It may typically range from 0.4 to 0.8 (the default value is here taken as 0.65) [24]. The building has balanced whole-house mechanical ventilation equipped with a heat recovery unit. The constant-air-volume 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). Standard hygienic flow rates for Norway are imposed [25], with a mean fresh airflow rate of 1.2 $\mathrm{m^3/m^2.h}$. It leads to an air change rate (ach) of 0.5 $\mathrm{h^{-1}}$ which is representative for other Nordic countries [26] such as Denmark, Finland and Sweden. Internal gains with a mean value of 4.2 $\mathrm{W/m^2}$ are applied to the building model following the Norwegian PH standard [19] (while 2.1 $\mathrm{W/m^2}$ is considered in the PHPP [27] used in Germany or Belgium).

The same detached single-family house is used as a benchmark geometry for all simulations. It is a typical Norwegian two-storey's building extracted from a house manufacturer catalogue [28]. The house is placed on a flat and open terrain without obstacles, and has a net heated area (A_{fl}) of 173.5 $\mathrm{m^2}$. The house and its internal organization are shown in Figure 1 : the building is divided into 8 thermal zones. The living room where the stove is placed faces the south while no solar shading is activated (even though cold climates are often characterized by low solar altitudes). This can be seen as the most severe situation in terms of thermal comfort (i.e. risk of overheating).

A specific definition of the passive house standard has been developed for the Norwegian context, the NS 3700 [19]. This standard is often considered as the future legal requirement for new Norwegian buildings after 2015. Practically, the NS 3700 defines a minimal performance requirement for each envelope component (e.g. external walls, windows) as well as a maximum value allowed for the annual net SH needs (Q_{max}). This last criterion is made dependent on the local weather conditions and the building geometry :

$$Q_{corr} = max\left(\left(250 - A_{fl}\right), 0\right)/100, \tag{1}$$

$$Q_{max} = 15.0 + 5.4 \times Q_{corr} + \left(2.1 + 0.59 \times Q_{corr}\right) \times max\left(\left(6.3 - \Theta_{ym}\right), 0\right) \tag{2}$$

where Θ_{ym} is the annual mean outdoor temperature. The SH set-point temperature (T_{set}) is fixed at 21°C in accordance with the NS 3700.

Three different building locations are considered in order to span the wide range of conditions found in cold climates: Oslo, Bergen and Karasjok (see Figure 2). Typical weather characteristics are reported in Table 1, as the heating degree-days based on an outdoor temperature of 18°C (HDD_{18}). HDD_{18} enable to identify the corresponding climatic zone following the ASHRAE classification [29]. They range from *Cool*, *Cold* to *Subarctic* so that these climates are sufficiently diverse to derive conclusions representative for many countries.

The building envelope performance has been defined in order to comply with the NS 3700. This has been verified using the building simulation software SIMIEN [30] which is equipped with modules to compare a building performance to usual Norwegian building codes. As three locations are considered here, three levels of building envelope performance have been defined, see Table 2. Again, the number of test cases is limited and dependant on a local PH definition. Nevertheless, the nominal net SH power ($P_{SH,n}$) for these three cases are rather different, ranging from 17.1 to 30.5 W/m^2. An extended analysis, not reported here, has also shown that conclusions are not sensitive to limited changes of the envelope performance (as long as it is still representative for PH) .

Different construction modes may lead to the same envelope performance (e.g. using masonry or wood). Therefore, five possible construction modes that correspond to five different levels of internal thermal mass have been defined using technical guidelines [31]. They range from *very-heavy* to *very-light* (see Table 4). In practice, these different construction modes lead to different levels of thermal insulation located inside the building envelope (i.e. essentially placed in partition walls for acoustic reasons). This difference strongly influences the heat diffusion between rooms [12]. In general, the higher the internal thermal mass, the lower the insulation level in partition walls inside the building. In conclusion, 3 locations multiplied by 5 construction modes lead to a total of 15 different test cases for the building envelope.

2.2. Stove model and parameters

The model structure and the notation of its main physical parameters are illustrated in Figure 3. The coupling between the building and stove models has been simplified [11]: the stove geometry and its envelope are not integrated directly inside the building geometry. In fact, the power emitted by the stove (P_e) by convection and radiation is injected into the building model in form of internal gains. Furthermore, the stove envelope is modeled using a 1-D unsteady heat transfer problem. Nevertheless, the effect of the heat flux through the stove glazed surfaces is not accounted for. At the stove emitting surfaces, the convective heat transfer is evaluated using correlations for flat plates while a simplified formula is used for the radiative heat transfer. The conversion efficiency is not investigated here. Only the net heat delivered to the stove envelope, P_d, is fixed as a parameter. This convention simplifies the analysis as all the energy delivered to the stove envelope is subsequently emitted to the room, this last quantity being of high interest for the thermal comfort analysis. In practice, this approach focusing on P_d instead of P_c does not alter results significantly (modern wood stove having a conversion efficiency higher than 80%).

In practice, the pellet and the log stoves have different combustion characteristics and control :

- The combustion process in *pellet* stoves can be assumed instantaneous [14] compared the characteristic time scales of either the stove or the building envelopes. The power is here controlled continuously by a Proportional Integral (PI) action to enforce the zone air temperature (T_s) to T_{set}. The limitation in terms of power modulation is directly integrated in the PI control. In this case, the stove is started if T_s is lower than a start temperature (T_{start}). The stove is then stopped if T_s is higher than a stop temperature (T_{stop}) AND if the stove has operated longer than a minimal cycle length fixed by the user (τ_{min}). In practice, T_{start} is here set equal to T_{set}, the difference between T_{start} and T_{stop} is 2°C, while τ_{min} is investigated up to 90 min. A stove with a power modulation of 30 % and an on-off stove are considered here. A nominal $P_{c,n}$ of 8 kW is representative for the lowest power available in the market with a few models proposing $\sim$ 6 kW [32, 33, 34]. Therefore, $P_{d,n}$ of 6, 8 and 12 kW are here investigated for the pellet stove.

- The combustion process in *log* stoves cannot be considered as instantaneous compared to the stove envelope and building dynamics. It should be considered as a batch process [35]. A specific software package developed by SINTEF Energy Research [13] is used to establish the time profile of the log-combustion power, P_c. It is here assumed that the combustion process is not continuously controlled: the power modulation level is selected a priori by the user at the beginning of each batch (e.g. by adjusting the air intakes) and assumed constant for the remainder of the batch cycle. It is also assumed that the log stove starts automatically when T_s is lower than T_{set} while in practice this operation is most often manual. A stove with a power modulation of 50 % and no modulation are considered here. Furthermore, a $P_{c,n}$ of 8 kW is also taken as representative for the lowest available power with very few models proposing 4 kW [32, 33, 34]. Therefore, $P_{d,n}$ of 4, 8 and 12 kW are investigated for the log stove. The amount of wood for each batch depends on the combustion chamber size and is thus also physically related to the stove $P_{c,n}$ (in order to ensure an efficient combustion). This amount is adapted consistently in the present study [36]. In this respect, the batch load (Q_d) is here defined as the total energy delivered to the stove envelope per batch. It ranges from 5 to 30 kWh depending on $P_{c,n}$. The combustion cycle length, τ, expressed in [h] is therefore equal to :

$$P_{d,min} = P_{d,n} \times (P_{c,min}/P_{c,n}) , \tag{3}$$

$$\tau = Q_d/P_{d,min}. \tag{4}$$

The difference between the stoves and their control is illustrated in Figure 4. Here a 8 kW stove without modulation is operated on a cold day (i.e. -20°C) for the Oslo climate. If a pellet stove has no τ_{min}, the air temperature (T_s) oscillates between T_{start} and T_{stop}. If a pellet stove has a τ_{min} of 1.25 h, large temperature overshoots above T_{stop} then appear. Using a log stove with the same cycle length of 1.25 h, a cycle is started each time T_s falls below T_{start}. Comparing both cases for a 1.25 h cycle, one clearly notices the influence of the heat release profile of the log batch combustion compared to the continuous heat release from the pellet stove (i.e. T_s rises faster for the log stove). This clearly shows that it is important to integrate the combustion dynamics when considering log stoves.

A typical stove geometry taken as a box of 0.6 x 0.6 x 1.2 m is considered. It is assumed that the delivered power (P_d) and the wall composition is distributed uniformly. The stove envelope is not equipped with radiation shields or designed to improve convection. Its thermal mass, I_{th}, is set between 50 and 150 kJ/K, which is representative of stoves without any large heat storage capacity. This choice leads to surface temperatures of about $\sim$ 200°C for a typical convective fraction of the heat emission, t_c, ranging from 35 to 45 %. With such small thermal masses and given the modeling approach, a change of stove geometry would essentially affect t_c. This effect was discussed in the Belgian context [12]. It leads us to assume that the performance of the selected geometry is representative of other stoves over a large range of external area and emissivity. Only results for a constant T_{set} are reported here. The stove control and airflow computation require a time step lower than 1 min. It was checked using a time-step convergence analysis. The range of stove properties investigated are reported in Table 3.

2.3. Thermal comfort assessment

The thermal comfort is evaluated globally using the T_{op} assuming that the user is far from the stove: a distance where the effect of radiation asymmetry and the direct radiation from the combustion chamber can be neglected. In this case, the thermal comfort can be evaluated globally using a method based on the Fanger's approach [37]. The mean radiant temperature is here computed using accurate view factors (i.e. not a surface-averaged distribution). The maximal and minimal acceptable T_{op} are taken to be 24.5 and 21°C. Using the EN ISO 7730 [38], this is the limit for a PMV < 0.5 with a *clo* and *met* of 1.0 (with a relative air speed < 0.1 m/s).

A distinction is made between the stove performance during a Typical Meteorological Year (TMY), here generated using Meteonorm, and during standard design conditions (SDC). The heating period of the TMY is further split into cold and warm hours, CTMY and WTMY, respectively. The threshold outdoor temperature (Θ) is taken as the temperature where the net SH power is at about 60% of its maximal value during a TMY (i.e. -4°C for Oslo, 1°C for Bergen and -17°C for Karasjok). SDC are characterized by a steady design outdoor temperature, $\Theta_{SH,dim}$, while no solar and internal gains are applied in the building. $\Theta_{SH,dim}$, reported in Table 1, is here taken as the lowest 3-days mean temperature in a 30-years measurement period.

These conditions are rather severe and can be considered as a cold wave. Given the article length, a limited number of thermal comfort indicators are reproduced in the manuscript : essentially the maximal and minimal T_{op} found during the analyzed period. Nevertheless, conclusions are based on an extended analysis of the thermal comfort (e.g. using 5% and 95% percentile of T_{op} during the heating season).

Combining all building, stove and climate alternatives, the total number of simulations is about 4000 that were run in parallel on a 32-core workstation. Only the most representative figures are reported in the result sections, Sections 3 and 4.

3. Analysis of the overheating

3.1. Baseline case

The baseline case considers the 8 kW stove with 50 kJ/K inertia and the Oslo climate. The overheating risk is here monitored using the maximal operative temperature ($T_{op,max}$) found during the heating season based on a TMY. The performance of the 8 kW pellet stove is shown in Figure 5 for each construction mode. As expected, the overheating increases progressively with the imposed cycle length, τ_{min}. Even for very short cycles, an overheating exists that is generated by solar and internal gains. In the remainder of the discussion about pellets, comments are only given for τ_{min} longer than 60 min as the motivation is to promote long combustion cycles. With closed doors, Figure 5(a), the overheating is under control using a 30% power modulation : only a slow increase of $T_{op,max}$ takes place with τ_{min}. On the contrary, the on-off operation quickly leads to unacceptable temperatures even though heavy construction modes significantly reduce this effect. Opening the internal doors reduces overheating so that a combination of a heavy construction mode with open doors may lead to an acceptable thermal comfort (see Figure 5(b)). As a result, the passive house response to the 8 kW pellet stove under the Oslo climate is similar to the Belgian case (summarized in the Introduction, Section 1). Results for the 8 kW log stove are given in Table 5 for each construction mode. As for the Belgian case, the 50% power modulation is a necessary condition and should be complemented with heavy thermal mass and door opening to get an acceptable thermal comfort.

3.2. Stoves and climates comparison

This last analysis leads us to distinguish between three types of scenarios :

- Firstly, the overheating is under control and independent of the architectonic properties. A scenario further symbolized by $\oplus$.
- Secondly, the overheating is under control if architectonic measures are taken (i.e. heavy construction mode or opening of the internal doors). With a distinction if a single measure is enough (symbolized by $\odot$) or both types of measures should be implemented (symbolized by $\odot\odot$).
- Thirdly, the overheating is prohibitive whatever the architectonic measures taken. A scenario further symbolized by $\ominus$.

Given these qualitative criteria, performance with different pellet stoves and climates can be summarized in Table 6. It is interesting to notice that the overheating properties are again similar between the three locations investigated. The 30% power modulation is effective to prevent the overheating, even though this property is not enough anymore with a 12 kW pellet stove. The on-off 8 kW stove requires architectural measures to prevent overheating. Reducing the power from 8 to 6 kW (i.e. the lowest power we found on the market) does not change this behavior. For an on-off pellet stove to be properly integrated regardless of the building properties, a power significantly lower than 6 kW should be developed. These results prove that the same characteristics for pellet stoves can be used for the three climatic zones : a stove power lower or equal to 8 kW, with 30% power modulation or without modulation but combined with architectural measures.

The performance of the different log stoves and climates are summarized in Table 7. Again, the overheating risk is rather similar between the three locations investigated. Log stoves present longer combustion cycles than pellet stoves so that the integration is more critical. In any case, it is impossible to integrate a 12 kW log stove. 8 kW is already a limit as strong architectural measures should be taken in combination with the 50% power modulation to prevent strong overheating. Reducing the power to 4 kW significantly helps but, in most cases, one architectural measure is still required. For a log stove to be installed regardless of the building properties, a power lower than 4 kW should be developed, cycle lengths reduced or a better power modulation reached.

For all cases, the effect of the thermal mass was investigated by increasing it from 50 to 150 kJ/K. Results are not reported here. This level of thermal inertia is only able to store the delivered heat, P_d, for less than half an hour before saturating. It has thus a positive but limited effect on overheating for long combustion cycles. As previously concluded, stove thermal masses significantly higher than 150 kJ/K should rather be considered.

4. Analysis of the heat distribution

4.1. Baseline case

Again, the baseline case corresponds to a 8 kW stove with 50 kJ/K thermal inertia considering the Oslo climate. No other SH system is applied. The underheating risk is monitored using the minimal operative temperature ($T_{op,min}$) found during the heating season based on a TMY. It appears in bedrooms. The performance of the pellet stove is shown in Figure 6 for each construction mode. Firstly, the architectonic properties of the building turn out to be the dominating parameter. For closed doors, the underheating strongly depends on the construction mode : the higher the internal thermal insulation, the lower $T_{op,min}$. It also translates that the main heat transfer process in the building with closed doors is the transmission through walls. With open doors, the natural convection generates large flow rates which become the dominating heat transfer process between rooms. It explains that $T_{op,min}$ is then nearly independent of the construction mode. Secondly, results show that $T_{op,min}$ is almost independent of the stove properties. This conclusion is also confirmed for the log stove with equivalent $T_{op,min}$ (not reported here). At least, it is the conclusion obtained by the resolution of the present simulation model (i.e. essentially one airnode by zone with a large opening approximation between them).

4.2. Stoves and climates comparison

Given the previous conclusion, the analysis of the heat distribution can be simplified. It is indeed sufficient to apply a so-called *perfect heating* in the living room rather than a complicated stove model. The perfect heating is ideal as it presents no limitations in nominal power ($P_{c,n} = \infty$), power modulation ($P_{c,min} = 0$) and is fully convective ($t_c = 1$). The test case for underheating consists in imposing a T_{set} of 23°C in the living room and analyzing whether the thermal comfort could be met in other rooms when internal doors are open. Results are reported in Table 8 for different discharge coefficient for doors (C_d). The thermal comfort is nearly reached for the milder climate of Bergen, proving that the stove can mainly contribute to the SH. Strictly speaking, the thermal comfort requirement of 21°C is nevertheless not met. With colder climates, the comfort is significantly reduced. The temperature may be critical in Oslo during SDC while they are often not acceptable in the case of Karasjok.

5. Conclusions and recommendations

The integration of wood stoves in passive houses under cold climates has been investigated using detailed dynamic simulations on a detached single-family house (with a heated area of 173.5 m^2). The whole-year thermal comfort is analyzed in order to monitor possible overheating and the distribution of heat between rooms. Only stove products already available on the market and with a limited heat storage were tested (i.e. $I_{th} \leq 150$ kJ/K).

Firstly, simulations suggest that the overheating risk is comparable between Belgium and the different cold climates. Common recommendations for the integration and future developments of stoves can thus be given. As long as combustion cycles shorter than 1.5 h are concerned, the pellet stoves can already be properly integrated in passive houses. The pellet stove should have a $P_{c,n}$ lower than 8 kW and be equipped with an efficient power modulation (i.e. $P_{c,min} < 0.3P_{c,n}$). On the contrary, the integration of log stoves is still critical using the state-of-the-art market products. This is due to the combination of high P_c and relatively long combustion cycles (here from 1.25 to 5 h). Nevertheless, simulations show that the integration is still possible if the $P_{c,n}$ is limited to 8 kW, the power modulation lower than 50% and if additional architectonic measures are taken (i.e. a heavy building thermal mass and opening of the internal doors). Results also suggest that the development of log stoves with a $P_{c,n}$ lower than 4 kW or with shorter combustion cycle lengths makes sense. High thermal storage could also be considered (i.e. $I_{th} \gg 150$ kJ/K). This can for example be realized using Phase-Change Materials (PCM) to limit the stove size and weight. Finally, the present simulation methodology can be used in order to perform the quick prototyping of these new stove technologies (i.e. investigating the potential improvement from new stove concepts).

Secondly, the potential for a single stove to ensure alone the thermal comfort inside the entire building envelope was investigated. Simulation results also suggest that the stove potential to prevent underheating is lower with colder weather conditions (i.e. higher P_{SH}): starting with Bergen where the stove can cover a large part of the SH needs (if internal doors are open), the autonomy of the stove is progressively reduced from Oslo to Karasjok where one stove is most of the time not enough for the SH. Except for the cool climatic zones as Bergen (i.e. climatic zone 5 following the ASHRAE classification [29]), we do not recommend a single stove to simplify the SH distribution in passive houses under cold climate.

6. Acknowledgments

The authors acknowledge Mette Maltha from SINTEF Byggforsk for her contribution to define the benchmark house. They also want to thank the Norwegian Research Council for their support, as this work was performed in the framework of the Research Centre for Zero Emissions Buildings (ZEB) and in collaboration with the StableWood project.

[1] M. Sturc, Renewable energy: analysis of the latest data on energy from renewable sources, Eurostat Statistics in focus 44/2012 (2012).

[2] Eurostat, In the EU27, almost half of renewable energy comes from wood and wood waste, Eurostat Newsrelease 168/2012 (November 2012).

[3] E. Karlsvik, Current firewood firing technology in Slovenia, Spain, Austria, Finland and Norway, in: Workshop on Next Generation Small Scale Biomass Combustion, IEA Bioenergy Task 32, Amsterdam, 2008.

[4] European Commission, Energy Roadmap 2050, COM(2011) 885 final (December 2011).

[5] Norwegian Ministery of Oil and Energy, Strategi for økt utbygging av bioenergi, Tech. rep., Norwegian Ministery of Oil and Energy (2008).

[6] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy and Buildings (40) (2008) 394–398.

[7] European Parliament, Directive 2010/31/EU of the European Parliament and of the Council of 19th May 2010 on the energy performance of buildings (recast), Official Journal of the European Union (May 2010).

[8] 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.

[9] 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.

[10] W. Feist, W. Hasper, H. Krause, J. Nitsch, R. Pfluger, R.-P. Strauβ, Protokolland nr. 36 : heizung mit biobrennstoffen für passivhäuser, Tech. rep., Passiv Haus Institut, Darmstadt (December 2007).

[11] 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.

[12] L. Georges, Ø. Skreiberg, V. Novakovic, On the proper integration of wood stoves in passive houses: Investigation using detailed dynamic simulations, Energy and Buildings (59) (2013) 203–213.

[13] 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).

[14] T. Persson, 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.

[15] 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.

[16] R. Carvalho, O. Jensen, A. Afshari, N. Bergsøe, Wood-burning stoves in low-carbon dwellings, Energy and Buildings (59) (2013) 244–251.

[17] F. Fiedler, T. Perrson, Carbon monoxide emissions of combined pellet and solar heating systems, Applied Energy (86) (2009) 135–143.

[18] T. Persson, 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.

[19] Standard Norge, NS 3700 : Criteria for passive houses and low energy houses (residential buildings) (2010).

[20] Sveriges Centrum för Nollenergihus, Kravspecifikation för nollenergihus, passihus och minienergihus, FEBY 12 (2012).

[21] L. Georges, Ø. Skreiberg, V. Novakovic, On the integration of wood stoves in Norwegian passive houses: investigations using dynamic simulations, in: Proceedings of the 11th REHVA World congress, CLIMA 2013, Prague, 2013.

[22] TRNSYS a transient system simulation program, volumes 1 to 8 (2011).

[23] TRNFLOW a module of an air flow network for coupled simulation with TYPE 56 (multi-zone building of TRNSYS), version 1.4. (2009).

[24] P. Heiselberg, Modelling of natural and hybrid ventilation, Tech. rep., Aalborg University, lecture notes no. 004 (2006).

[25] KRD, Kommunal- og regionaldepartementet, TEK 10 : Byggteknisk forskrift (2010).

[26] C. Dimitroulopoulou, Ventilation in European dwellings : a review, Building and Environment (47) (2012) 109–125.

[27] W. Feist, R. Pfluger, B. Kaufmann, J. Schnieders, O. Kah, Passive House Planning Package 2007, Passiv Haus Institut, Darmstadt (June 2007).

[28] Mesterhus, Mesterhus Nanne (November 2012).
URL `http://www.mesterhus.no/`

[29] ANSI/ASHRAE/IESNA, Standard 90.1-2007 : Normative Appendix B, building envelope climate criteria (2007).

[30] ProgramByggerne, SIMIEN (March 2013).
URL `http://www.programbyggerne.no/`

[31] S. Byggforskserien, Byggdetaljer, Tech. rep., SINTEF Byggforsk, Trondheim (2012).

[32] 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.

[33] RIKA, Stove manufacturer website (June 2012).
URL `http://www.rika.at/en/B2C/`

[34] MCZ, Stove manufacturer website (Januar 2013).
URL `http://www.mcz.it/en/`

[35] 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.

[36] Standard Norge, NS 3058 : Enclosed wood heaters, Smoke emission -Part 1: Test facility and heating pattern- (1994).

[37] K. Ghali, N. Ghaddar, M. Salloum, Effect of stove asymmetric radiation field on thermal comfort using a multisegmented bioheat model, Building and Environment (43) (2008) 1241–1249.

[38] 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).

[39] European Committee for Standardization, European standard EN ISO 13790 : energy performance of buildings, calculation of energy use for space-heating and cooling (2008).

Table 1: Local weather characteristics for the three locations and the corresponding climatic zone [29] : $I_{tot,rad}$ is the mean total radiation on a horizontal surface, $\Theta_{SH,dim}$ is the SH design outdoor temperature.

Location	Θ_{ym} [°C]	$I_{tot,rad}$ [W/m²]	$\Theta_{SH,dim}$ [°C]	Q^*_{max} [kWh/m².y]	HDD$_{18}$ [°C.day]	Climatic zone [n° and name]
Oslo	6.3	110	-20.0	19.0	4423	6, *Cold*
Bergen	7.5	87	-11.7	18.9	3858	5, *Cool*
Karasjok	-2.5	79	-48.0	41.2	7538	8, *Subarctic*

$^*Q_{max}$ is computed using Eqs. 1 and 2 following NS 3700.

Table 2: Building envelope performance as a function of the location : thermal transmittance (U) of external wall (U_{ext}), the roof (U_{roof}), the slab (U_{slab}) and the windows (U_w); normalized cold bridges (Ψ"), efficiency of the heat recovery (η_{ex}), infiltration rate at 50 Pa (n_{50}), the net SH needs computed using SIMIEN (Q_{SH}).

Location	U_{ext} [W/m².K]	U_{roof} [W/m².K]	U_{slab} [W/m².K]	U_w [W/m².K]	Ψ" [W/m².K]	η_{ex} [%]	n_{50} [1/h]	Q_{SH} [kWh/m².y]	$P_{SH,n}$† [W/m²]
Oslo	0.15	0.12	0.11	0.72	0.03	85	0.6	18.9	20.8
Bergen	0.15	0.13	0.11	0.80	0.03	85	0.6	16.0	17.1
Karasjok	0.12	0.10	0.08	0.72	0.03	85	0.6	41.0	30.5
NS 3700*	0.15	0.13	0.15	0.80	0.03	80	0.6	Q_{max}	-

*Minimal requirement by building component imposed by the Norwegian passive house standard, NS 3700.

†Computed in Standard Design Conditions (SDC) ($\Theta_{SH,dim}$ with no internal and solar gains).

Table 3: Range of the stove parameters used in simulations.

Stove	$P_{d,n}$ [kW]	$P_{c,min}$ [% $P_{c,n}$]	I_{th} [kJ/K]	τ [min]
Pellet	[6;12]	[30;100]	[50;150]	[5;90]
Log	[4;12]	[50;100]	[50;150]	[75;300]

Table 4: Construction modes of the benchmark detached passive house : overall building thermal inertia (using EN 13790 [39]), constitution of walls and corresponding thermal transmittance for the partition walls.

Construction mode	Thermal inertia (MJ/K)	Envelope thermal insulation				Internal thermal insulation (W/m².K)		
		External wall	Ground slab	Roof	Glazing/ Window	Floor/ ceiling	Partition wall	Bearing wall
Masonry heavy	**Very-heavy** (86)	C+EPS	C+EPS(d)	WS+WF	TGW	C (1.6)	C (3.2)	C (2.8)
Mixed wood-masonry	**Heavy** (41)	WS+GW	C+EPS(d)	WS+GW	TGW	C (1.6)	WS+MW (0.33)	C (2.8)
Wooden heavy	**Medium** (35)	WS+WF	C+EPS(u)	WS+WF	TGW	WS+WF (0.23)	WS+MW (0.33)	C (2.8)
Masonry light	**Light** (26)	LWA+EPS	C+EPS(u)	WS+GW	TGW	WS+GW (0.21)	WS+GW (0.33)	LWA (1.1)
Wooden light	**Very-light** (14)	WS+GW	C+EPS(u)	WS+GW	TGW	WS+GW (0.21)	WS+GW (0.33)	WS+GW (0.25)

LWA for lightweight aggregate 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 5: $T_{op,max}$ in [°C] for the baseline 8 kW log stove in Oslo with values $\lesssim$ 24.5°C in bold.

Doors	Closed				Open			
$P_{c,min}$	100% $P_{c,n}$		50% $P_{c,n}$		100% $P_{c,n}$		50% $P_{c,n}$	
Batch load, Q_d	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	28.9	28.0	26.1	**25.3**	26.7	**25.8**	**24.8**	**24.4**
Heavy	31.3	30.4	28.1	26.8	28.6	27.2	25.9	**25.2**
Medium	33.7	32.3	30.2	27.7	29.6	28.1	26.9	26.0
Light	35.8	34.5	31.6	29.6	30.9	29.2	28.1	26.7
Very-light	42.1	40.2	36.6	32.4	34.2	31.6	30.9	28.3

Table 6: Qualitative performance against overheating of pellet stoves equipped with 50 kJ/K thermal inertia and using τ_{min} between 60 and 90 min : function of the stove nominal power, $P_{d,n}$, and power modulation [%] computed for different locations and weather conditions.

Location	Oslo			Bergen			Karasjok		
Weather	TMY	CTMY	SDC	TMY	CTMY	SDC	TMY	CTMY	SDC
6 kW, 30%	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
6 kW, 100%	⊙⊙	⊙⊙	⊙	⊙⊙	⊙⊙	⊙	⊙⊙	⊙⊙	⊙
8 kW, 30%	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
8 kW, 100%	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙
12 kW, 30%	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙
12 kW, 100%	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖

⊕ : Good control independent of the architectural measures

⊙ : Control if one set of architectural measures is taken

⊙⊙ : Control if complete set of architectural measures taken

⊖ : Overheating whatever the architectural measures taken

Table 7: Qualitative performance against overheating of log stoves equipped with 50 kJ/K thermal inertia : function of the stove nominal power, $P_{d,n}$ in [kW], power modulation [%] and batch load, Q_d in [kWh], computed for different locations and weather conditions.

Location	Oslo			Bergen			Karasjok		
Weather	TMY	CTMY	SDC	TMY	CTMY	SDC	TMY	CTMY	SDC
4 kW, 50%, 10 kWh	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊗
4 kW, 100%, 10 kWh	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙
4 kW, 50%, 5 kWh	⊙	⊙	⊕	⊙	⊙	⊕	⊙	⊙	⊕
4 kW, 100%, 5 kWh	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊕
8 kW, 50%, 20 kWh	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙
8 kW, 100%, 20 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
8 kW, 50%, 10 kWh	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙	⊙⊙
8 kW, 100%, 10 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
12 kW, 50%, 30 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
12 kW, 100%, 30 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
12 kW, 50%, 15 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
12 kW, 100%, 15 kWh	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖

⊕ : Good control independent of the architectural measures

⊙ : Control if one set of architectural measures is taken, ⊙⊙ : Control if complete set of architectural measures taken

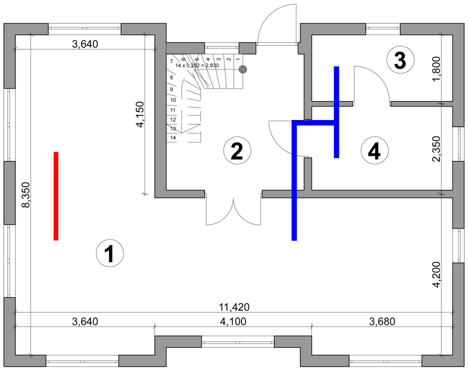
⊖ : Overheating whatever the architectural measures taken

⊗ : Underheating because lack of emitted power

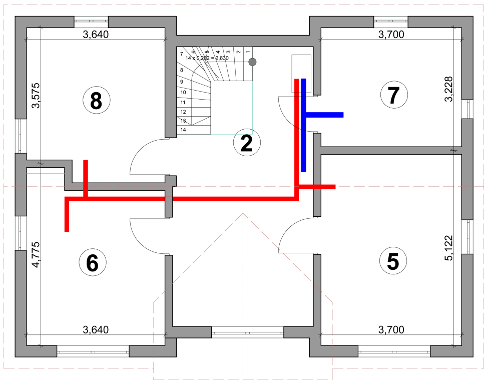
Table 8: Performance against underheating with open internal doors : a perfect heating with a T_{set} of 23°C is applied in the living room, while $T_{op,min}$ is reported in [°C] for different locations, weather conditions and discharge coefficients of internal doors (C_d).

Location	Oslo			Bergen			Karasjok		
Weather	TMY	WTMY	SDC	TMY	WTMY	SDC	TMY	WTMY	SDC
$C_d = 0.65$	[18.2; 18.9]	[18.9; 19.8]	[17.2; 18.3]	[18.7; 19.9]	[19.5; 20.2]	[17.9; 18.9]	[16.8; 17.7]	[17.4; 18.4]	[15.6; 15.7]
$C_d = 0.40$	[17.2; 19.0]	[17.9; 19.3]	[16.0; 17.5]	[17.7; 18.7]	[18.6; 19.8]	[16.7; 18.2]	[15.5; 17.5]	[16.2; 17.4]	[14.0; 15.7]
$C_d = 0.80$	[18.6; 19.8]	[19.3; 20.1]	[17.8; 18.6]	[18.6; 19.9]	[19.4; 20.2]	[18.5; 19.1]	[17.4; 18.1]	[17.9; 18.7]	[16.2; 16.7]

As all the five construction modes are considered, the range of values spanned by them is reported between brackets.



(a) First floor



(b) Second floor

Figure 1: Sketches of the first and second floors : kitchen coupled to the living-room (zone 1), corridor with an open staircase (zone 2), technical room (zone 3), bathrooms (zones 4, 7), bedrooms (zones 5, 6, 8); the layout of the ventilation network is shown in colour (red for the fresh air and blue for the exhaust air).

Figure 2: Location of Oslo, Bergen and Karasjok in Norway (authorized reproduction from the website *stepmap.com*).

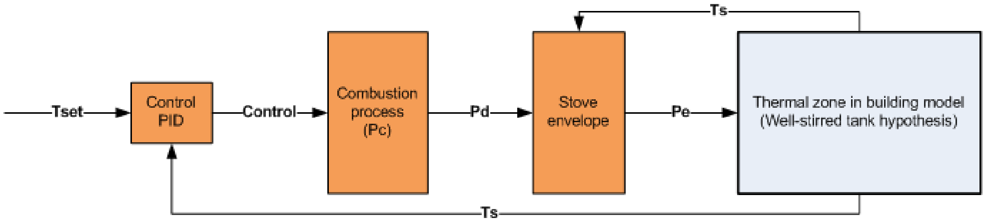


Figure 3: Block diagram illustrating the structure of the stove model and its coupling with one thermal zone: stove and buildings models are colored in orange and grey, respectively.

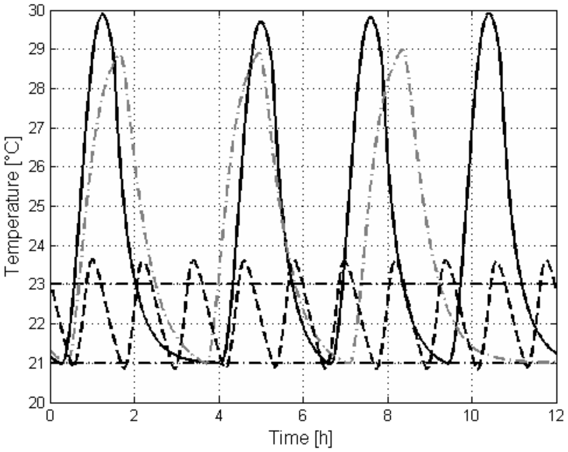
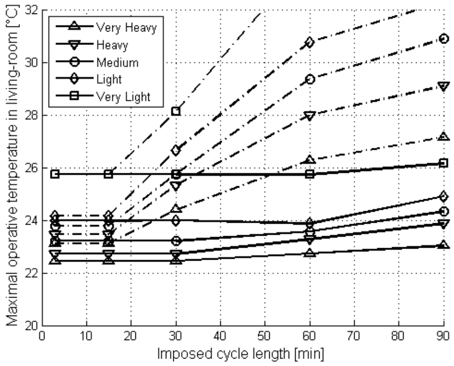
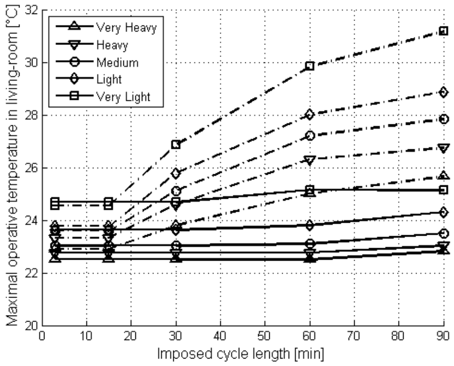


Figure 4: Example of computed air temperature (T_s) in the living room with a 8 kW stove for the Oslo test case : an on-off pellet stove without τ_{min} (in black dashed line), an on-off pellet stove with a τ_{min} of 1.25 h (in grey dash-dotted line) and a log stove operated without modulation and a 1.25 h cycle (in black solid line).

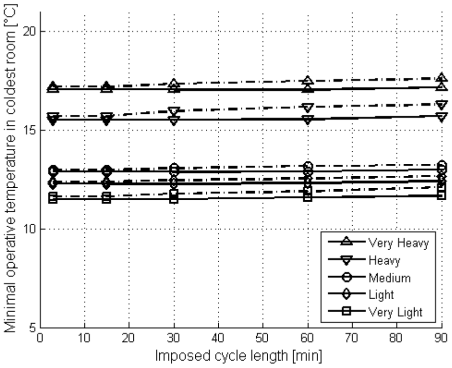


(a) Closed doors

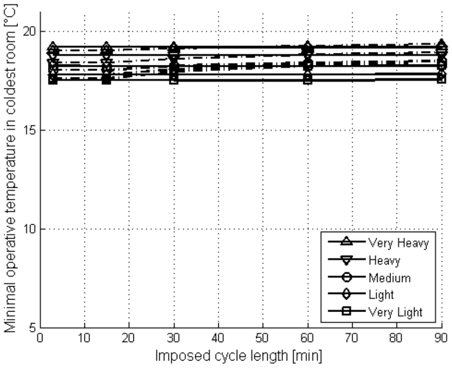


(b) Open doors

Figure 5: $T_{op,max}$ in [°C] as a function of τ_{min} and construction mode for the baseline 8 kW pellet stove in Oslo : the stove with a 30% power modulation is in solid lines while the on-off stove is in dash-dotted lines.



(a) Closed doors



(b) Open doors

Figure 6: $T_{op,min}$ in [°C] as a function of τ_{min} and construction mode for the baseline 8 kW pellet stove in Oslo : the stove with a 30% power modulation is in solid lines while the on-off stove is in dash-dotted lines.