ON THE INTEGRATION OF WOOD STOVES FOR THE SPACE-HEATING OF PASSIVE HOUSES: ASSESSMENT USING DYNAMIC SIMULATION

Laurent Georges[1] and Vojislav Novakovic[1]
[1]Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

ABSTRACT

State-of-the-art wood stoves could be an attractive solution for the space heating of passive houses. The question of the integration of wood stoves in passive envelopes is rather new and still open, the main constraints being the power oversizing ant the heat distribution. The paper proposes a low-resolution simulation approach to provide an insight into the whole-year thermal comfort using a stove, and into the relative effect of the large number of physical parameters involved in the problem. In particular, a simple stove model is developed for detailed dynamic simulations in order to fairly represent the heat emission properties of small airtight stoves. As an example, the methodology is finally applied to a test case, here a typical detached passive house.

INTRODUCTION

Wood stoves could be an attractive solution for the space heating (SH) of passive houses. They could indeed combine low CO_2-emissions, acceptable energy efficiency and cost effectiveness. In fact, the investment in a wood stove is relatively low compared to other environmental-friendly SH techniques, a quality that is proved to be important to ensure cost effectiveness in very-low heating demands (Georges 2012). Nevertheless, the question of the proper integration of wood stoves is rather new and still open. The case of *hydro-stoves* is not considered here. Stoves that only emit the delivered heat to the ambiance is addressed. The question of the stove integration in passive houses is then particular due to following constraints:

- **Oversizing and cycle length:** As many SH systems, the wood stove is oversized compared to the losses of the passive envelope. For example, the envelope has typical nominal losses of ~2kW while the minimal available nominal power (Pn) of wood stove is about 6-8kW. Furthermore, the power modulation is typically limited to 30-50% of Pn (depending on the stove technology). Even using power modulation, oversizing is thus present. Finally, an on/off cycling strategy cannot be applied to reduce the power: wood stoves need long production cycles to reach their best performance, in terms of energy efficiency, but also to limit the emissions of pollutants. Typically, the minimal cycle length should larger than ~30min for wood pellets and ~45min for one wood-log batch.
- **Single emitter:** Ideally, a single stove should be able to perform the SH in a passive envelope. In this way, it promotes the cost effectiveness through the simplification of the SH system, which is the basic concept of the passive house (Feist 2005).

These two features lead to severe issues in terms of thermal comfort, respectively:

- **Overheating:** The oversizing combined with the minimal cycle length could lead to overheating in the thermal zone where the stove is placed.
- **Temperature default:** A single heat source should ensure the thermal comfort within the entire envelope. Then, a temperature default may arise in the coldest rooms of the house.

The present work is the continuation of a research work where the integration of wood stoves in passive envelopes was investigated (Georges 2011a, Georges 2011b). Nevertheless, the present paper investigates more on the model quality and the resulting thermal comfort assessment. The article first presents the stove and building models. The stove model accuracy is then compared to more detailed simulation approaches. Finally, the complete methodology is applied to a typical passive house typology in order to illustrate the potential of the approach.

STOVE MODEL

Originality

Research has already been performed in order to develop reliable simplified wood boiler models for dynamic simulations (Persson 2009, Haller 2011). These models mainly evaluate the boiler efficiency, characteristics of the fumes and the emissions of pollutants. In particular, the model of Persson et al. (Persson 2009) can also be applied for small wood-pellets stoves. In this model, based on system theory and experiments, the stove thermal mass is modelled using a single capacitance while the combustion process is assumed instantaneous. The present work follows these two assumptions while a special effort is here performed to evaluate the heat emission properties and the resulting thermal comfort.

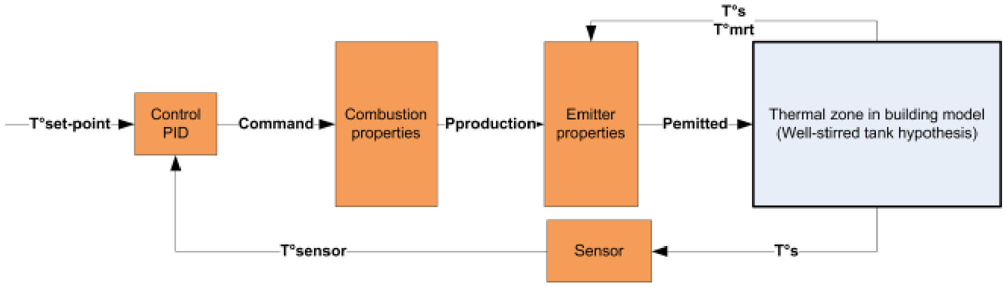


Figure 1: Loosely-coupled modelling approach where functions covered by the stove model are coloured in orange while the building model is coloured in grey.

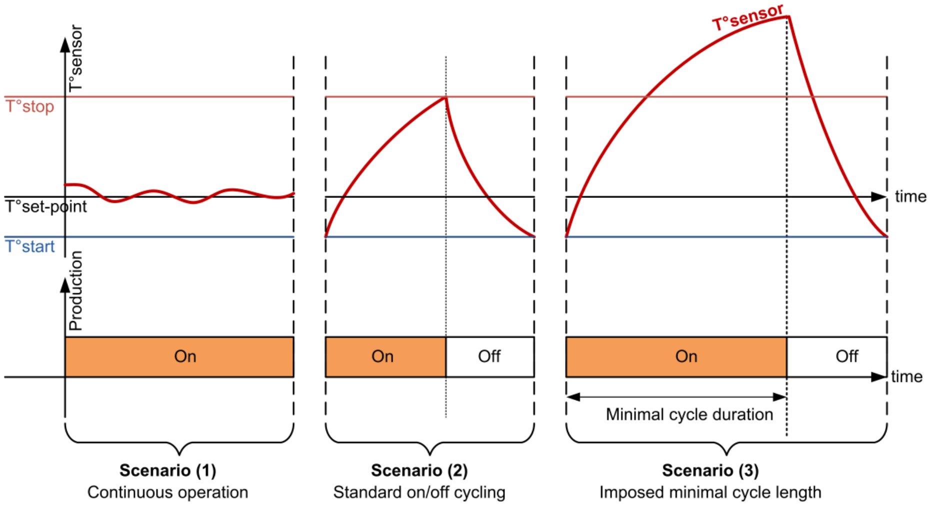


Figure 2: Stove control strategy and stove limitations: Scenario (1) is the ideal control case without limitation, Scenario (2) introduces the power modulation limits and Scenario (3) also enforces a minimal cycle length.

This last objective was also followed by Ghaddar et al. (Ghaddar 2006) but their space-heat model was not aimed to be integrated directly in a dynamic simulation tool.

Stove simplified model

The principle of the stove modelling is shown on Figure 1. For the sake of simplicity, the stove and the building models are **loosely coupled**. In other words, the stove is not "*physically*" integrated in the building model. Its action is mimicked by the injection in the building zone of an internal gain equivalent to the power emitted by the stove. Accordingly, the building model does not influence directly the stove model. For instance, the stove model does not know all the walls temperature of the zone. In fact, the power emitted by the stove is computed only using the air sensible temperature of the zone (Ts) as well as the global mean radiant temperature of the walls (Tmrt). The model of state-of-the-art airtight stove for low-energy houses can be summarized in the following way:

- Ts is compared to the set-point temperature and a PID controller gives the command applied to the combustion process. The PID parameters are here tuned using a *Ziegler-Nichols* step response method.
- The combustion process is here assumed instantaneous: the power transferred from the combustion to the stove thermal mass is adapted directly as a function of the PID command. This assumption is more representative of wood-pellets than wood-logs combustion (as this last process may have physical timescales comparable to the dynamics of the room). Finally, the model does not evaluate the stove efficiency and its emissions of pollutants.
- As a starting point, the stove heat dynamics is modelled using a single capacitance. Therefore, the model can currently only be applied to stoves with an envelope temperature that can be considered as uniform : it is then not meant to be applied for large heat storing stoves (Saastamoinen 2005) or stove with complex envelope configurations. No direct radiation from the combustion chamber or a flame towards the room is considered in the model.
- The power emitted by the stove surface by convection (Qc) is obtained using the well-known Churchill and Chu correlation for laminar and turbulent flows over an isothermal plate (Churchill 1975). Given the temperatures and characteristic lengths considered here, the

correlation for the convection coefficient is further simplified into: $h_{stove}^{conv} \approx 1.22(T_{stove} - T_s)^{1/3}$.

- The power emitted by the stove surface using radiation (Qr) is here evaluated simply by assuming that the stove is very small compared to the room: $Qr \approx \sigma A \varepsilon \, (T_{stove}^4 - T_{mrt}^4)$, where σ is the *Stefan-Boltzmann* constant, ε the emissivity of the stove and A its surface.
- Once the convective and radiative powers of the stove are evaluated, equivalent internal gains are injected into the building model. The Qc is applied to the zone air-node while Qr is distributed among the walls of the room as a function of the view factors (from the stove to the different walls).
- As many stoves developed for super-insulated envelopes, the stove is here assumed airtight, extracting its combustion air directly from the outside using a proper air-intake duct. Then, the stove does not use the air from the building envelope and does not interact with the balanced mechanical ventilation.

Stove control

Two main limitations of the stove are introduced by the way of the PID control as shown in Figure 2:

- If the combustion power can be modulated continuously from 0 to Pn, the PID controller is able to track the set-point temperature and the stove operates continuously to counterbalance the envelope losses (see Scenario 1).
- First, the limitation of the minimal combustion power is mimicked by a saturation of the PID at this minimal stove power (Pmin). If the zone heat losses are lower than Pmin, the stove starts to cycle between a start and a stop temperature, for example set as 20° and 22°C, respectively (see Scenario 2).
- Second, the minimal cycle length of production (to ensure the optimal operation of the stove) is also enforced in the control. The stove is only stopped if the stop temperature is reached AND if the stove has operated at least during a given period: the minimal cycle duration imposed by the model user (see Scenario 3).

Thermal comfort assessment

Another question is the evaluation of the thermal comfort in the room containing the stove. Without loss of generality, the thermal conditions are here *transient* with an *asymmetric* radiation field that could be strong close to the stove. Under these conditions, it has been shown that the classical overall thermal comfort models based on the Fanger's approach are not suitable (Cheng 2012). These models indeed consider the thermal environment as steady and uniform. It is typically the case of the EN ISO 7730 (CEN 2005). Even though this standard proposes a correction for the radiant asymmetry, the scope of validity is not compatible with the present case.

Assessing the local thermal comfort asks for more advanced models that are often not compatible with the level of simplicity aimed here. For example, Ghali et al. investigated the effect of stove asymmetric radiation field using a bioheat model (Ghali 2008). They nonetheless showed that an overall comfort criterion is enough accurate far from the stove to assess the thermal comfort. Close to the stove, they have shown that there is a region where the radiant asymmetry causes a local discomfort while the global comfort criterion is still respected. In this case, it demonstrates the need for a local comfort assessment in vicinity of the stove.

In the present work, the thermal comfort is based on the mean radiant temperature (Tmrt) and air temperature (Ts). The Tmrt is evaluated using view factors that are function of the occupant location in the room. As a first estimate, the direct radiation of the stove is not integrated (as the coupling between the stove and building models is loose). Nevertheless, the user can always integrate this effect afterwards using the stove surface temperature (if the application requires it). Finally, the thermal comfort is assessed globally using the operative temperature, the PMV or PPD (CEN 2005).

Scope of the model

The present model aims to evaluate the thermal comfort at a distance where the effect of the radiation asymmetry is negligible, and where the effect of the direct radiation from the combustion chamber is negligible. Furthermore, it considers that the stove envelope is isothermal, airtight and does not take its combustion air from the room. Finally, the combustion process is supposed to be instantaneous, an assumption that is quite well accepted for pellets.

The model can be further improved to remove these limitations. Furthermore, if the local thermal comfort close the stove should be evaluated, another kind of models and tools must be applied (Ghali 2008, Cheng 2012), models that are not directly compatible with the relative simplicity of detailed dynamic simulation tools (e.g. TRNSYS). In theory, these advanced models could be applied as post-processing tools using, as inputs, air and wall temperatures computed from the dynamic simulation.

BUILDIND MODEL

The building thermal dynamics is simulated using a detailed multi-zones approach (here using TRNSYS 17). Even though this model can incorporate stratification, a single air-node is only applied for each zone (i.e. well-stirred tank hypothesis).

Ventilation model

In terms of ventilation, a constant air volume (CAV) strategy is considered. It is representative of passive houses equipped with a balanced mechanical ventilation.

The flow rates are evaluated during the simulation using an embedded ventilation network model (here TRNFLOW), and this, in order to capture the natural convection induced by temperature gradients. Indeed, the temperature mixing within the envelope could be significantly increased if doors within the building are open. In this case, the flow through the open doors will be modelled using a *large opening* approximation (Etheridge 1996).

The standard hygienic airflow rates are enforced through the appropriate calibration of the flow dampers position in supply and exhaust rooms. These positions are kept fixed throughout the simulation.

An important parameter in the ventilation network model is the discharge coefficient (Cd) to be applied to doors inside the building. Heiselberg et al. made a review of the measured Cd for doors and found values ranging from 0.4 to 0.8 (Heiselberg 2003,Heiselberg 2006). The authors suggested that this large discrepancy in Cd could be simply explained by the rough assumptions lying behind the large opening model (e.g. one dimensional flow connecting two large isothermal rooms seen as infinite reservoirs). The present approach proposes to apply a sensitivity analysis, comparing results using Cd ranging from 0.4 to 0.8 and using a medium value of 0.65 (often encountered in the literature).

Wall composition and thermal mass

The thermal comfort is strongly related to the accessible internal thermal mass. During operation, the higher the thermal mass, the higher the amount of heat delivered by the stove can be stored in the walls. It could prevent from quickly reaching an overheating when the stove is oversized. In the methodology, different wall compositions are considered in order to span a large range of internal thermal masses. The heaviest solutions typically use masonry while the lightest use a wooden structure.

The thermal insulation in internal walls, often installed to reduce for acoustic transmission, has also a strong influence on the way the heat will diffuse within the building (i.e. from the room containing the stove to other rooms). In general, the lightest solutions are characterized by the higher internal thermal insulation.

In terms of envelope performance, the building model should comply with the particular passive house standard enforced in the country considered. Furthermore, the local official assessment method to establish the building composition should be used, e.g. the PHPP (Feist 2007) for Germany or Belgium.

MODEL VALIDATION

The stove model integrates strong simplifications. In terms of heat emission, one may wonder how accurate is a method combining the loose coupling, convective coefficients evaluated using correlations and a simplified radiation computation. The present section investigates these questions by comparing the present approach to other models, models that are more refined (i.e. capturing the physics more properly).

This comparison is made possible here because all the simulation methods are applied to one simplified problem: the stove surface temperature, the air and walls temperatures are evaluated for a same room in a building in **steady-state regime** during design outdoor weather conditions:

1. The first model is exactly the same simulation set-up but where the stove surfaces are directly integrated into the building model. A wall gain equivalent to the power emitted by the stove is introduced at the back of the stove wall. This is a **strongly coupled** approach where the stove walls are taking directly part, with the other room walls, to the radiation computation.
2. The second approach considers a **CFD** of the living room including the stove (here using FLUENT). Heat conduction in walls is modelled using *thin shell elements* that use, in steady-state conditions, the same wall modelling as in TRNSYS (i.e. one-dimensional conduction model). Boundary conditions around the room, i.e. constant temperatures, are extracted from the steady-state solution of the TRNSYS simulation. Given the high Rayleigh number, the simulation converges to a steady-state regime using an URANS method (using the RNG k-ε model). The radiation is quite detailed as the radiosity is computed for each boundary mesh element (here using the so-called S2S algorithm). The 1.1 1^{06} nodes mesh is here composed of tetrahedra.

In all 3 cases, the solar and internal gains are assumed null, as it is often done for the assessment of the heating system in design outdoor weather conditions.

Building geometry and simulation set-up

A benchmark building geometry has been created (Georges 2011a,Massart 2011). It is a detached single-family house representative of the Belgian market. The building has two storeys with a net heated surface of 150 m². The envelope has a protected volume of 420 m^3, 360 m² of transmission surfaces including 35 m² of tripled-glazed windows. A picture of the house and its internal organisation is shown on Figures 3, where the South direction is pointing upwards.

Two energy performance levels of the envelope are considered. First, the envelope is complying with the Belgian passive house standard. This includes the envelope insulation, the airtightness and the balanced mechanical ventilation equipped with a heat-recovery unit (here using an efficiency of 0.85). Second, the envelope has the minimal Belgian EPBD requirements valid before 2010 (Walloon government 2008). The building is there equipped with a natural ventilation.

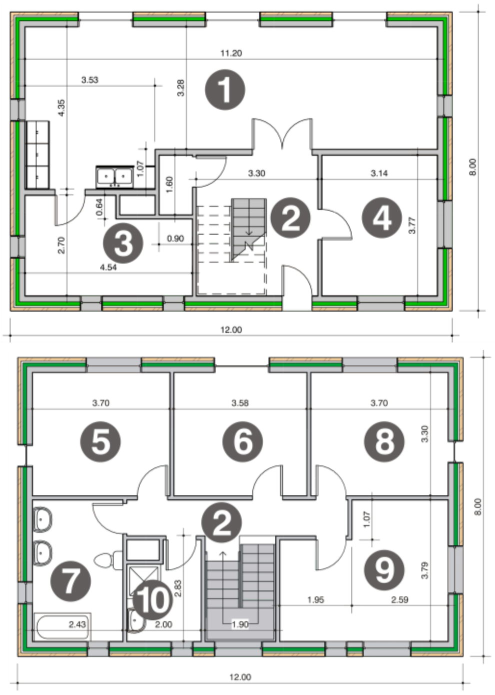


Figure 3: Sketches of the first and second floors, respectively: kitchen and living room (1), corridor (2), laundry (3), office (4), bedrooms (5-6-8-9) and bathroom (7-10).

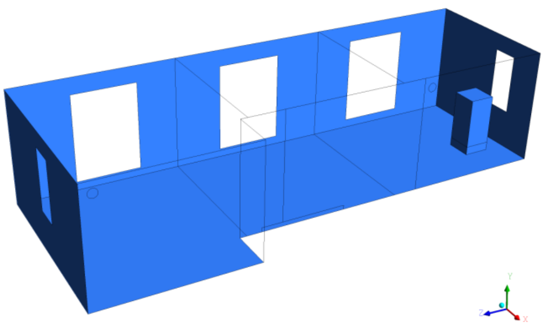


Figure 4: Living room and stove geometries for the CFD computation.

In the first case, a stove of 2kW is able to maintain a temperature of 20°C in the living room while, in the EPBD case, the power is 5.06kW. The geometry of the stove is a box with a basis of 0.6m x 0.6m and a height of 1.2m. Its surface emissivity is 0.9 and is 0.8 for the room surfaces. The comparison between models focuses on the thermal comfort and the stove temperature. The doors of the living room are assumed closed. The mean radiant (Tmrt) and operative temperatures (Top) are evaluated for two locations: a distance of 2.5m and 8.2m away from the stove, termed *close* and *far* locations respectively.

Model comparison

The Table 1 summarized the temperatures found for the 2kW stove in the passive house test case. The overall agreement between results is good. For instance, the rather similar stove temperatures prove that the way to evaluate the heat flux for the convection and radiation is enough accurate using the loosely-coupled approach.

In particular, the loosely and strongly-coupled approaches give comparable results, in terms of Ts and Tmrt. It proves that the decoupling gives acceptable results. Furthermore, a difference is made in the loosely-coupled approach where the Tmrt is evaluated both with and without including the radiation of the stove (respectively termed *std.* and *corr.* in Table 1). The difference is only 0.5°C close to the stove and is negligible far from the stove.

The absolute value of the temperature for the CFD should not be compared directly with the TRNSYS results. For example, it is difficult to get exactly the same wall resistances between the two approaches. The CFD results indeed show an average temperature level that is higher than the TRNSYS runs. The most important is to check the relative variation of the temperatures within the room. The agreement between approaches is then quite good. The CFD show a good mixing within the room so that the air temperature is not very different far and close to the stove (see Figure 5). Nevertheless, a significant temperature stratification appears in the vertical direction. The temperature gradient is more pronounced in the vertical direction than in the horizontal one. Stratification is not accounted for in the stove model.

Table 1: Computed steady-state temperatures for the 2kW stove in the passive house test case.

METHODS	LOOSE-C		FULL-C.	CFD
Tstove	74.1		74.9	72.8
Position: 2.5m				
Ts	19.7		19.7	[19.2;22.3]
Tmrt (std. | corr.)	19.5	20.2	20.0	20.9
Top (std. | corr.)	19.6	19.9	19.9	[20.0;21.6]
Position: 8.2m				
Ts	19.7		19.7	[19.1;22.3]
Tmrt (std. | corr.)	17.3	17.4	17.4	17.9
Top (std. | corr.)	18.5	18.5	18.5	[18.5;20.1]

Std. = without stove contrib to Tmrt./ Corr. = with stove contrib

Table 2: Computed steady-state temperatures for the 5.06kW stove in the EPBD house test case.

METHODS	LOOSE-C.		FULL-C.
Tstove	129.4		130.1
Position: 2.5m			
Ts	21.6		21.5
Tmrt (*std.* | *corr.*)	22.2	23.7	23.7
Top (*std.* | *corr.*)	21.9	22.7	22.6
Position: 8.2m			
Ts	19.7		19.7
Tmrt (*std.* | *corr.*)	17.3	17.4	17.4
Top (*std.* | *corr.*)	18.5	18.5	18.5

Std. = without stove contrib to Tmrt./ Corr. = with stove contrib

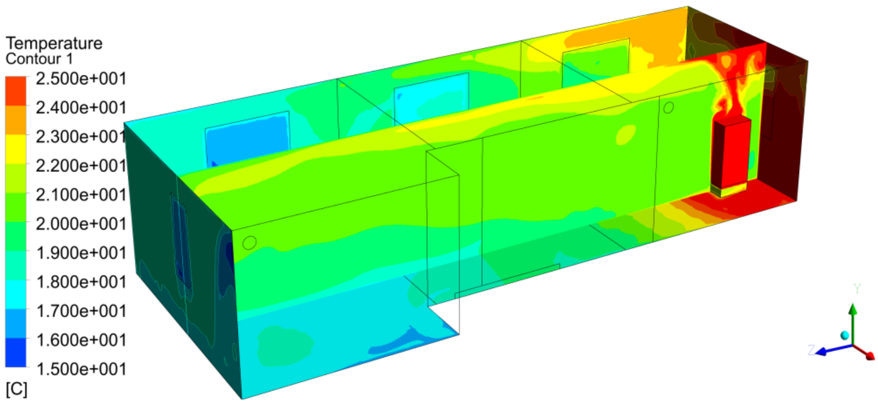


Figure 5: Snapshot of the unsteady temperature field computed by a CFD for the passive house test case. The temperature is shown on the internal faces of the walls and along a longitudinal cut-plane (the colour scale is saturated outside the range of 15° to 25°C).

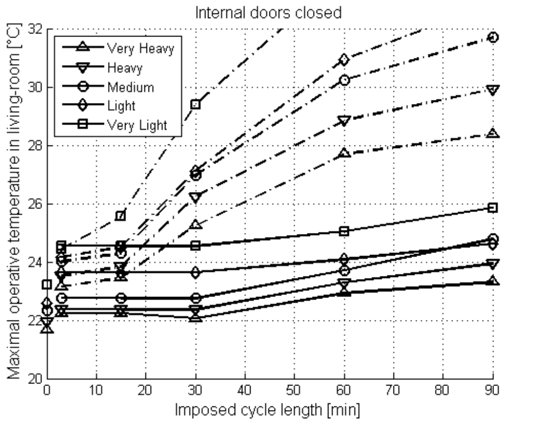
In Table 2, results for the EPBD test case and the stove of 5.06kW confirm these conclusions. CFD results are not reported for this case. As expected, the variation of thermal comfort with distance to the stove is more pronounced with an increased stove power.

Even though the model presents limitations, one may conclude that it captures the physics with enough accuracy to be able to reach the present research objectives. Indeed, the model should at least be able to detect critical configurations where the stove could generate pronounced overheating.

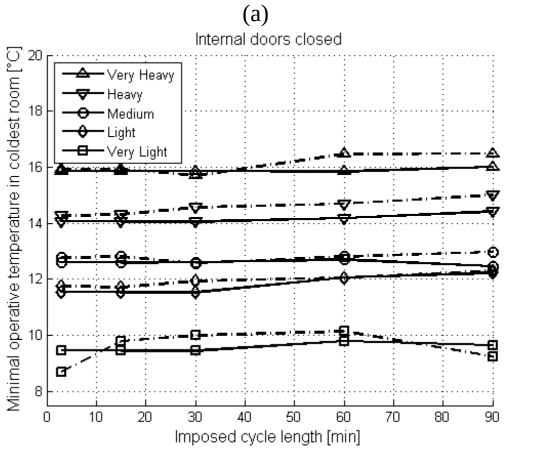
TYPICAL APPLICATION

As an example, the methodology is now applied to investigate a stove integration in the benchmark Belgian passive house (see previous section). TRNSYS are performed using the loosely-coupled stove model. A full year is simulated using a time step of 1min and a typical meteorological year (TMY2) for the city of Uccle (Belgium). Time-varying internal gains have an average value of 2.1W/m² as in the passive house standard. Five walls compositions are considered, see (Georges 2011a). Following the EN ISO 13790 (CEN 2008), they range the five levels of internal mass from *very light* to *very heavy*. Furthermore, the lower the thermal mass, the higher the internal thermal insulation. The investigated pellet stove has a Pn of 8kW and small thermal mass of 50kJ/K. Two levels of power modulation are considered: Pmin = Pn (i.e. no modulation) and Pmin = 0.3Pn. The set-point temperature in the living-room is 20°C and start/stop temperatures are 20°C/22°C. No pre-heating of the ventilation air is here considered after the heat recovery unit. The quality of the stove integration is here monitored using the maximal overheating found during the heating season in the living room (Figures 6.a. and 7.a.) and the minimal temperature found in the building during the heating season (Figures 6.b. and 7.b.). This coldest temperature is found in a bedroom (i.e. zone n°9 in Figure 3). The abscissa in these graphs represents the minimal imposed cycle length (see principle in Figure 2). For the maximal overheating, results obtained using a perfect heating is plotted on the ordinate axis: it clearly shows that solar and internal gains already produce temperature overshoots during the heating season.

Internal doors closed



(a)



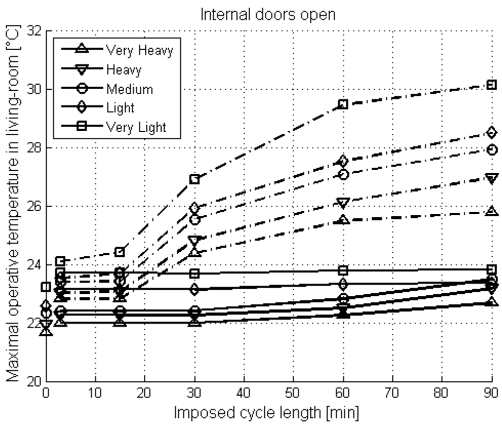
(b)

Figures 6: Maximal (a) and minimal (b) operative temperatures during the heating season considering ***closed internal doors*** *and five different thermal masses: stove 30% modulation (solid lines) and without modulation (dash-dotted lines).*

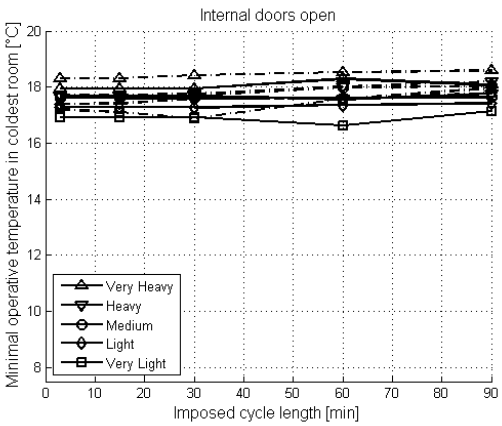
Figure 6.a. clearly shows that higher the internal thermal mass, the lower the overheating. The overheating increases quickly with the cycle length if the stove has no power modulation, while with 30% of modulation, the stove is able to maintain an acceptable thermal comfort for long production cycles. If the stove cannot modulate, the building thermal mass cannot prevent to reach overheating.

Figure 6.b. shows that the minimal operative temperature found in the building is not dependant on the stove properties (i.e. the cycle length or power modulation properties). In fact, it depends essentially on architectonic properties (here the internal thermal insulation): the lower the internal thermal insulation, the higher the minimal temperature and better the thermal comfort. On the contrary, a high internal thermal insulation leads to quite low temperatures (i.e. 10-13°C) which can be regarded as unacceptable. In this case, an additional process should be found in order to better homogenize the heat within the envelope. It leads us to consider the case where internal doors in the building are open.

Internal doors open



(a)



(b)

Figures 7: Maximal (a) and minimal (b) operative temperatures during the heating season considering ***open internal doors*** *and five different thermal masses: stove 30% modulation (solid lines) and without modulation (dash-dotted lines).*

Results for a door discharge coefficient (Cd) of 0.65 are reported on Figures 7. The opening the internal doors reduces the overheating in the living room. Nevertheless, the stove without power modulation seems again to be unacceptable. To the limit, one may accept this approach with a high internal thermal mass. In this case, the computed overheating is approximately 26°C for cycles of 60 to 90min. As a conclusion, using a 8kW pellet stove with a small thermal mass, the power modulation remains an important aspect to prevent overheating. Figure 7.b. gives very interesting results. Compared to Figure 6.b. where the doors are closed, it seems that opening the internal doors is a very efficient process to distribute heat in the building. The minimal operative temperature is then limited to 17-18°C for all the internal thermal insulation considered. This temperature range may not be acceptable for all users. Nevertheless, a slightly lower temperature in a bedroom is said to be often appreciated by occupants. If so, simulations show that the proper integration of a 8kW pellet stove in a passive house could be possible.

CONCLUSION

The proper integration of wood stove in passive houses is still open. As existing wood stoves are oversized for passive houses and need to operate on long production cycles, it is important to check if no overheating occurs. Furthermore, one can expect that only one wood stove can ensure the thermal comfort in the complete envelope during the heating season, including in bedrooms. It is well in line with the passive house concept where the SH distribution sub-system is simplified to reduce costs.

In order to address these questions, a low-resolution dynamic model has been developed for small airtight stoves devoted to low-energy houses. Even though simple and relying on many assumptions, the article showed that the model seems to capture fairly the thermal comfort far from the stove. Furthermore, the article proposes a baseline modelling of the stove envelope but this one can be easily extended in order to better mimic a specific stove configuration (e.g. large storing mass). In practice, the modelling approach should be able to give reliable insight into the whole-year thermal behaviour produced by a stove heating. After the detection of the critical cases using the low-resolution approach, a more detailed assessment of the thermal comfort can then be applied. Nevertheless, it requires other simulations techniques that are more complex and computationally more expansive (e.g. local comfort assessment using CFD).

As an illustration of the model potential, the approach is also applied to the integration of a 8kW pellet stove in a passive house. Results show that a stove 30% power modulation is an important parameter to prevent overheating. The building thermal mass could also reduce the overheating but this effect alone is not expected to be always enough to enforce the thermal comfort. Regarding the minimal temperature found in the building, this value is driven by the architectonic properties, as the internal thermal insulation, and seems to be rather independent of the stove properties (i.e. power modulation or minimal cycle length). The higher the internal thermal insulation, the lower the thermal comfort. If this thermal insulation is high and internal doors closed, unacceptable temperature may occur in the envelope (e.g. 10-13°C). Nevertheless, simulation results show that opening the internal doors in the building is an efficient process to distribute heat within the envelope. In this case, the minimal temperature then ranges from 17 to 18°C.

As a conclusion, simulations show that the integration of a 8kW pellet stove in a passive house seems feasible. The test case also demonstrates that the number of relevant physical phenomena and parameters to be investigated is large so that a low-resolution modelling approach is indeed required before a more detailed assessment of the thermal behaviour could be applied.

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