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The Process of Batch Combustion of Logs in Wood Stoves – Transient Modelling for Generation of Input to CFD Modelling of Stoves and Thermal Comfort Simulations

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CFD modelling of wood stoves are a challenge due to the transient behavior of the combustion process, due to their batch combustion principle. Various initial and boundary conditions needs to be specified to carry out a CFD simulation of a wood stove, and many of these will be a result of sub-models that again can be partly based on experimental results. This paper deals with these boundary conditions and the generation of representative values for these as input to stationary and transient CFD simulations throughout the batch combustion process as well as thermal comfort simulations. Additionally, heat production profiles and stove wall properties are needed to calculate heat release profiles to the room in which the stove is placed. These heat release profiles are essential input for evaluating the thermal comfort of wood stoves in houses, a subject which has received considerable attention recently as energy efficient houses are increasingly introduced.
Necessary boundary conditions relates to the fuel and air introduction into the computational domain and the thermal and radiative properties of the surfaces within and enclosing the computational domain. In addition initial conditions must be specified as starting point for the transient models generating the boundary conditions at any time in the batch combustion process. The ultimate goal would be to carry out transient CFD simulations where the boundary conditions are derived for each new stationary simulation based on the results from the previous time step. The choice of models and the degree of detail of these regarding e.g. the handling of the gas phase chemistry are very important. In this paper a feasible modelling approach is presented that together with experiments could be used to cost-efficiently design future's high performance wood stoves.

1. Introduction

Poor wood stove technology and/or operation results in excessive and harmful emission of various compounds (van Loo, 2008). The main reason for this is the batch combustion principle utilized in these rather small combustion units, where the aim usually is direct space heating in a single room. Efficiencies in, and emissions from, wood stoves and fireplaces are greatly varying, for many reasons. In addition to the ultimate goal of stable heat release, the goal is also to achieve a highest possible overall energetic efficiency and the lowest possible emission levels. Considerable improvements in combustion performance and emission reduction have been achieved the last couple of decades due to new designs based on staged air combustion and improved control options. These improvements are primarily a result of experimental work, i.e. experience combined with trial and error, and not modelling and simulations. Combining experiments and modelling could be used to cost-efficiently design future's high performance wood stoves, which will need to comply with increasingly stricter demands towards emissions, efficiency and user-friendliness, and also heat comfort in future's energy efficient buildings.
For biomass particle combustion, such as pellets, wood chips and logs, the fuel conversion process consists of successive and overlapping processes, i.e. drying, pyrolysis/devolatilization, heterogeneous char

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conversion and homogeneous gas phase reactions. Three approaches of representing a bed of biomass particles are commonly applied; 1) assuming the fuel bed as a porous or packed zone (e.g. Scharler, 2009; and 2011); 2) representing the bed with a discrete number of sized particles, as a an empirical model based on experimental measurements (e.g. Scharler, 2001) or with a physical particle model (e.g. Galgano, 2006; Sand, 2008; Yang, 2008; Mehrabian, 2012; and 2014). Both can be coupled or un-coupled with the freeboard model. The first approach is physically more similar to that of pellet or wood chips combustion and the latter to that of wood log combustion; 3) empirical distributions for and from the bed based on either simplified physics or experimental data to describe the heat release and species formation as a function of time (e.g. Saastamoinen, 2006). Fixed-bed combustion simulation capabilities in CFD programs are often limited. Three main approaches are commonly taken; 1) use inlet conditions for the top of the fuel bed based on the experimental measurements; 2) develop a separate sub-model that calculates the temperature, species and velocity at the top of the fuel bed. The CFD code can then be coupled (e.g. Hajek, 2012; Mehrabian, 2014) with the bed sub-model, and the radiative flux emitted by the flame and furnace walls to the top fuel layer can be fed back for the next iteration of the bed model; 3) define a user defined sub-routine (UDF) within the CFD code, converging quicker than a separate bed-CFD coupled model, typically for parts of the model.
In principle, CFD calculations should be good enough for an increased understanding of the influence of design and process variables on the environmental and energetic performance of the wood stove. As such, CFD calculations of wood stoves are a very useful tool, however, demanding appropriate sub-models, process data and boundary conditions. Here, a feasible modelling approach is presented.

2. The models/system

The models that are needed to provide input to stationary or transient CFD calculations of wood stoves are basically connected to a fuel decomposition model taking into account the generation of volatiles from a specified fuel geometry through pyrolysis/devolatilization and the products of heterogeneous char oxidation/gasification. The transient fuel decomposition model must take into account drying, pyrolysis/devolatilization and its products composition and char oxidation/gasification and its products composition. The total products of the fuel decomposition must conform to an overall conservation of each fuel element in the batch combustion process as well as to energy conservation. The driving force for the fuel decomposition model is the transient heat flux to the fuel and its further time-delayed transfer inside the fuel geometry, creating drying, pyrolysis and char reaction fronts with characteristic temperatures at positions in the log dictated by both conditions around the log and the properties of the log itself. The complete oxidation of the fuel, with a certain transient excess air ratio, generates the heat production profile, where the major fraction of this is transferred through the walls (time-delayed) and the glass (directly by radiation) of the wood stove, to the room in which the stove is placed. This becomes the transient heat release profile to the room, an effect profile which ideally should be as flat as possible. The transient heat storage in the stove walls and their heat storage capacity becomes a possibility to dampen the heat release profile, which is important with respect to thermal comfort in a room/house. However, the stove walls/materials and their properties influence the temperature in the combustion chamber and consequently the heat flux to the fuel.
The modelling approach aims at estimating both the transient heat production and release profiles for different design, fuel and operating conditions, as well as generating needed input for CFD calculations, both for the stove itself and for thermal comfort simulations.

2.1 Transient fuel model for a single wood log

Wood logs are so-called thermally thick particles, where internal heat transfer is limiting the drying process and the decomposition rate of the volatile content. Hence, it’s necessary with models that can estimate the transient rate of drying and devolatilization, as well as the surface temperature and the gas composition escaping through the surface, and its temperature. Here, a 1D transient modelling approach is applied where the wood log is divided into 50 layers, with mass and energy fluxes passing the layer borders. An external heat flux to the surface is the driving force, which will vary through the transient wood log combustion process, since the combustion of the volatiles mainly provides the heat flux. As the surface is heated, the net heat flux to the surface is reduced accordingly. The internal energy flux taken into account during drying and devolatilization includes heat conduction and preheating of the water vapour from drying and the products of the devolatilization, assumed to be gaseous, before they leave the surface, here assumed at the surface temperature. This preheating will slow down the heat transfer into the wood log, together with the heat needed for moisture evaporation. As the incident heat flux on a wood log in a stove may also vary depending on the position of the wood log relative to the radiating flames, the 1D model is made so that two different incident heat fluxes can be applied, opposite to each other on the axial sides of the wood log. The length of the wood log is assumed to be significantly longer than the width, making it in principle possible to use a 1D modelling approach. As wood logs are inherently anisotropic with respect to the fibre direction and gases flow more easily in the axial direction, this is a simplification. Figure 1 illustrates the modelling approach.

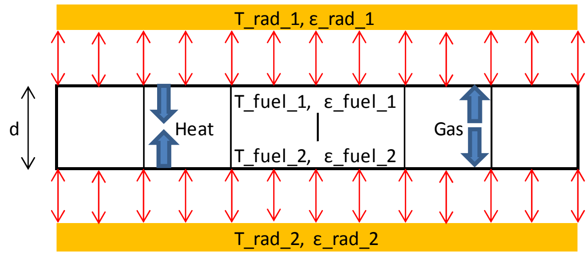

Figure 1: The modelling approach for the single wood log

A number of physical properties need to be included in the modelling approach, as well as kinetic parameters required in the Arrhenius expressions for the decomposition of the hemicellulose, cellulose and lignin in the wood. Physical properties values used in this work include; emissivities for the radiation source and the wood log surface; proximate and ultimate composition of the wood, elemental composition of the volatiles and char; chemical composition of the wood (hemicellulose, cellulose, lignin); densities; specific heat capacities; conductivities; and Arrhenius reaction rate constants (activation energy and pre-exponential factor) for hemicellulose, cellulose and lignin. Finally, a char conversion model is needed.

2.2 Single wood log modelling results

Here, an example of the capabilities of the model is presented, for a radiation temperature (the temperature of the radiation source, which is assumed to account for the heat transfer to the wood log surface) of 800°C (on both sides), an initial wood log moisture content of 20 wt% and a wood log width of 50 mm. Here, wood log shrinkage is not taken into account. Figure 2 shows the temperature evolution as a function of time and position (layer) for the base case. Here, all layers have the same width. The temperature in the outer layer increases rapidly towards the radiation temperature (their emissivities are assumed equal), while the intrinsic temperatures lags increase towards the centre of the wood log, due to conductive heat transfer limitations.

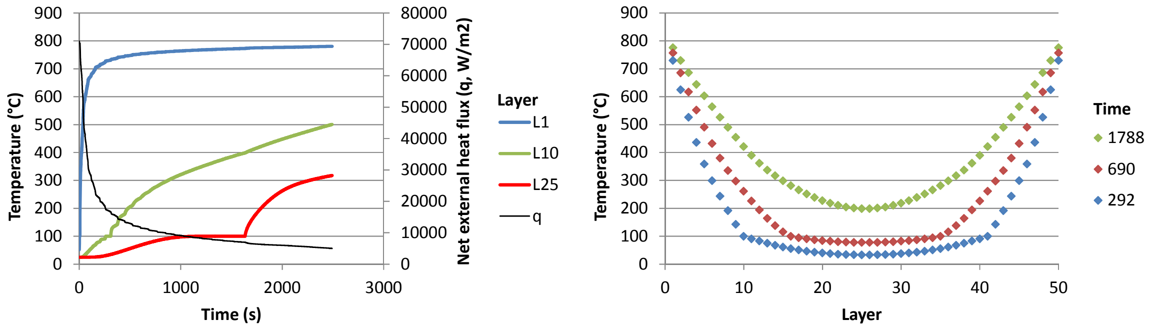

Figure 2: Temperature evolution as a function of time and position (layer)

2.3 Boundary conditions

In the wood log decomposition model, subject to an incident transient heat flux, drying and devolatilization take place and water vapour and volatiles are released from the wood log, to be combusted and thus contribute to the heat flux to the fuel. Heterogeneous char oxidation completes the conversion of the wood log, leaving ash behind. This transient conversion of the single wood log results in a transient heat production profile. Each single wood log in a batch can be modelled individually, stacked in some geometry in the combustion chamber, contributing to an overall transient heat production profile.

In a CFD simulation a number of boundary conditions are needed for a stationary simulation, and additional initial conditions for a transient simulation. The boundary conditions concern temperatures for all boundary surfaces, the surface emissivities, and the flow speed, direction and composition of all streams into the calculation domain. The emissivities of the surfaces must be set, as realistic as possible. Glass surface properties must also be included and set, if a glass is present (as it usually is). The air flow can be calculated for a specific air inlet configuration, knowing all the physical dimensions of the air inlets and the distribution of the air between primary, secondary and (usually) window flushing air, becoming tertiary air. This distribution will depend on the regulation of the air inlet valves, usually two valves, for primary air and secondary/window flushing air. If natural draft is applied it becomes trickier to calculate the amount of air entering the stove, as the draft needs to be established first. Forced draft by a fan makes it possible to set the air flow, to a value corresponding to a desired excess air ratio based on an expected wood log decomposition behaviour, or rather the transient oxygen need matching the desired excess air ratio. The temperatures of the inlet air are trickier when the air is preheated (as it usually is, but to varying degree) before entering the CFD simulation domain. Ideally, the calculation of air preheating should be included in the CFD domain, however, in practise this might be challenging. The single fuel model must provide the fuel gas amount and composition, while the fuel gas flow speed and direction are decided by the amount and the selected dimensions and method of treatment of the wood log surfaces. Of course, mass/elemental and energy balances must be satisfied for the computational domain.

If knowing the heat production from the fuel conversion and the fraction of this that is or needs to be transferred through the walls, simplified transient calculations for the (composite) walls of the wood stove can be carried out, which in addition to providing the transient heat release profile, also provides the wood stove wall temperatures. Such an approach can provide through an user defined function (UDF) the necessary wall temperatures either for transient CFD simulations or for a selected moment in time, for a stationary simulation.

Regarding the gas phase combustion of the fuel gas, chemical kinetics is required. This should be sufficiently detailed to enable pollutant formation studies, e.g. NOx and soot through soot precursors in the fuel gas. The computational time should also be minimised. In addition a turbulence-chemistry interaction model must be applied, as well as a radiation model. Figure 3 shows the modelling approach for the combustion chamber.

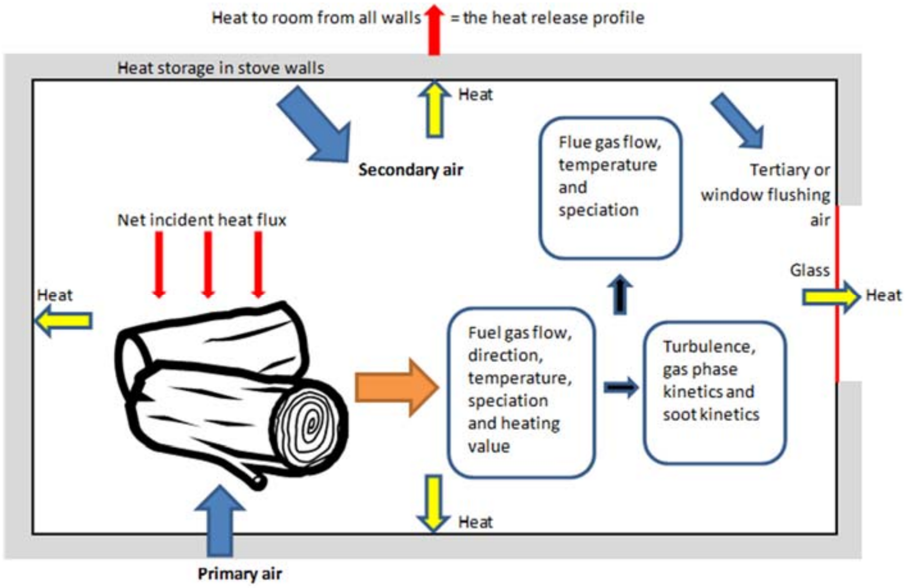

Figure 3: The modelling approach for the combustion chamber

The key factor in such a modelling approach is possibly the accuracy of the fuel model, providing the fuel gas related input. For the other input and models it is more a question of selecting the appropriate model level or detail to be able to carry out the CFD simulation within a reasonable time. The latter means that reduced or simplified models must be used when possible, e.g. for gas phase kinetics. However, too simple models give unreliable results. A trade-off optimum should be sought, which in practise can be rather difficult.

2.4 Transient fuel model for a batch of wood logs

Here, the single wood log model is taken further by modelling the thermal decomposition of a stack of wood logs inside a combustion chamber. For simplicity they are identical and go through an identical decomposition process, however, not at the same time. The wood logs are ignited one after the other, with a certain time interval. For the single wood logs, which are square with sides of 50 mm and having a moisture content of 20 wt% (wet basis), the heat flux is applied on all sides, i.e. the drying, devolatilization and char combustion fronts are moving towards the wood log centre line from each side with equal speeds. Results are shown in Figure 4 for the transient fuel decomposition rate and heat production profile and the fuel elemental composition for a batch of 9 wood logs placed into a bed of charcoal and igniting in series.

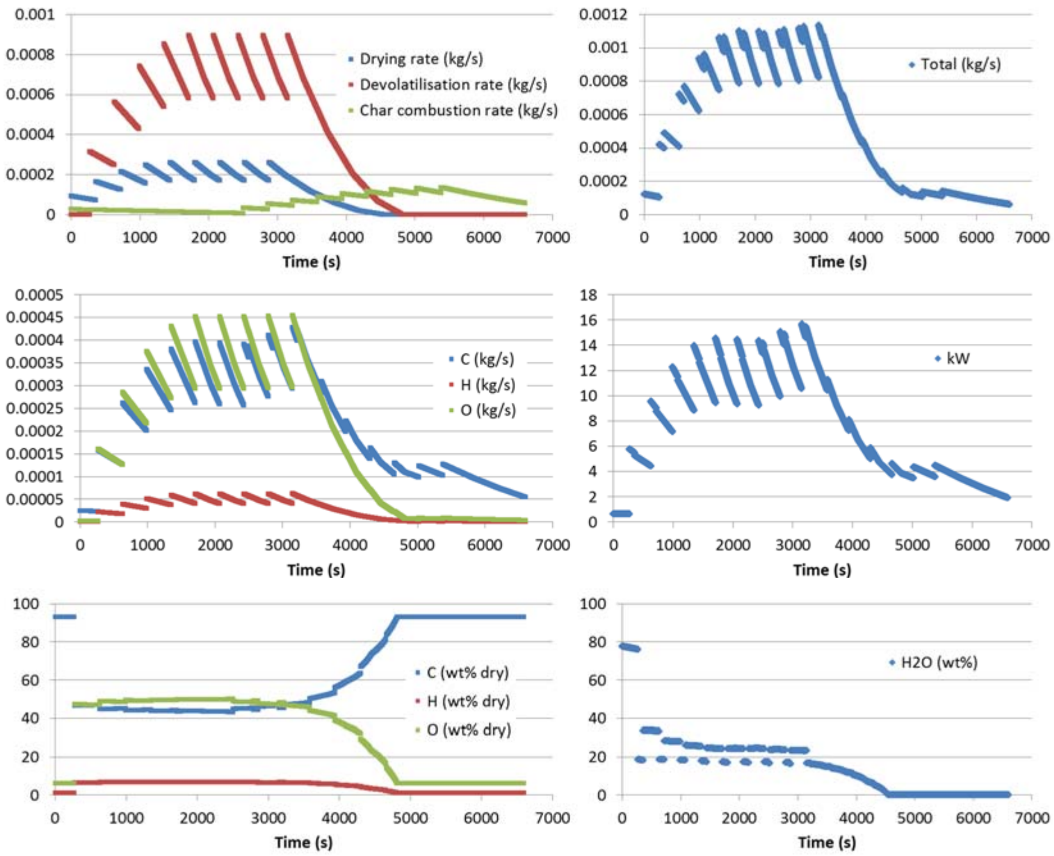

Figure 4: Transient heat production profile, drying, devolatilization and char combustion rates and fuel composition for a batch of 9 uniform wood logs placed into a bed of charcoal and igniting in series

2.5 Stove wall calculations

The heat production profile generated by the batch combustion process will be transferred through the stove glass if present and the stove walls, where typically composite walls are used in the combustion chamber and single material walls are used in the downstream heat transfer section. Depending on the heat storage capacity of the walls, there will be a time delay before the heat is released to the room in which the stoves is placed, giving the heat release profile. This heat release profile and the stove surfaces' temperature are essential input to thermal comfort simulations for future's energy efficient residential buildings of the single family type. A result example is shown in Figure 5 for the transient heat production and release profiles for a stove using phase change material (PCM) as a heat storage material in the outer wall layer (Skreiberg, 2013).

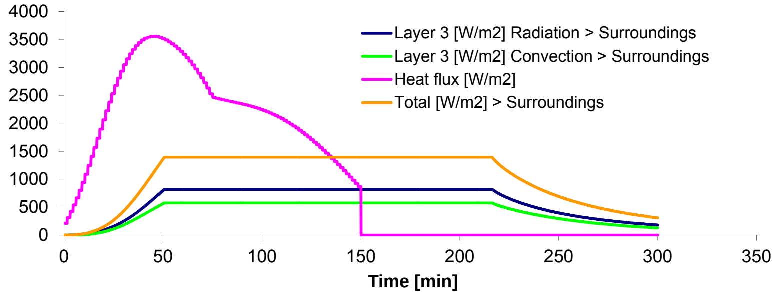

Figure 5: Transient heat production profile (heat flux) and heat release profile (total = convection + radiation to the room) for a wood stove with a composite wall containing a phase change material. Phase change material - Erythritol, 20 kWh fuel load, 8 kW net stove effect

2.6 Building integration modelling

Representative heat production profiles for wood stoves with different heat storage capacities and combustion cycle lengths have been generated for a large range of stove effects and have been used in two recent publications investigating the resulting thermal comfort in passive houses with different thermal inertia in both central European climate (Georges, 2013; Belgian context) and cold climates (Georges, 2014; Norwegian context, different climate zones). The results show that wood stoves do have a natural place also in future's energy efficient single family houses, however, proper measures must be taken to prevent overheating in the living room. Reducing the stoves' nominal effect and applying measures to flatten out the heat release profile, through improved combustion control and/or increased heat storage capacity, makes wood stoves very attractive also in this building segment.

3. Conclusions

In this paper, transient modelling of wood stoves has been discussed. Selected results have been presented and the link towards CFD simulations and generation of necessary boundary conditions for these has been discussed. The key factor in the modelling approach is possibly the accuracy of the fuel model, providing the fuel gas related input. For the other input and models it is more a question of selecting the appropriate model level or detail to be able to carry out the CFD simulation within a reasonable time.

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