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Validation of a dynamic model for wood pellet boilers and stoves

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ABSTRACT

Optimising systems with wood pellet boilers or stoves using simulations requires realistic computer models. The objective of this work was to develop and verify a mathematical model for wood pellet boilers and stoves for use in system simulations with the dynamic simulation programme TRNSYS, calculating both the energy balance and the CO-emissions (carbon monoxide emissions). Laboratory measurements have been carried out and a mathematical two-node model was developed and implemented as a TRNSYS component. Parameters were identified and the model has been compared with measurements. The model shows in general good agreement with measured data, however there are details that could be improved. This involves improved modelling of the dynamic response for boilers with large water volumes and improved modelling of the air factor and the CO-emissions, especially during start and stop conditions. Further improved methodology and accuracy for measuring and parameter identification is recommended.

1. Introduction

In this work, the development and verification of a model for simulation of small pellet boilers and stoves is described. The model is intended for dynamic simulations of small heating systems with time steps in the range of 0.1–1 min using the dynamic simulation programme TRNSYS [1] and has been given the number Type 210. The market for wood pellet heating systems has developed strongly during the last 10 years, but wood pellet heating technology is a relatively new technology for house heating. The major difference, from a system perspective, to oil and gas burners is that the ignition takes much longer time and that there is a considerable amount of emissions during this period [2,3]. Studies [4,5] have shown that emissions at start and stop are significant also in gas and oil boilers. There are obligatory limit values for emissions from pellet boilers and stoves [6]. These however, are based on steady state measurements. The main aim of developing the model was to make it possible to make calculations of average efficiency and emissions from complete systems on an annual basis as the literature suggests that standard emissions labelling underestimates total emissions in real conditions.

An inventory [6] shows that emission regulations and labelling organisations concern emissions from operation on full load and on part load (often 30% of full load). The start and stop emissions are usually not considered in the labelling, but may be included to some extent if the part load tests requires the boiler to start and stop. Refs. [7,8] show that the carbon monoxide (CO) emissions during start and stop periods are often the dominating source of emissions from systems operated under realistic conditions.

Konersman et al. [9] have investigated a commercial combined solar and pellet heating system. Lab tests and system simulations using the TRNSYS model from Haller [10] led to suggestions for modifications of the control and the hydraulics of the system that improved the system performance and reduced the emissions of the boiler. Chasapis et al. [11] have studied a combined solar and pellet heating system manufactured in Greece. The results showed that the boiler had a low efficiency due to the overdimensioned size and the non-optimised use with wood pellet fuel. Furthermore, the control of the boiler required substantial improvements.

Simulation results from [7] using the TRNSYS model from Haller [10] show that the annual emissions of CO and hydrocarbons from a wood pellet boiler can be more than halved by increasing the buffer store volume. Simulations with TRNSYS Type 210 [8] show that it is possible to almost halve the CO-emissions if the pellet heater is combined with a solar heating system. This reduction is mostly due to a reduced number of starts and stop. The results also show that the CO-emissions of existing combined solar and pellet heating systems can be drastically reduced if the pellet heater is properly controlled and some basic design rules are observed.

Pettersson et al. [12] measured the emissions and efficiencies of five different pellet boilers during summer conditions with only domestic hot water load. The boilers that operate with a pilot flame have in general much higher emissions than the boilers applying electrical ignition. The emissions of carbon monoxide are 6–13 times higher for the boilers with a pilot flame and the corresponding values for organic gaseous carbon are 20–60 times higher. For

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Nomenclature

A_f	theoretical air to fuel mass flow ratio at stoichiometric combustion conditions (kg humid air/kg humid fuel)
B_{mod}	operation mode
$c_{p,g}$	average flue gas specific heat (J/(kg · K))
$c_{p,wat}$	specific heat of water (J/(kg · K))
D_{CO0}	CO-emission per fuel equivalent at $\gamma = 0$ (kg/J fuel)
D_{CO1}	CO-emission per fuel equivalent at $\gamma = 1$ (kg/J fuel)
K	coefficient for calculation of flue gas density (kg · K/m^3)
K_{dry}	coefficient for calculation of flue gas density (kg · K/m^3)
LHV	lower heating value of fuel (J/kg)
m_1	thermal mass of mass 1
m_2	thermal mass of mass 2
$\dot{m}_{air}$	combustion air mass flow (kg/s)
$\dot{m}_{air50}$	air leak flow rate at (T_{g2}–T_{outd}) = 50 °C (kg/s)
$m_{C,fuel}$	mass of carbon in the fuel (kg)
m_{CO}	CO-emissions (kg)
$\dot{m}_{CO}$	mass flow rate of CO-emissions (kg/s)
$m_{COstart}$	mass of lumped CO-emissions during start phase (kg)
m_{COstop}	mass of lumped CO-emissions during stop phase (kg)
m_{fuel}	mass of pellet fuel (kg)
$\dot{m}_{fuel}$	mass flow rate of pellet fuel (kg/s)
$\dot{m}_g$	flue gas mass flow rate (kg/s)
$m_{H_2,fuel}$	mass of H_2 in the fuel (kg)
$m_{N_2,fuel}$	mass of N_2 in the fuel (kg)
m_{steel}	mass of steel in the boiler (kg)
m_{wat}	mass of water in the boiler (kg)
n	number of start (–)
n	number of stop (–)
P_{cmb}	current combustion power (W)
P_{cmbsta}	P_{cmb} during second part of start phase (W)
P_{cmbstp}	P_{cmb} during the 5 min before a stop (W)
P_{el}	current electrical power consumption (W)
P_{el0}	P_{el} at $\gamma = 0$ (W)
P_{el1}	P_{el} at $\gamma = 1$ (W)
P_{max}	maximum combustion power (W)
Q_{amb}	energy delivered to ambient air in room (J)
Q_c	calculated transferred energy (J)
Q_{comb}	energy content of combusted pellet fuel (J)
Q_{flue}	energy losses through chimney (related to indoor air temperature) (J)
Q_{int}	internal energy change (J)
Q_{wat}	energy delivered to the water circuit (J)
Q_m	measured transferred energy (J)
T_a	ambient room air temperature (K)
T_{bin}	boiler inlet temperature (°C)
T_{bout}	boiler outlet temperature (°C)
tc_{glow}	time constant for stop phase of combustion (h^{-1})
T_{g0}	combustion gas temperature before m_1 (K)
T_{g1}	combustion gas temperature before m_2 (K)
T_{g2}	flue gas temperature at exit of stove/boiler
T_{gin}	combustion air temperature
TIME	simulation time (h)
T_{outd}	outdoor temperature (K)
T_{start}	average boiler internal water temperature at start of measurement (K) (°C)
T_{stop}	average boiler internal water temperature at stop of measurement (K) (°C)
t_{stp}	simulation time when the stop phase begins (h)
UA	Overall heat transfer coefficient (W/K)
UA_{g-m1}	UA value between gas and m_1 (W/K)
UA_{g-m2}	UA value between gas and m_2 (W/K)
UA_{m1-amb}	UA between m_1 and ambient air (W/K)
UA_{m1-m2}	UA between m_1 and m_2 (W/K)
UA_{m2-wat}	UA value between m_2 and water (W/K)
$\dot{V}_{wat}$	volume flow rate of water (m^3/s)
$x_{H_2O,air}$	water content in air per kg of dry air (kg/kg)
$Y_{H_2O,fuel}$	water content in the fuel per kg of humid fuel (kg/kg)

Greeks

ε_Q	relative errors in transferred energy (%)
γ	ratio of P_{cmb}–P_{max} (–)
η	efficiency (–)
λ	air factor (–)
λ_0	air factor at $\gamma = 0$ (–)
λ_1	air factor, power dependant part (–)
ρ_{wat}	density of water (kg/m^3)
ω_{CO}	CO volume fraction in dry gas (vol%)
ω_{CO_2}	O_2 volume fraction in dry gas (vol%)
ω_{O_2}	O_2 volume fraction in dry gas (vol%)

$PM_{2.5}$ particles the values are 10–75 times higher with a pilot flame. Boiler efficiencies are between 27% and 39%. Eskilsson et al. [13] investigated gas sensors for controlling of the excess air and concludes that they can reduce emissions of both NO_x, CO and OGC and also increase the efficiency. In [14] houses with pellet stoves were investigated by simulations using the TRNSYS Type 210 model validated here and it was concluded that the control strategy of pellet stoves can have a great influence on both CO-emissions and annual stove efficiency.

The internal design and control of the burner and the boiler are not the only parameters affecting the annual efficiency and emissions. The performance is highly dependant on system design and control algorithms. Developing models and parameters for pellet boilers and stoves that can be used in modular system simulations is therefore important. Such models can (if they are available in a wide spread simulation programme) be used by researchers for developing general guidelines and for engineers optimising a specific plant. The simulations can also be used to more exactly determine annual national emissions reported to United Nations Framework Convention on Climate Change, as boiler cycling is not fully taking into account by the calculation methods [15].

The TRNSYS simulation program [1] is used among researchers and engineers for dynamic simulations of systems for heating and cooling of buildings. There are many components available for simulating solar heating systems and photovoltaic systems as well as multi zone buildings and HVAC systems. The TRNSYS program allows the user to specify the components in the system and the manner in which they are connected. In order to make a model that can be used in system simulations by both researchers and engineers it was decided to develop a pellet boiler/stove model for use in TRNSYS. At the time when this work started there were no suitable TRNSYS model for wood pellet boilers and stoves and our model Type 210 was originally presented in 2003 by Nordlander [16]. In 2006 another model for pellet boilers was presented by [10].

There are at present four boiler models in TRNSYS: Type 370 [17], Type 147 [18], Type 210 [16], and Type 269 [10]. Type 370 uses a single or multi-node model that treats the boiler essentially as a counter-flow heat exchanger with mass, and models flue gas condensation. It does not simulate the start and stop sequence in detail and there is no literature on its validation for small boilers. Type 147 is a multi-node store model that uses an immersed heat exchanger for heat transfer from flue gas to water. It models flue