Journal of Physics: Conference Series

Modeling operation mode of pellet boilers for residential heating

To cite this article: D Petrocelli and A M Lezzi 2014 *J. Phys.: Conf. Ser.* **547** 012017

Journal of Physics: Conference Series **547** (2014) 012017 doi:10.1088/1742-6596/547/1/012017

Modeling operation mode of pellet boilers for residential heating

D Petrocelli, A M Lezzi

Dipartimento di Ingegneria Meccanica ed Industriale,
Università degli Studi di Brescia, via Branze 38, 25123 Brescia

E-mail: adriano.lezzi@unibs.it

Abstract. In recent years the consumption of wood pellets as energy source for residential heating has increased, not only as fuel for stoves, but also for small-scale residential boilers that produce hot water used for both space heating and domestic hot water.

Reduction of fuel consumption and pollutant emissions (CO, dust, HC) is an obvious target of wood pellet boiler manufacturers, however they are also quite interested in producing low-maintenance appliances. The need of frequent maintenance turns in higher operating costs and inconvenience for the user, and in lower boiler efficiency and higher emissions also.

The aim of this paper is to present a theoretical model able to simulate the dynamic behavior of a pellet boiler. The model takes into account many features of real pellet boilers. Furthermore, with this model, it is possible to pay more attention to the influence of the boiler control strategy. Control strategy evaluation is based not only on pellet consumption and on total emissions, but also on critical operating conditions such as start-up and stop or prolonged operation at substantially reduced power level. Results are obtained for a residential heating system based on a wood pellet boiler coupled with a thermal energy storage.

Results obtained so far show a weak dependence of performance – in terms of fuel consumption and total emissions – on control strategy, however some control strategies present some critical issues regarding maintenance frequency.

1. Introduction

In recent years the diffusion of boilers fueled by wood pellet has increased [1, 2]. On one hand some governments encourage usage of renewable energy sources by means of financial incentives and tax reduction. On the other hand, in some areas, especially areas not reached by the natural gas distribution network, pellet boilers are an alternative to coal, oil and LGP boilers.

End users and legislation have paid increasing attention to energy efficiency and pollutant emissions and that has prompted manufacturers to improve their products. Pellet boilers must comply the European Standard EN 303-5 which defines methods to determine the quality of combustion and thermal efficiency, and establishes also minimum requirements that must be satisfied by the appliances. This Standard classifies boilers in three classes and the best class requires an efficiency of at least $87+\log_{10}(\mathrm{Pn})$, where Pn is the nominal power expressed in kW. Limits on emissions and efficiency may be further restricted by national and regional legislation that regulate the access to the market or distribution of subsidies and tax incentives [3–5].

Results of tests to obtain certification show that over the last few years emissions of pollutants have reached a very low level [6]. These tests are performed according to the procedure specified by EN303-5, which prescribes to measure emissions and efficiency at steady continuous operation, both at the maximum and at the minimum power level (not larger than 30% of maximum power level), excluding transient periods during which emissions can be much higher [7–9].

Conversely, in everyday use, duration of transient conditions amounts to a considerable fraction of total operating time. Thermal load usually varies within a day and from day to day depending on weather and on user's usage. This implies that the boiler does not usually work at maximum power or that frequent changes from maximum to minimum power may occur or that start-ups and shutdowns may alternate several times. Reduction of fuel consumption and pollutant emissions (CO, dust, HC) is an obvious target of wood pellet boiler manufacturers, however they are also quite interested in producing low-maintenance appliances, because the need of frequent maintenance turns in higher operating costs and inconvenience for the user. In addition, factors that increase maintenance frequency are responsible for lower boiler efficiency and higher emissions. Some physical characteristics of the boiler, such as geometry of the combustion chamber and of the heat exchanger, have great influence on performances of course, but also control strategies of pellet boiler can influence consumption, emissions, ash production and fouling deposition.

In literature, efficiency and emissions of pellet boilers during real working conditions have been addressed through both experimental studies and numerical modeling. Measurement of pellet stove and boiler emissions in real conditions can be found in [9–12]. In all these works authors focus their attention also on emissions of stoves and boilers in transient conditions measuring emissions in real cases or realizing a test bench for boilers in which some conditions are simulated [7].

The study of performances in real conditions can be done by computer simulation upon performing a dynamic simulation of the whole heating system. Numerical simulation is useful for optimization of heating systems without the need of long experimental tests, in fact several variables, that influence the operation of the boiler, can be varied. In these simulations models of the heating system and of the house must be used. A few models for simulation of a pellet boiler are available. They calculate fuel consumption, heat transferred to water and emissions. Earlier models consider only steady state conditions, neglecting the typical long transient of these appliances. They compute efficiency and emission as a function of the power of the boiler only. Later on dynamical models that simulate also start-up and stop conditions have been developed [13–16]. The model proposed in [14], for instance, calculates the CO emissions as function of power for normal operation and a constant amount for each start and stop. These models are implemented to be used in TRNSYS or similar programs.

In this paper we present a dynamical model of a pellet boiler in which the control strategy can be modified. In this way it is possible to evaluate its influence on performances. After a description of the model, we present the preliminary results on the behavior of a pellet boiler for different control strategies. For the case presented here, the boiler is connected to the heating system through a thermal energy storage (water tank). Assuming a time dependent thermal load as input data, the time history of thermal energy storage temperature is computed. On the basis of the thermal energy storage temperature and of control strategies, the control system of the boiler determines whether to start-up or to stop the boiler, and controls the current power level. Several quantities are estimated on a weekly base, such as emissions, pellet consumption, number of start-ups and shutdowns, duration of operation at minimum power, etc, with particular regard to those that may influence maintenance frequency.

2. Characteristics of pellet boilers

Pellet boilers are appliances designed to produce hot water from combustion of wood pellet. Wood pellet derives from the compression in grains of sawdust of untreated wood. The main components of wood are mainly carbon, hydrogen, oxygen and water, therefore the products of complete combustion are CO_2, H_2O. The most relevant pollutant substances are CO, dust,

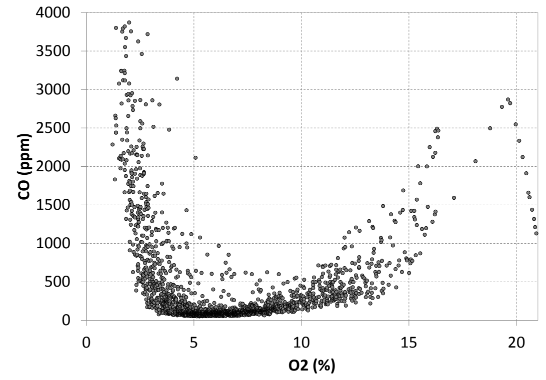

Figure 1. CO concentration in flue gas of a real pellet boiler as function of O_2 concentration for the whole cycle (from start up to switch off). The optimal range of O_2 is between 5% to 7%. [21]

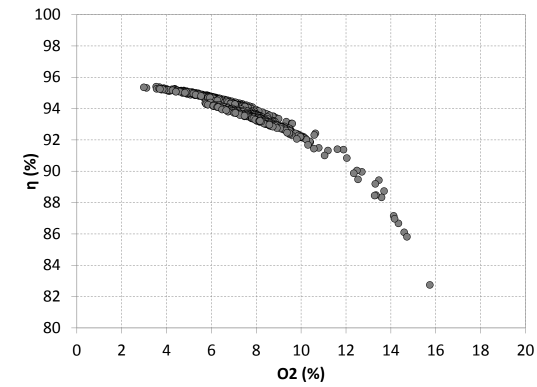

Figure 2. Efficiency of a real pellet boiler as a function of O_2 concentration for steady state regime. [21]

hydrocarbons (HC) and NOx. Their concentrations, in modern pellet boilers, are of the order of 10^{-2} g/m^3 of flue gas. Other substances with concentrations of the order of 10^{-5} g/m^3 of flue gas such as SOx, HCl, PCDD/PCDF Policyclic Aromatic Hydrocarbons (PAHs), may also be present [12, 17, 18], but they are currently neglected by standards and legislation. Also NOx is often omitted. Excess air is the parameter that has the greatest influence on pollutant emission [19, 20]. It has been shown that it exists an interval of excess air (i.e. interval of concentration of oxygen in flue gas) in which combustion takes place in optimal conditions, yielding a low concentrations of pollutant [21], as one can see in figure 1.

All modern pellet boilers are equipped with an electronic control system. On the basis of user's needs and of few measured temperatures, the control system regulates power, start-up and stop procedures, and other functions. In particular, it regulates the pellet mass flow rate and the combustion air mass flow rate.

The typical pellet feeding system of boilers is a screw auger conveyor. Pellet mass flow rate is never exactly constant [21]: consequently the instantaneous burning rate (i.e. the mass of pellet burned per unit time) fluctuates as well as the power supplied to water, the composition and temperature of flue gas, etc. Only quantities averaged over time intervals of a few minutes can be considered roughly constant.

The combustion air mass flow rate is regulated by controlling the speed of rotation of a blower that is usually placed at the flue gas outlet port.

An important component of pellet boiler is the heat exchanger. To reach high efficiency values it is necessary that flue gas transfers as much heat as possible to water, while the heat released to the room is considered as wasted.

Because flue gas of wood pellets is dirtier than that of LGP, for example, ducts inside the boiler must be large enough to avoid obstruction due to fouling, therefore compact flue gas-water heat exchangers cannot be used. This turns in large thermal inertia of pellet boilers, longer response time to a load demand change and the need of a periodic cleaning to remove bottom ashes and fouling deposits on exchange surfaces.

Effectiveness of heat exchanger is a decreasing function of flue gas mass flow rate $\dot{m}_f$ [21] and, as a consequence, of the excess air of combustion n. Since $\dot{m}_f = \dot{m}_p\,(1+n)$, where $\dot{m}_p$ is the pellet mass flow rate, high values of excess air n cause low effectiveness and should be avoided. At the same time excess air cannot be too low otherwise combustion quality would be poor. Typically, excess air is kept larger than 1.3-1.5, corresponding to an oxygen concentration in flue gas of about 6% . Figure 2 shows the actual efficiency of the boiler as a function of oxygen concentration calculated from experimental data [21].

A pellet boiler is characterized also by long start-up/shutdown processes. After the start signal of the control unit, it takes some minutes before the flame lights. Afterwards, it takes some other minutes before the rate of combustion reach the maximum.

With regard to the maintenance of boilers, high efficiency of exchange implies a low temperature of flue gas and this can be a problem because if flue gas temperature is too low, some substances, in particular unburnts, can condensate and attach on cold surfaces of the boiler or of the chimney, forming a layer of deposits (often called creosote). Deposits worsen the heat exchange and can obstruct the flow of gas. Deposition of creosote is also dangerous because it is flammable.

There are no law requirements about the exhaust gas temperature from the boiler: at the nominal power it usually ranges between 120 and 160°C [2, 22, 23]. But, for instance, at the minimum power the exchange area results over-designed and flue gas temperature is easily under 100°C. Furthermore, combustion occurs in non optimal condition because of the high excess air. All that turns into higher concentration of unburnt substances in flue gas and increasing rate of deposit build up on exchange surfaces and chimney walls. Working at the minimum power, as well as at start-up and at shutdown, are operating conditions characterized by low temperature of flue gas and high concentration of dust and HC, thus promoting formation of deposits on heat exchanger surfaces and reducing the time interval between maintenance operations.

3. Pellet boiler model

In the model presented here the boiler is composed by three submodules: the control unit, the combustion chamber, and the flue gas-water heat exchanger.

The control unit determines whether the boiler has to be started up or to be shut off, and regulates the nominal power, on the basis of water temperature T_t measured in the hot water tank. Two threshold values for T_t are introduced: $T_{t,lo}$ and $T_{t,hi}$. In this study they have been set equal to $T_{t,lo} = 60$°C and $T_{t,hi} = 70$°C, respectively.

The control strategies considered here are the following:

- CS 1 When water temperature is increasing: the boiler works at maximum power until $T_t \leq T_{t,lo}$; it switches to minimum power (as in real case, 30% of the maximum power [24]) between the two thresholds, $T_{t,lo} < T_t \leq T_{t,hi}$; above the higher threshold, $T_{t,hi} < T_t$, the boiler is switched off. As water temperature decreases, the boilers either starts up again or resumes operating at maximum power when $T_t < T_{t,lo}$.
- CS 2 It is a modified version of CS 1: the minimum power is set equal to 70% of the maximum power.
- CS 3 It is a modified version of CS 2: as water temperature is increasing between $T_{t,lo}$ and $T_{t,hi}$, the boiler power is varied linearly between maximum power and minimum power (equal to 70% of maximum power).
- CS 4 When the boiler is on, it works at maximum power only: when water temperature in the hot water tank reaches the higher threshold, $T_{t,hi} < T_t$, the boilers is switched off. As water temperature decreases, the boilers starts up again when it falls below the lower threshold $T_t < T_{t,lo}$.
- CS 5 It is a modified version of CS 4. When water temperature in the hot water tank reaches the higher threshold, $T_{t,hi} < T_t$, the power is reduced to minimum (30% of the maximum power): if temperature remains higher than $T_{t,hi}$ for 5 minutes, the boilers is switched off, otherwise it keeps on operating at minimum power. As water temperature decreases, the boilers either starts up again or resumes operating at maximum power when $T_t < T_{t,lo}$.

CS1, CS4 and CS5 are implemented in boiler produced by some manufacturer. On the basis of water temperature, the control unit computes the mass flow rate of pellet and combustion air. The fluctuations in time of pellet mass flow rate are modeled summing up an increment randomly distributed between ±10% of the nominal pellet flow rate.

Characteristic time delays of pellet boiler are taken into account: it takes 4 minutes from the start signal until the actual ignition of the flame; it takes additional 5 minutes from ignition until pellet flow rate reaches its maximum value.

Finally, as in real boilers, the control unit governs the pump that forces water through the boiler heat exchanger (P1 in figure 3): in particular, the pump is switched off when the outlet water temperature, $T_{b,o}$, falls below 40°C.

The combustion chamber submodule simulates the reactions of combustion. On the basis of imposed mass flow rate of air and pellet we compute the mass flow rate $\dot{m}_f$ and composition of flue gas and the adiabatic flame temperature T_{ad}. The pollutant substances taken into account are CO, PM, HC, NOx. They are calculated as a function of the excess air with these methods:

(i) CO and NOx by use of correlations based on experimental data measured during the operation of a real pellet boiler, including start-up and shutdown, and shown in figure 1 as a function of oxygen concentration in flue gas;

(ii) PM and HC by use of interpolation of data taken from [25, 26], and from [7] for start-up and shutdown.

In the heat exchanger the flue gas produced in the combustion chamber heats the water that returns from the hot water tank. Heat exchanger is characterized by its effectiveness ε which is calculated as a function of flue gas mass flow rate through the equation

$$\varepsilon = A\,(\dot{m}_f)^{-B} \tag{1}$$

coefficients A and B are chosen in order to match the experimental results. The outputs from the heat exchanger submodule are the outlet water temperature, $T_{b,o}$, and the flue gas temperature at the discharge, T_f. We use a plug flow model for the heat exchanger, dividing it in 4 parts in which the temperature of water is T_k and the inlet temperature of flue gas is $T_{f,k}$. The energy balance for each part of the exchanger is

$$\frac{C_b}{4}\frac{dT_k}{dt} = \dot{m}_b\,(T_{k-1} - T_k) + \frac{\varepsilon\,\dot{m}_f c_f\,(T_{k-1} - T_{f,k-1})}{4} \qquad \text{for k} = 1, 2, 3, 4 \tag{2}$$

where $T_0 = T_{b,i}$, $T_{f,0} = T_{\text{ad}}$, $T_4 = T_{b,o}$, $T_{f,4} = T_f$, C_b is the heat capacity of the boiler that takes into account both the mass of water in the boiler and the mass of the metal parts.

In the model the start-up is divided in two periods: the first in which no combustion occurs, and the second in which the rate of combustion grows linearly from zero to maximum value.

4. Heating system model

In order to study whether pollutant emissions, pellet consumption and maintenance frequency can be significantly modified by the choice of a proper control strategy, we implemented a model of a heating system, for which a dynamical simulation was run on MatLab. For simplicity we describe the case of a pellet boiler used as energy source for space heating, with only one temperature probe monitoring the hot water tank. However the model has been extended to the case of production of hot water used for both space heating and domestic hot water, with two temperature probes. A sketch of the model is shown in figure 3: from right to left one can recognize the boiler (represented by three submodules, control unit CU, combustion chamber CC, and heat exchanger HE), the hot water tank, the heat distribution system, and the house or heated space. Each model element is briefly described in what follows.

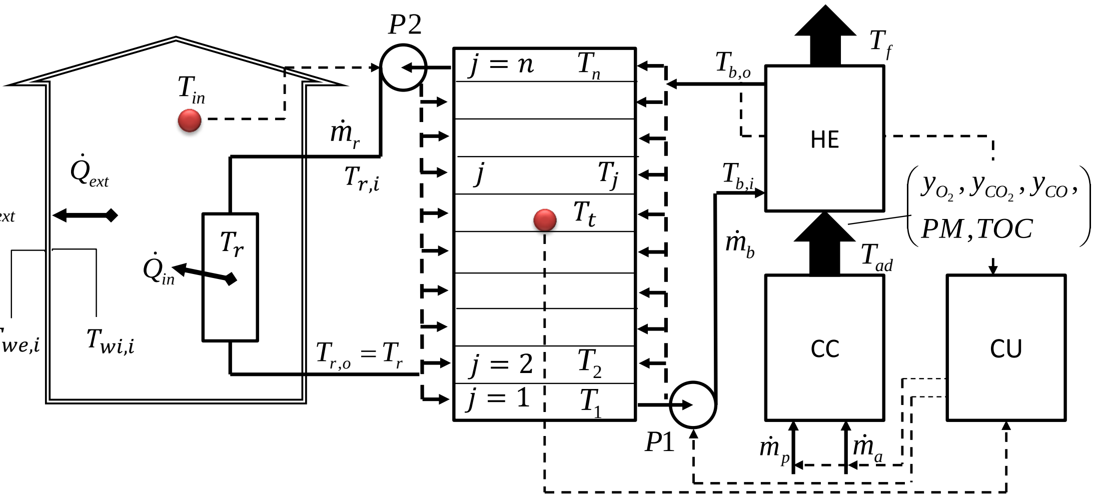

Figure 3. Scheme of the heating system modelled.

4.1. Water tank

In heating systems with a pellet boiler there should be a water tank for the storage of energy. It uncouples the boiler from the heating distribution system. That allows to reduce the duration of transient conditions and, hopefully, total emissions, fouling and maintenance frequency. Here we use a vertical cylindrical stratified water tank that we model as in [27]: temperature depends on time and elevation only. Space dependence is discretized upon dividing the tank in n horizontal disks of equal thickness.

The water outlet towards the boiler is in the disk 1, while the water outlet towards the heating system is in disk n. The position of water inlets from the boiler and from the heating system is chosen based on temperature: water enters in the tank in the disk with the closest temperature. Results of this model were successfully compared with experimental data in [28].

4.2. Heating system

In this example space heating is provided by means of radiators. They are characterized by their heat capacity C_r and by the heat exchange coefficient UA with the air of the room. For the radiators the heat balance is

$$\frac{dE_r}{dt} = C_r \frac{dT_r}{dt} = \dot{m}_r c_r \left(T_{r,i} - T_{r,o}\right) - UA \left(T_r - T_{\text{in}}\right) \tag{3}$$

On the basis of the room temperature, T_{in}, a thermostat switches on or off the pump (P2 in figure 3) that forces hot water flow $\dot{m}_r$ through the radiators.

4.3. House

The energy balance for the house (heated space) is rather simple,

$$\frac{dE_{\text{in}}}{dt} = C_{\text{in}} \frac{dT_{\text{in}}}{dt} = UA \left(T_r - T_{\text{in}}\right) - \sum_i h_{\text{w,i}} A_{\text{w,i}} \left(T_{\text{in}} - T_{\text{wi,i}}\right) \tag{4}$$

In equation (4) the house heat capacity C_{in} takes into account heat capacity of air and inner elements like furniture and internal walls. $h_{\text{w,i}} A_{\text{w,i}}$ represents the heat exchange coefficient between air and the ith wall of the building shell. The building shell was modeled as in [29] with a single-node model. In this model the shell is composed by two layers, hence it is characterized by three temperatures: inner side temperature $T_{wi,i}$, contact temperature between layers and the

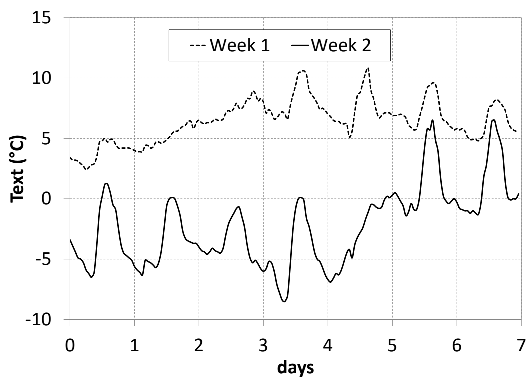

Figure 4. Time history of the temperature of the external environment.

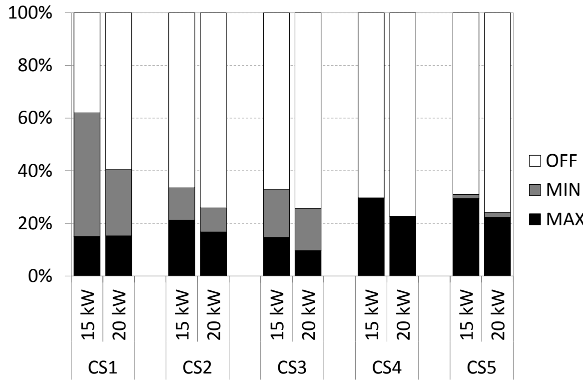

Figure 5. Fraction of time at maximum and minimum power for a 15 kW and a 20 kW boilers.

outer side temperature $T_{we,i}$. In this way it is possible to take into account also the heat capacity of the layers of the shell and their temperatures. The external side of the building shell exchanges heat with external environment only by convection, h_{ext} denoting the convective heat transfer coefficient. Real data are used for the time history of the external environment temperature. In particular, data refer to hourly temperature in Lonato (Bs, Italy) from January 3 to January 9, 2014 (week 1) and from February 3 to February 9, 2012 (week 2) [30].

5. Results

The model briefly sketched in Sec. 3 and 4 has been implemented in MatLab.

With reference to figure 3 the house size is 100 m^2 $\times$ 2.7 m filled by air and other objects (heat capacity 7.3 MJ/K); heat capacity of the external walls is 1.25 MJ/m^{3}K, their thermal conductivity 0.2 W/m K; convective heat transfer coefficients are $h_{\text{w,i}} = 8$ W/m^{2}K and $h_{\text{ext}} = 20$ W/m^{2}K. With regard to the heating distribution system, we consider 55 cast iron radiators elements each one has mass equal to 9.27 kg and is filled with 1 kg of water.

The desired room temperature T_{set} is set equal to 18°C from 5:00 to 7:00, 20°C from 7:00 to 23:00, 18°C from 23:00 to 24:00, while the heating system is off from 00:00 to 5:00. The dead-band is set equal to 1.5 K.

Simulations have been performed over a time interval of one week, for:

- two different external temperature time histories, denoted "week 1" and "week 2" (shown in figure 4);
- two boiler nominal powers: 15 kW, 20 kW;
- six water tank volumes: 283 l, 503 l, 754 l, 1005 l, 1571 l, 1963 l;
- five different control strategies (see Sec. 3).

The power of the boiler was chosen after a preliminary calculation of the thermal power demand of the house.

The water mass flow rate circulating through the boiler heat exchanger is such as to have a 15 K difference between outlet and inlet when boiler works at the maximum power ($T_{b,o} - T_{b,i} = 15$ K). As long as $T_{b,o} < 40$°C water recirculates in the boiler.

The water tank is discretized in $n = 40$ disks. Temperature of the 20th disk is taken as the water temperature T_t used by the control unit.

Fuel consumption does not seem to depend on control strategy nor on water tank volume: it has been estimated close to 155 kg/week for week 2 and 94 kg/week for week 1 for boiler of 15 kW. For boiler of 20 kW 159 kg/week for week 2 and 96 kg/week for week 1. Differences for different control strategies and water tank volumes fall within $\pm 1.5\%$. Figure 5 reports the

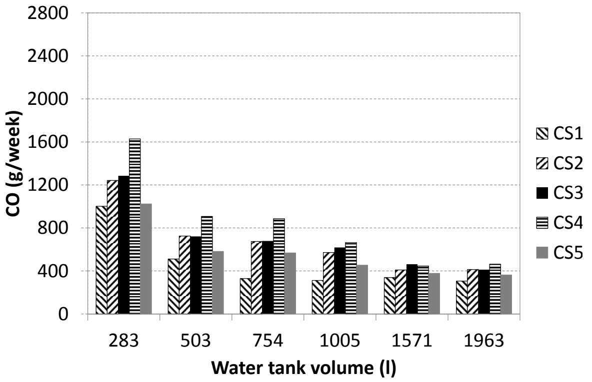

Figure 6. Total CO emissions for a 15 kW boiler during the week 2.

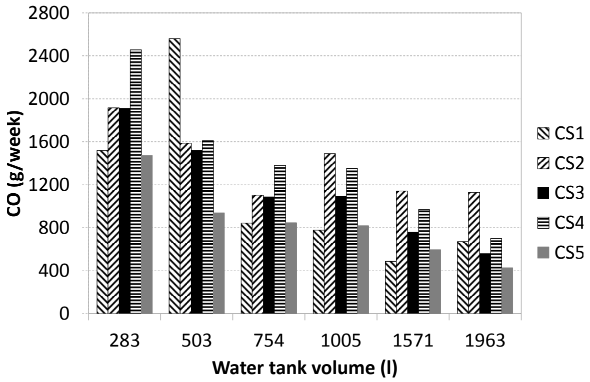

Figure 7. Total CO emissions for a 20 kW boiler during the week 2.

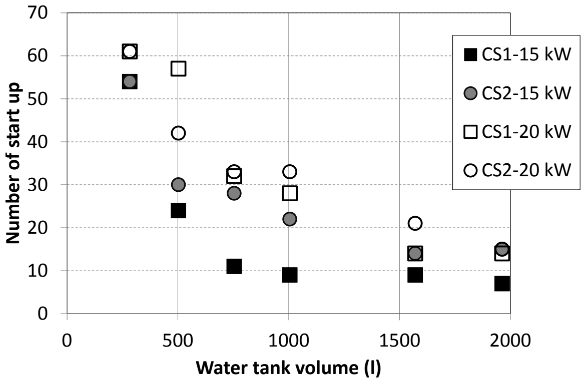

Figure 8. Number of start-ups vs. water tank volume, for strategies CS1 and CS2 for both 15 kW and 20 kW boilers.

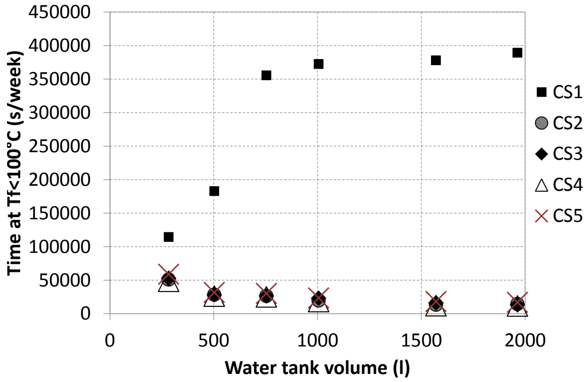

Figure 9. Total time flue gas temperature is below 100°C vs. water tank volume, for different strategies and 15 kW boiler.

fraction of time the boilers of 15 kW and 20 kW are off or are working either at maximum or minimum power. From figures 6 and 7 it is evident that the CO production of boiler of 20 kW is higher than the CO production of boiler of 15 kW. Production rates of CO at the maximum power for both 15 kW and 20 kW boilers are about 28 mg/MJ. The large difference is due to the CO emitted during the start-up and stop phases. In figure 8 the number of start-ups is plotted versus the water tank volume for control strategies CS1 and CS2. Number of start-ups of CS3, CS4 and CS5 are very close to those of CS2. Control strategy CS1 ensures less start-ups/stops than other control strategies.

From these first observations, we can assert that the 20 kW boiler, which is over-designed for this house, presents more critical issues than the 15 kW boiler, therefore we focus our attention on the latter only. Figure 9 reports the total time flue gas temperature is below 100°C. For CS1 flue gas temperature is below 100°C for about 2/3 of the time: this is due to the long time of working at the minimum power and to start-ups and stops. Figures 10, and 11 show total emissions versus water tank volume for different control strategies.

The calculated emission rate are the following: during operation at the nominal power the average emission rate are 28 mg/MJ for CO and 6 mg/MJ for PM. When boiler operates at the 70% of nominal power emission rates are 42 mg/MJ and 11 mg/MJ, while when it operates at 30% they are 75 mg/MJ and 16 mg/MJ. For each start-up, which takes place in the same way for all strategies, the CO and PM production are 20 mg/start-up and 1 mg/start-up, respectively. During the switch off the production of CO and PM is strongly influenced by the power at which the boiler works just before the stop: if the boiler works at the maximum power (CS4) CO and PM production are 15 mg/switch off and 1 mg/switch off, respectively, if it works at the 70% of

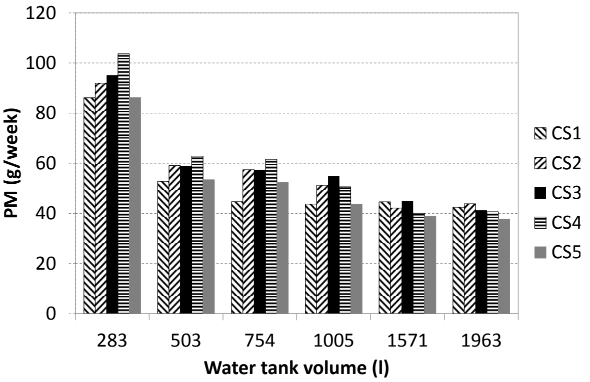

Figure 10. Total PM emissions for a 15 kW boiler during the week 2.

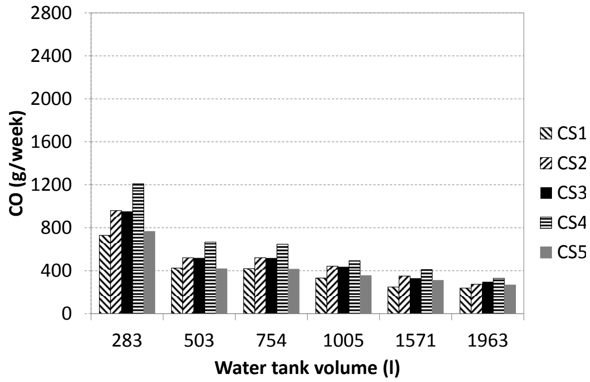

Figure 11. Total CO emissions for a 15 kW boiler during the week 1.

the maximum power (CS2 and CS3) 5 mg/switch off and 0.2 mg/switch off, while if it work at the 30% (CS1 and CS5) 1 mg/switch off and $<$ 0.2 mg/switch off.

Although these results must be considered preliminary and need confirmation, we observe what follows with regard to the five control strategies.

CS1) The number of start-ups is smaller than those for the other control strategies for water tank volume greater than 250 l: that should reduce emissions and fouling deposition. However this effect is counterbalanced by the low temperature of flue gas and by the long time of operation at minimum power (characterized by higher pollutant concentration).

CS2) This control strategy produces more CO and PM emission than CS1 even if number of start-ups is much larger and flue gas temperature is below 100°C for a shorter time.

CS3) There are not clear differences between CS3 and CS2.

CS4) This control strategy yields the highest value of CO emissions. CO and PM emissions per unit of energy produced in normal operation are the lowest, but the high number of start ups/shutdowns and the shutdown from the maximum power give a large contribution on pollutant emissions.

CS5) This control strategy provides low emissions: they are larger than emissions of CS1, but smaller than emissions of other strategies. With respect to CS1 emissions during normal operation are smaller because the time of working at the minimum power is significantly reduced, but total emissions result larger because of the higher number of start-ups/shutdowns especially for tank volumes between 503 l and 1005 l. This control strategy is currently implemented in some pellet boilers to avoid short time interval between a stop and the subsequent start-up.

The volume of the hot water tank appears to be more important than control strategy in reducing both the number of start-ups and emissions. As expected, number of start-ups is a decreasing function of water tank volume for all strategies. Also CO and PM emissions decrease with tank volume and differences between strategies become less important. However it can be observed that PM emissions fall abruptly when tank volume is increased from 250 l to 500 l.

Finally, results for HC have similar trend to those for PM.

In order to find the control strategy that optimizes the operation of the boiler in most conditions as possible, it is necessary to extend this sensitivity study varying other variables, such as thermal load, heating system, temperatures $T_{t,lo}$, $T_{t,hi}$, minimum power, etc, and the simulation can be performed over a longer time interval. For the example presented here, the optimal solution is the 15 kW boiler, working with strategy CS5 and a water tank of 500 liters. Larger water tanks imply higher cost and the differences in term of pollutant emissions and time at low temperature are negligible. Even if there are relations to calculate the rate of deposition of fouling and creosote are not available yet, experience suggests to discard CS1 due to the long time of working with low temperature of flue gas.

6. Conclusions

In this work we studied the performance of a heating system based on a wood pellet boiler coupled with a thermal energy storage. Upon use of a theoretical model implemented in MatLab the heating system performance can be estimated in terms of fuel consumption, pollutant emissions, number of boiler start-ups, time of operation at minimum power. Performances are studied for five different control strategies and for varying volume of the hot water tank.

Only few preliminary results have been obtained insofar. Although they need confirmation and a systematic and careful analysis, nevertheless they do show a weak dependence of performance on control strategy. In particular,

(i) fuel consumption is independent for all practical purposes from both control strategy and water tank volume;

(ii) total CO and PM emissions over a week substantially decrease for increasing volume of the water tank, but for water tank larger than 500 l the difference can be considered negligible.

(iii) control strategies do affect parameters like number of start-ups or fraction of time at minimum power, however the combined effects on total emissions tend to compensate each others: only CS 1 seems to show CO emission somehow lower than other CS, but the use of this strategy can increase the formation creosote and fouling.

References

[1] Miguez J, Moran J, Granada E and Porteiro J 2012 *Renewable and Sustainable Energy Reviews* **16** 3867–3875
[2] Thek G and Obernberger I 2012 *The Pellet Handbook: The Production and Thermal Utilization of Biomass Pellets* (Taylor & Francis) ISBN 9781136539916
[3] BAFA (Germany) 2013
[4] DM 28/12/12 (Italy) 2012
[5] Art 15a B-VG (Austria) 2012
[6] Brunner T, Barnthaler G and Obernberger I 2006 *Proceedings 2nd World Pellets Conference* 87–91
[7] Win K, Kaung M, Persson T and Bales C 2012 *Atmospheric Environment* **59** 320–327
[8] Boman C, Nordin A and Ohman M 2005 *Umea University*
[9] Bafver L, Leckner B, Tullin C and Berntsen M 2011 *Biomass and Bioenergy* **35** 3648–3655
[10] Dias J, Costa M and Azevedo J 2004 *Biomass and Bioenergy* **27** 531–539
[11] Wiinikka H and Gebart R 2004 *Biomass and Bioenergy* **27** 645–652
[12] Johansson L, Leckner B, Gustavsson L, Cooper D, Tullin C and Potter A 2004 *Atmospheric Environment* **38** 4183–4195
[13] Persson T, Fiedler F, Nordlander S, Bales C and Paavilainen J 2009 *Applied Energy* **86** 645–656
[14] Nordlander S and Persson T 2003 *ISES Solar World Congress, june 2003*
[15] Schnetzinger R, Jofre M, Hebenstreit B, Schwarz M and Hoftberger E 2012 *WSED 2012*
[16] Haller M, Haberl R, Droscher A and Frank E 2009 *11th Int. IBPSA Conference*
[17] Kjallstrand J and Olsson M 2004 *Biomass and Bioenergy* **27** 557–561
[18] Olsson M, Kjallstrand J and Petersson G 2003 *Biomass and Bioenergy* **24** 51–57
[19] Eskilsson D, Rönnbäck M, Samuelsson J and Tullin C 2004 *Biomass and Bioenergy* **27** 541–546
[20] Petrocelli D and Lezzi A 2014 *J. Phys.: Conf. Ser.* **501** 012036
[21] Petrocelli D 2013 *Indicazioni sperimentali per la progettazione di stufe a pellet ad alta efficienza* Ph.D. thesis University of Brescia
[22] Obenberger I and Thek G 2006 *Proceedings 2nd World Pellets Conference* 31–41
[23] BLT 2011 *http://blt.josephinium.at*
[24] EN 303-5:2012 2012 *Heating boilers - Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW - Terminology, requirements, testing and marking*
[25] Kelz J, Brunner T and Obernberger I 2012 *Environmental Sciences Europe* 1–18
[26] Brunner T 2009 *Proceedings of the 17th European Biomass Conference & Exhibition, June 2009, Hamburg*
[27] Klein S 1989 *A design procedure for solar heating system* Ph.D. thesis University of Wisconsin
[28] De Cesaro, Oliveski, Rejane, Krenzinger, Arno, Vielmo and Horacio 2003 *Solar Energy* **75** 121–134
[29] De Rosa M, Bianco V, Scarpa F and Tagliafico L A 2014 *Applied Energy* **128** 217–229
[30] Provincia di Brescia 2011 *http://meteo.provincia.brescia.it*