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Experimental study on the optimisation of staged air supply in the retort pellet burner

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Abstract. The use of biofuels for heating purposes is beneficial from a greenhouse gas emission point of view. But combustion of solid biofuels typically is related with high emission rates of CO, NO_x, PAHs, VOCs and particle matter.
The most important factor that is affecting the formation of harmful emissions is the way the combustion process is organised. The amount of air injected and approach for the air supply system, are the most important factors affecting combustion process. Air staging is one of the most effective technical solutions for achieving complete combustion and low emissions. The main idea of air staging is to inject air into different zones of a combustion process. The main goal of this study is to optimise pellet combustion process in a 500 kW boiler with staged air supply.
The research is based on on-site experiments and application of scientific instrumentation. Fly-away unburned fuel particles were discovered during the on-site experiments. Reduction of the amount of fly-away particles was set as a target function for the optimisation. The amount of emissions (CO, NO_x and particle matter) and the amount of incombustibles in fly ashes were identified. Two different solutions with applied secondary air supply nozzles were analysed. The results of the study show that even small changes in the way the combustion air is injected can significantly affect the combustion process.

Key words: air staging, air supply, pellet boiler, vertical pellet burner.

Nomenclature

CO	Carbon monoxide content in dry flue gases, % of volume
NO_x	Nitric oxides content in dry flue gases, % of volume
O_2	Oxygen content of dry flue gases, % of volume
PAHs	Polycyclic aromatic hydrocarbons content in dry flue gases, % of volume
PID	Proportional-integral-derivative
PM	Dust content of dry flue gases, % of volume
RH	Relative humidity of air supply, %
T_{air}	Temperature of air supply, °C
T_{fg}	Temperature of flue gas, °C
V_{air}	Velocity of air supply, m s^{-1}
V_{fg}	Velocity of flue gas, m s^{-1}
VOCs	Volatile organic compounds content in dry flue gases, % of volume
w-%	Weight-percentage
w-%,d	Weight-percentage, dry basis

INTRODUCTION

The first wood pellets were produced in North America in the 1970s. Nowadays pellets are produced on a global scale and the amount of production is growing each year (Vinterback et al., 2002). With increased oil prices the need to decrease CO_2 emissions and lower costs are the main cause of production growth and it has high potential to develop (Junginger et al., 2009; Olsson et al., 2011). In Latvia, the production of wood pellets follows the global trend and has increased 1.9 times from 378,000 tons in 2008 to 722,000 tons in 2011 (Energy statistics, 2011).

Pellet boilers vary by the types of systems for fuel feeding, air supply, heat exchange and other parameters. Modern pellet boilers have high levels of efficiency, but there is still room for improvement (Fiedler, 2004). Air supply is one of the most important factors affecting the efficiency of boilers and CO, NO_x, PAHs, VOCs and particle matter emission rates.

Every pellet boiler has an optimal oxygen concentration in flue gas, which results in the least CO concentration and heat losses (Yin et al., 2008). Optimal concentration of oxygen varies, and usually is not higher than 10% (Haapa-Aho et al., 2011). But there are exceptions, like the paper presented by Dias, (2004) describing a 13 kW commercial domestic pellet boiler that has the least CO concentration when oxygen concentration is around 13%. Temperature in the combustion zone depends on the amount and the velocity of the injected air. Temperature in the combustion zone has a strong influence on the quality of fuel combustion (Tullin et al., 2005).

Optimisation of the air supply can decrease CO concentration in flue gas and improve the combustion process (Carvalho et al., 2007; Menghini et al., 2008). Increase of efficiency and decrease of heat losses, CO and NO_x was achieved by decreasing excess air during the investigation run by Eskilsson et al. (2004) for a modified burner with horizontal grate. Insufficient air supply can lead to increased accumulation of ash, soot and other similar particles.

Pellet boilers without air staging can be improved and a secondary air supply can be added. Work done by G. Qiu (2013) describes methods for investigating emissions (CO, NOx, PM), decreasing heat losses and increasing efficiency in pellet boilers.

The amount of CO, NO_x and PM emissions in flue gas vary depending on the capacity of boiler. Each boiler has its optimal capacity, which gives the least emissions. Research done by Fernandes et al. (2012) presents the results of tests performed on a pellet boiler with maximal capacity of 22 kW. Tests carried out with different loads showed, that the least amount of CO and PM emissions were achieved around 16–18 kW. It also showed that the share of 10 μm PM is larger when the capacity of boiler is bigger than nominal. The amount of CO emissions with similar boiler testing conditions varies for different fuels. Research by Carvalho et al. (2013) shows that CO emissions and boiler efficiency can change when different biomass is used.

Air staging is one of the methods to improve the combustion process. There are diverse technologies for organising air staging and secondary air supply in pellet boilers (Biomass…, 2008; Nussbaumer, 2003; Slāpekļa…, 2009). A paper presented by Klason (2007) describes how staged air supply improves regulation of the combustion process. Secondary and tertiary air injections create turbulent flow in the boiler furnace and improve mixing of volatiles and air. Study by Staiger et al. (2005)

shows that decreasing the primary air flow and using the secondary air improves combustion processes and reduces the concentration of emissions, particularly NO_x. Air staging and qualitative combustion process require that dimensions of the boiler's chamber are large enough for combustion of all volatiles (Nussbaumer, 2003).

To achieve a reduction in emissions, secondary air must be in the correct ratio with primary air and must be injected in the correct place and under the right angle. Research done by Chaney et al. (2012) showed that minimal CO emissions were observed when primary air was joined by a small amount of secondary air. The biggest emissions were observed when secondary air was supplied more than the primary. If the distance between the fuel bed and the injection points of secondary air are chosen correctly, mixing of fuel and air is improved and emissions of NO_x and CO are decreased (Janvijitsakul et al., 2011; Liu et al., 2013).

Modern boilers are equipped with controllers. While they make boilers more expensive, improvements gained from automatic regulation of combusting processes improve efficiency and make it worth the added price. PID controllers are one of the most popular boiler controllers (Haapa-Aho et al., 2011). The use of a lambda sensor is one of the methods to control oxygen concentration in the flue gas. Work done by L. Carvalho et al. (2007) shows that boilers with lambda sensors have lower CO emissions than boilers without them. Regulation can be made with CO controller, with CO and temperature controller and other type of controllers (Biomass…, 2008).

METHODS AND MATERIALS

Description of the on-site 500 kW boiler

For the combustion tests a Grandeg Turbo 500 pellet boiler was used. The boiler is installed in the municipal boiler house and used for district heating purposes. All combustion tests have been carried out in real operational conditions.

The experimental system includes boiler, heat consumer and monitoring equipment (Fig. 1.). Because of the real life operational conditions the number of parameters useful for analysis is limited. Detailed explanation of the selection of parameters to be measured is described in the chapter 'Optimisation criteria'.

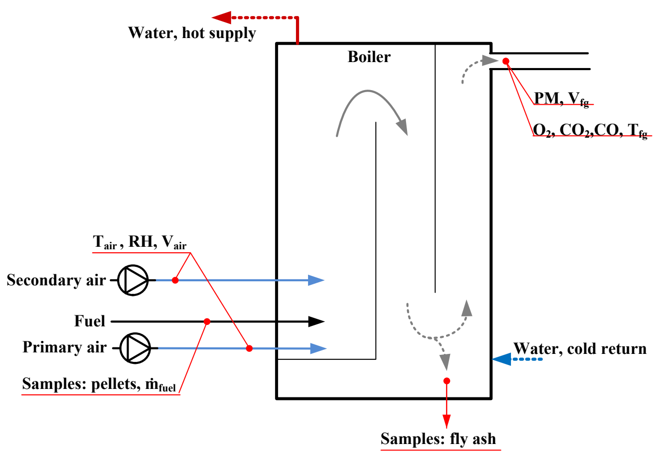


Figure 1. On-site pellet boiler and experimental system.

The boiler is equipped with an experimental retort-type burner and two independent air supply systems. During the tests different combustion power was achieved by changing control strategy of the pellet supply system. Air is supplied to the combustion chamber by two separately powered and controlled fans. According to the aim of this study three different air supply strategies have been tested and analysed (Fig. 2).

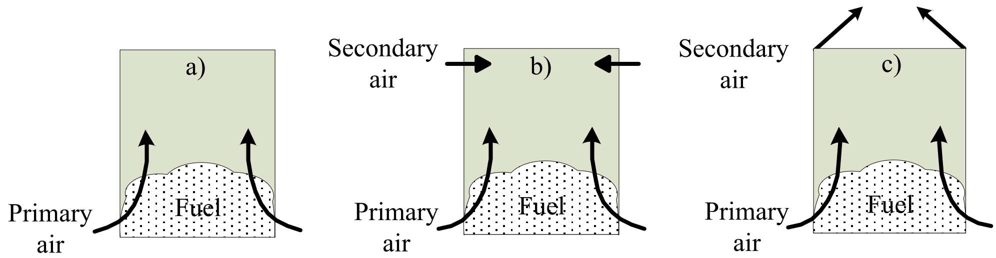


Figure 2. Cross-section of the burner. Air supply strategies (a – only primary air supply, b – secondary air supply with horizontal nozzles, c – secondary air supply with 45° oriented nozzles).

Primary air is supplied into the bottom part of the burner where heating and drying of the fuel occurs. Secondary air is supplied into the upper part of the burner for combustion of volatiles. Two technical solutions for secondary air supply have been tested: with horizontal and 45° oriented nozzles.

Fuel used for tests

Two types of pellets were used for combustion tests: wood pellets and straw pellets. Both types of pellets are made in a factory and available on the market for household use. The physical and chemical parameters of the pellets used for tests are described in Table 1. Laboratory analysis was based on the methodology given in the CEN/TS standards, see Table 1. Pellet samples were taken every 10 minutes and analysed in a laboratory. The data included in Table 1 represents the average values from all samples.

Table 1. Chemical and physical parameters of the pellets

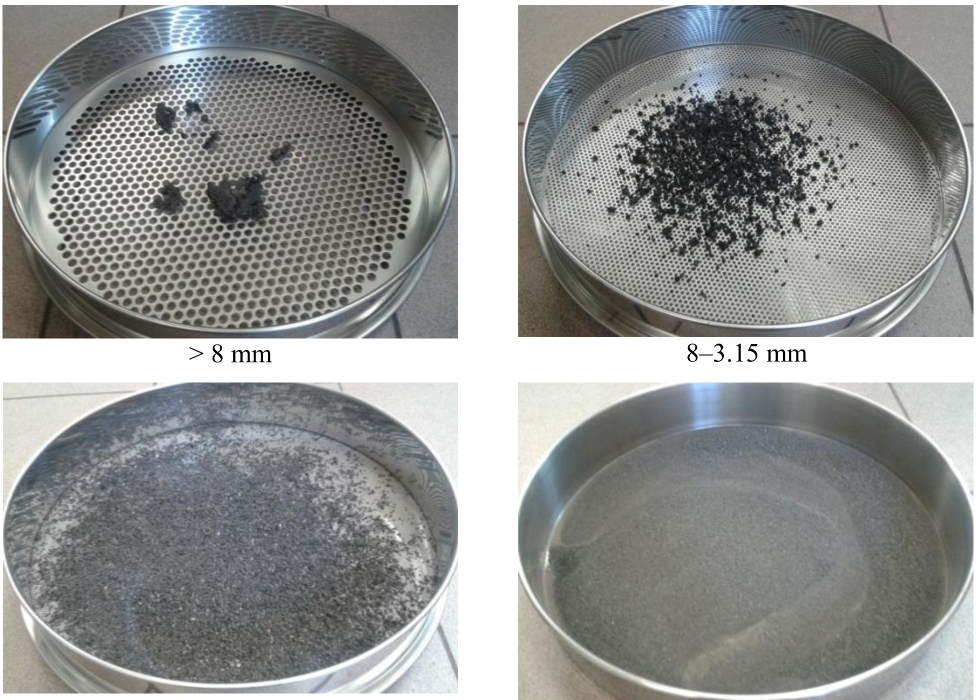
Parameter	Value		Method
	Wood pellets	Straw pellets	
Ash content, %	0.8	4.3	CEN/TS 14775 (EN, 2009)
Moisture content, %	6.7	10.6	CEN/TS 14774-3 (EN, 2009)
Net calorific value, MJ kg^{-1}	17.72	15.3	CEN/TS 14918 (EN, 2009)
Gross calorific value, MJ kg^{-1}	20.45	18.7	CEN/TS 14918 (EN, 2009)
Durability, %	98.7	96.9	CEN/TS 15210-1 (EN, 2009)
Mean diameter, mm	8.0	8.1	---
Mean length, mm	18.7	13.8	---

Optimisation criteria

The way in which air is supplied to the burner directly affects aerodynamics in the chamber and combustion efficiency. To find out how staged air supply is affecting combustion process the following parameters were settled as optimisation criteria:

- CO emissions (as indicator of mixing process and incomplete combustion);
- combustion efficiency (not related with thermal efficiency of boiler);
- PM emissions (as indicator of aerodynamic processes in the chamber and amount of solid matter carried out from the boiler by flue gases);
- amount of ash in the ash box (indicates amount of solid matter carried out from the burner by flue gases);
- size distribution of fly ashes (indicates the share of unburned fuel in ashes);
- amount of combustibles in fly ashes (indicates the amount of fuel carried out from the burner by flue gases).

An example of fly ash size distribution is shown in Fig. 3. A well organised and controlled combustion process will always be indicated by a higher share of small ash particles (< 1mm).



> 8 mm | 8–3.15 mm | 3.15–1 mm | < 1 mm

Figure 3. Size distribution of ashes.

Excess air causes an increase of velocities in the chamber and creates extra force which can take small fuel particles out from the burner. This problem is common in boilers with a single air supply and without automatic air supply regulation. The velocities of gasses are also proportional to the cross-section area of the nozzles, burner, chamber and flue ways. This means that incorrect design geometry of the boiler can cause incomplete combustion of fuel. The ash particles with nominal size 8–3.15 mm in most cases are partly combusted pellets. During the tests several big pieces of melted ash were also observed.

Temperature of heat carrier is affecting temperature of flue gases, thermal efficiency and power of the boiler. The boiler was used in real life operating conditions and it is not possible to keep a constant temperature inside the district heating circuit and boiler. Because of this all the parameters related with temperature of heat carrier were excluded from the study.

RESULTS

In total 8 combustion tests were carried out with two types of pellets and different strategies for combustion air supply:

- T1w – reference test, wood pellets, only primary air;
- T2s – reference test, straw pellets, only primary air;
- T3w – wood pellets, horizontal injection of secondary air, distribution;
- T4s – straw pellets, horizontal injection of secondary air, distribution;
- T5w – wood pellets, 45° injection of secondary air, distribution;
- T6w – wood pellets, 45° injection of secondary air, distribution;
- T7w – wood pellets, 45° injection of secondary air, distribution;
- T8s – straw pellets, 45° injection of secondary air, distribution.

In general, tests have been carried out according to the standard EN 12952-15 (2004). The main difference from the standard methodology is related to the uncontrollable test conditions and duration of the tests. Each test performed in this study was limited to 30 minutes. The results represent averaged or total values of the readings and calculations.

A summary of the operational conditions for boiler operation is shown in Table 2. A Combustion power is used as an indicator for the amount of fuel energy supplied to the combustion process. The amount of combustion air is calculated as a sum of the volume of primary and secondary air and is expressed on volumetric basis. The test T6w was carried out with forced fuel supply and therefore a much higher than nominal combustion power was reached. The test T6w was carried out in order to check the stability of combustion process under overload conditions.

Table 2. Operational conditions

Test	Combustion power, kW	Air distribution, prim./sec.	G_{air}, m^3 h^{-1}	O_2, %
T1w	639	100:0	1121	6.04
T2s	468	100:0	807	4.97
T3w	624	50:50	1108	5.86
T4s	526	26:74	892	5.52
T5w	659	43:57	768	5.10
T6w	865	48:52	1158	6.55
T7w	620	54:46	730	5.39
T8s	561	45:55	938	8.69

The emissions of CO and PM for every test are shown in Table 3. All values are normalised and recalculated to reference oxygen concentration in flue gases. The amount of bottom ash is expressed on time basis. The results represent only the amount of combustibles in bottom ash. Fly ash was not analysed, but typically fly ash contains a higher share of combustible materials than bottom ash does.

Table 3. Emissions and ashes

Test	CO, mg $(nm^3)^{-1}$ at 10% O_2	PM, mg $(nm^3)^{-1}$ at 10% O_2	Amount of ash, g h^{-1}	Amount of combustibles in ash, %
T1w	2,165	51.5	512	82.1
T2s	4,012	194	310	50.2
T3w	342	39.4	342	50.1
T4s	705	126	705	80.4
T5w	138	43.7	138	26.7
T6w	613	106	613	45.6
T7w	252	78.0	252	29.2
T8s	137	51.4	137	45.6

The fractional distribution of bottom ashes is shown in Fig. 4. The results represent significant variations in the fractional distribution of ashes in the function of operational conditions, fuel used and air supply strategy applied. A higher share of big ash particles (> 3.15 mm) is observed for the cases when either the primary (T1w) air supply or forced secondary air supply (T4s) strategy is used. Therefore it is strongly recommended to organise a uniform air injection in the combustion chamber and to avoid the creation of strong and rapid aerodynamic flow in any part of the process.

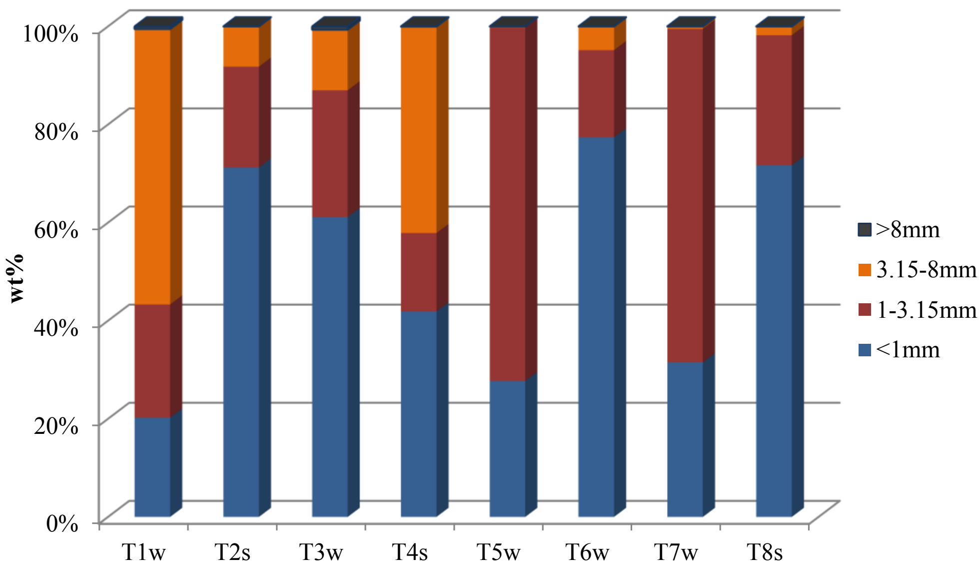


Figure 4. Size distribution of ashes.

Very high emissions of CO were observed during reference tests. During the reference test with wood pellets ashes were formed mostly by not fully combusted pellets. This results in 82% share of combustibles in ash and the 56% share of 3.15–8 mm fraction in ash box. The highest concentration of PM emissions was discovered during the reference test with straw pellets.

In general the staged air supply allowed reaching better combustion of fuel and lower amount of solid fraction taken out from the chamber. During the tests approx. 50:50% distribution of air was applied. The results of the test T4s (with 74% secondary air supply) proves the drawbacks of forced secondary air supply. Performance of the boiler was lower taking into account all the observed parameters. Test T6w has been carried out with much higher than nominal combustion power. As it was expected this also results in higher concentrations of emissions and higher amount of ashes.

CONCLUSIONS

During the study staged air supply in 500 kW pellet boiler was performed and analysed. Staging of a combustion air was applied for optimisation of combustion process. Three different air supply strategies have been analysed. The case with only a primary air supply was used as the reference scenario.

Taking into account different operational parameters during combustion tests and the lack of repetitive tests it is difficult to make a proper quantitative comparison of the results. Based on qualitative analysis it is possible to prove significant improvement of boiler performance in the case when staged air supply is used. During the reference combustion tests high emissions of CO were discovered. In general, the combustion process with staged air supply showed a higher performance in terms of emissions and ash parameters. Based on this it can be concluded that staged air supply can be used as an instrument for optimisation of the combustion process, reduction of emissions and maintenance costs. Therefore an improperly distributed air supply can reduce performance of the combustion process. The strategy for control of staged air supply should be based on empirical data for each case.

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