ANALYSIS OF VENECT COMBUSTION TESTS

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Abstract

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Calculating combustion efficiency is necessary if its parameters need to be controlled in order to maintain or improve its efficiency. However, determining combustion efficiency using the traditional method is difficult and complicated. As a consequence, it is not useful to check combustion efficiency on a regular basis.

The work presented in this thesis is concerned with developing a statistical model for combustion efficiency based on oxygen and carbon dioxide volume in flue gas. The efficiency is primarily determined by combustion parameters of the boiler and the predictive model is built using regression analysis.

The objective of this thesis was to use combustion control to optimize the combustion conditions in a small-scale pellet boiler. The combustion control was implemented using both theoretical and experimental data from the combustion process. The oxygen concentration and temperature at the upper end of the combustion chamber were the control variables for the combustion control. The amount of oxygen in the flue gas tells you about the status of the combustion and offers you an estimate of how much pollution was created. The tests were carried out on a pellet boiler on the HAMK's Valkeakoski campus.

Keywords Combustion efficiency, excess air, regression analysis.
Pages 24 pages

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1 Introduction

Throughout the entire range of energy generation, biomass, particularly wood combustion, has become increasingly attractive in recent decades (heat and power). The rising cost of fossil fuels is one of the major factors driving interest in biomass and wood combustion. In addition, increasing the usage of wood fuels is a theme in the quest for lower carbon dioxide emitting energy production. This is because the carbon dioxide created in combustion is offset by the carbon dioxide consumed when new trees are planted, assuming the trees are cultivated sustainably. However, if a significant number of hydrocarbons are created during burning, the performance of the combustion diminishes and the polluting effect of biomass combustion grows, compromising biomass's reputation as an ecologically favorable and carbon dioxide neutral form of energy.

The combustion process must be carried out effectively in order to fulfill the combustion conditions that ensure low hydrocarbon emissions. Continuous combustion control, which is frequent in large-scale boilers, is required. Combustion control has become more important in small-scale appliances as efficiency and emission restrictions have become more stringent. Typically, combustion in small-scale appliances is carried out with a large quantity of surplus air, which reduces the amount of hydrocarbons but lowers the boiler's efficiency and raises NOx emissions (Eskilsson;Rönnbäck;& Samuelsson, 2002). This is why air feed optimization is such an important aspect of combustion control.

The objective of this thesis was to use combustion control to optimize the combustion conditions in a small-scale pellet boiler. The combustion control was implemented using both theoretical and experimental data from the combustion process. The oxygen concentration and temperature at the upper end of the combustion chamber were the control variables for the combustion control. The amount of oxygen in the flue gas tells you about the status of the combustion and offers you an estimate of how much pollution was created. The tests were carried out on a pellet boiler on the HAMK's Valkeakoski campus.

2 Small Scale Pellet Boilers

Biomass boilers has been demonstrated to be clean, and effective. Modern biomass boilers may be found in all Europe, especially in Sweden and Finland. Biomass boilers have a 92 percent efficiency rating, which is equivalent to that of contemporary gas condensing boilers (Wood Fuel South West Advice Service, n.d.).

Since pellet combustion appliances have been on the market since the 1980s, it has only been in the last 10 years that a big breakthrough has occurred. During the 1990s, pellet heating appliances that could be used for central heating were created. Due to rising oil prices and tighter carbon dioxide limits, these appliances already provide a massive portion of home heat, and their popularity is only growing. Pellet heating is also appealing to consumers because of the fuel's ease and the ability to retrofit an existing boiler with a pellet burner that previously had an oil burner (Loo & Koppejan, 2008).

2.1 Pellets

Industrial wood waste, such as sawdust and cutter chips, is compressed into wood pellets. Pelletizing is also an option for bark and woodchips. The most common shape is cylindrical; however they can also be square (Alakangas;Hurskainen;Laatikainen-Luntama;& Korhonen, 2016). Pellets have a diameter of 8–12 mm, while pellets with a diameter of 6 mm are relatively common in Central Europe. A pellet can be anywhere between 10 and 30 mm in length. A pellet has a moisture content of 7–9% and a low ash content of 0.2–0.8% (Obernberger & Thek, 2004). A bulk cubic meter of pellets weighs 600–750 kg/m3, with a solid density of 1100–1500 kg/m3. Pellets contain 14–17.5 MJ/kg of calorific content (Alakangas;Hurskainen;Laatikainen-Luntama;& Korhonen, 2016).

Although most pellet boilers use volume-based fuel feeding methods, such as screw conveyors, the diameter and length of pellets are key variables in pellet combustion. Because a variable number of pellets (as well as a varied heat power) is fed at each turn of the screw conveyor, large variations in length induce uneven combustion. Pellet density is also important in pellet combustion since a high heating value necessitates a high density. Volatility in all of the above can cause issues, particularly in boilers with fixed air and fuel supplies. Abrasion, or the structural strength of a pellet, is an important quality criterion for pellets (Fiedler;Persson;Bales;& Nordlander, 2004). Abrasion creates a lot of dust, which leads to feeding issues such fuel vaulting in the storage. The abrasion can be reduced by using small doses of natural compatibilizer (Obernberger & Thek, 2004).

In 2007, 24 pellet mills in Finland produced around 330,000 t of pellets. Because domestic consumption is approximately 117,000 tons, Finland exports a substantial percentage of the pellets it produces. 61,000 tons of home consumption were utilized in small-scale applications (25 kw), the number of which peaked at around 15,000 units in 2008. The figure excludes pellet boilers, stoves, and buckets that are specifically designed to burn pellets in standard fireplaces. In comparison to Sweden, the number of households is quite low, owing to a lack of incentives for improving heating systems. The government has just begun to fund this type of heat appliance upgrade, which should stimulate interest in pellet heating systems. The small-scale pellet heating systems is predicted to reach about 50.000 by 2012, with domestic consumption increasing to over 300.000 tons as a result. The majority of output, 71 percent, is now sold in bulk and delivered by standard trucks or vehicles fitted with pneumatic pellet transfer devices. The bulk produce is kept in big silos in the factory as well as in specific silos or storage facilities at the customer's end. The issue with bulk delivery is the amounts of fines imposed. The cracking of pellets produced by mechanical stress during loading, transit, and unloading results in a larger amount of fines (Selkimäki;Mola-Yudego;Röser;& Prinz, 2010).

2.2 Combustion Process

The burning of a solid fuel particle is separated into stages: early warming, drying, pyrolysis, and char combustion or gasification. All these steps may occur concurrently in the event of a big particle. In addition, the ignition and combustion of flammable gases produced by pyrolysis may be thought of as distinct stages of the combustion process. Warming, drying, pyrolysis, and ignition are all endothermic processes, whereas burning of volatile gases and char is an exothermic response. The temperature on the particle's surface rises to the temperature where the second step, drying, occurs during the initial warming stage (Saastamoinen & Aho, 1984). Radiation from the burning of pyrolysis gases or gas phase combustion, radiation from the burning surfaces of the fuel particles, and convective heat transfer between particles all contribute to the warming (Saastamoinen;Horttanainen;& Sarkomaa, 2001).

The mixed water in the fuel particle is evaporated during the drying cycle (Saastamoinen & Aho, 1984). The drying stage is claimed to start when the particle's surface reaches evaporation temperature, although, drying starts as soon as the temperature is raised from the beginning temperature (Saastamoinen;Horttanainen;& Sarkomaa, 2001). The quantity of thermal energy used, the initial moisture content of the fuel bed, and the particle shape and size are all factors that influence drying. When the quantity of heat energy used is large, the initial moisture content of the fuel is low, and the particle size is tiny, the drying process is accelerated (Impola;Saastamoinen;& Fagernäs, 1996). The rate of evaporation is affected by the main air flow into the fuel bed. The evaporation rate will grow when the primary air flow is increased owing to a larger heat input to the evaporation zone, however beyond a certain critical point, the maximum heat input will be achieved. Both the heat intake and, as a result, the evaporation rate begins to diminish beyond this point. Increased heat input causes a higher flame front temperature and higher radiation heat transmitting to the evaporation zone (Yang;Sharifi;& Swithenbank, 2004).

After all the water has evaporated, or at least the water on the particle's surface, the temperature begins to climb until it reaches a point where pyrolysis occurs. Thermal breakdown causes the solid particle to dissolve into volatile materials and/or tar-like substance at this stage. The amount of fuel that is pyrolyzed is determined by the qualities of the fuel, the ultimate temperature, and the heating rate. Because pellets are made of wood, the percentage of mass that is pyrolyzed is like that of wood fuels in average, at 80%. Char is the material that remains after pyrolysis (Saastamoinen & Aho, 1984). As the heat rate rises, pyrolysis accelerates, producing more pyrolysis gases. As a result, the permeability of the particle increases, speeding up the burning and gasification process. The size of the particle has an impact on pyrolysis, the larger the particle, the lower the overall surface area. Also, because the warming is slower, there is less pyrolysis (Saastamoinen;Horttanainen;& Sarkomaa, 2001). The pyrolysis rate rises in lockstep with the primary air flow until a critical point is reached, just as it did with the evaporation rate. Because pyrolysis is highly temperature sensitive, a rise in temperature causes pyrolysis to accelerate (Yang;Sharifi;& Swithenbank, 2004).

When combustible gases react with oxygen, they ignite. To achieve ignition, the concentration ratio between these two must be suitable, i.e., the fuel/oxygen ratio must be greater than the lean limit. High temperature, which increases the velocity of the molecules and therefore the number of collisions between the two gases, low moisture content, and sufficient mixing of oxygen with the volatiles at the ignition location are all factors that impact ignition. Due to the enormous surface area of the particles relative to the flowing channels of gases, mixing of gases when burning pellets is typically excellent. When combusting wood particles in a packed bed, ignition normally occurs in the gas phase (Saastamoinen;Horttanainen;& Sarkomaa, 2001).

The heat energy from the combustion of pyrolysis gases is provided to the previous stages that use heat, but if there is air-staging in the process, the heat from the combustion of pyrolysis gas may occur that far from the reaction chamber that the heat rate to the fuel bed might be low. Once the lean limit of gases is reached, volatile gases ignite outside the fuel particle. When the percentage of gases is too high, i.e., there is not enough oxygen in the gas mixture to allow ignition, a scenario where ignition is prevented can occur. When this happens, the gas combination exceeds the rich limit. Temperature and the mixing of oxygen with gases are two factors that influence volatile gas combustion. The rate of volatilization in the fuel particles is affected by temperature, as is the volume of volatile gases entering the combustion zone. The gas must be appropriately combined to reach the lean limit. When these conditions are interrupted, the gas's burning slows. (Saastamoinen;Horttanainen;& Sarkomaa, 2001). Continuous combustion, on the other hand, does not have an ignition problem.

Char combustion and gasification are the ultimate stages of combustion. This stage is quite different from the pyrolysis stage. Unlike pyrolysis, which occurs because of heat transmission from the ambient to the fuel particle, char combustion and gasification occur as a result of reacting molecules diffusing to the surface and into the inner sections of char, where they induce heterogenic interactions with the char. The reaction is accelerated by the high temperature of a fuel particle. The atmosphere in char combustion is typically air or a mixture of air and flue gas, whereas the atmosphere in char gasification is a mixture of gasification gases and gasification products. In most cases, gasification takes place in an oxygen-depleted atmosphere. Char ignites when the temperature of the char reaches a critical point and there is enough oxygen on the particle's surface. The pace of pyrolysis limits char combustion because it prevents oxygen from reaching the char's surface if volatilization and/or drying is still taking place inside the particle. This impact is most pronounced when big fuel particles are present. Char combustion is also significantly slower than pyrolysis gas burning, which might result in a situation in which the pyrolysis gases consume all oxygen in the event of low air flow (Saastamoinen;Horttanainen;& Sarkomaa, 2001). As a result, the primary air flow has a noticeable influence on the char combustion rate. Because of the increased availability of oxygen, raising the main air enhances the char combustion rate (Yang;Sharifi;& Swithenbank, 2004). The char combustion rate is also boosted by a faster devolatilization rate and a higher flame front temperature. Mostly in case of wood-based fuel, the fraction of char from the dry composition is only 10-30%, but when combusted, char combustion generates around 25-50% of the overall heat generation (Flagan & Seinfeld, 1988).

2.3 Emissions

When hydrocarbons are burned, the results should ideally consist exclusively of water and carbon dioxide, assuming that the combustion is complete. In the case of wood combustion, various additional products are always present. Carbon monoxide, nitric oxides, unburned hydrocarbons, particle emissions, and dust are the most significant pollutants from wood pellet burning (Johansson;Tullin;Leckner;& Sjövall, 2003).

3 Pellet-fired Heating Systems

Pellet stoves and central heating units are the two types of pellet heating equipment available. Boilers for central heating are split into two types: integrated units, which contain both the boiler and the burner, and two-unit boilers, which contain both appliances separately. A pellet stove with a water jacket is another item that may be classified as a central heating unit. Pellet heating systems in household usage have a thermal output ranging from 10 to 40 kW, although most are less than 25 kW. (Fiedler;Persson;Bales;& Nordlander, 2004).

3.1 Central heating boilers

Pellet boilers are quite similar to oil boilers, with the exception of the fuel, the fuel input system, the 12 vertical heat exchanger surfaces, and the bigger combustion chamber. Heat exchanger surfaces are made vertical to avoid soot, fly ash, and slag from depositing on them and interfering with heat transmission, lowering the overall efficiency of the unit. Biofuel boilers, like oil boilers, require a bigger combustion chamber because if there is not enough room, the flame will hit a cool convection surface, lowering the temperature of the flame. This fall in temperature leads to worse gas combustion, which reduces efficiency, increases emissions, and fouls the exchanger surfaces. A conveyor transports pellets from the hopper to the combustion chamber. The igniting of the fuel in the combustion chamber is accomplished by the use of an electric device or by the maintenance of a pilot flame. Following ignition, combustion produces heated flue gases. Conduction across the heat exchanger transfers the heat of the flue gases to the boiler water. A circulation pump transports the warm water to the heat distribution system. An electric fan feeds combustion air into the system, which in many situations also delivers secondary air. The size of the combustion chamber is determined by the maximum power of the boiler and sufficient heat transmission over the whole power range. Some boilers can automatically adjust the heat output from 30 to 100 percent. (Loo & Koppejan, 2008)

Two-unit boilers are made up of a boiler and a burner. If the previously indicated parameters are satisfied, pellet burners can be installed in existing boilers. In many situations, the burner is manufactured by a different company than the boiler, which may result in lower efficiency owing to compatibility issues between the two devices. For example, pellets burner produce more flue gas than oil burners, which may result in a situation in which the residence period of the hot exhaust gases in the boilers is too short, leading in too hot flue gas departing the boiler, lowering the combustion's efficiency. Emissions of hydrocarbons are also caused by a short residence period of the flue gas. In Sweden and Finland, two-unit pellet boilers are the most common kind. (Fiedler;Persson;Bales;& Nordlander, 2004)

3.2 Pellet burners

There are burners specifically intended to combust pellets on the market, as well as burners that are meant to consume wood chips but can also combust pellets with various settings. Pellet burners are classified into three varieties based on how pellets are fed into them. Laterally fed burners, bottom fed burners, and top fed burners are the three types of burners. (Loo & Koppejan, 2008). The diverse types are illustrated in Figure 1.

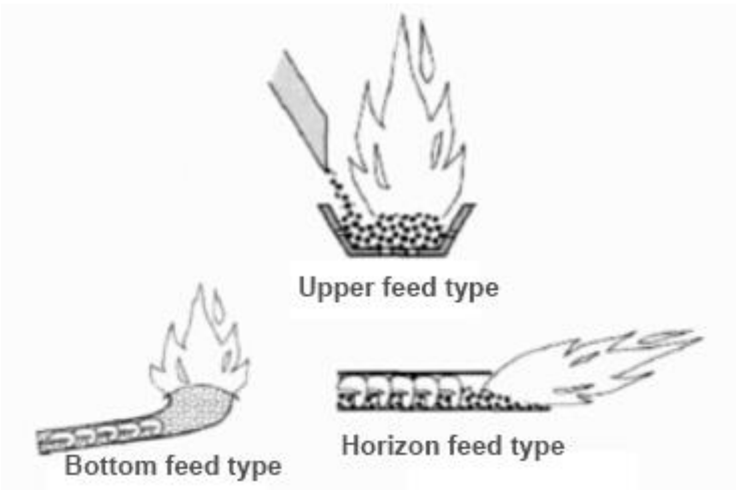


Figure 1: Three types of pellet burners (Anyang GEMCO Energy Machinery Co, n.d.)

3.3 Air supply

The combustion chamber is separated into primary and secondary zones in order to enhance the combustion process. Both zones have their own air supply, which includes both primary and secondary air. The main zone is where the initial heating, drying, pyrolysis, and char combustion occur. They also occur concurrently because new fuel is always being introduced to the fuel bed. These reactions are carried out using an air-to-gas ratio that is less than stoichiometric. The pyrolysis and gasification gases are combusted with surplus air in the secondary zone. (Fiedler;Persson;Bales;& Nordlander, 2004) Because air division is normally done structurally, if the boiler only has one air fan, it is not possible to adjust the ratio afterwards (Korpela,, 2005).

The chamber under the grate is normally supplied with primary air. The grate is used for drying, pyrolysis, and ultimate combustion, in which the char burns. If there is not enough primary air, the char burns more slowly, lowering the temperature and expanding the area of the fuel bed. NOx emissions rise when there is too much primary air (Kilpinen, 2002). The basic goal of air staging is to lower NOx emissions by introducing lowering zones into the primary zone.

Depending on the burner structure, secondary air is delivered into the chamber via the chamber walls or the ceiling. The aim of secondary air is to supply air for the burning of gases that have been pyrolyzed and/or gasified from the fuel. It is critical that the secondary air that is delivered into the chamber mixes effectively with the volatiles. This may be accomplished by supplying sufficient secondary air speed and by appropriately locating and dimensioning nozzles. (Kilpinen, 2002). Overfeeding of secondary air cools the flame, causing more co emissions and shortening the residence time of the gas in the combustion chamber, resulting in a drop in efficiency since all of the pyrolysis gases are not consumed in the boiler. Furthermore, because the flue gas has a shorter residence time in the boiler, the ability of the boiler to accept heat is diminished because there is less time for heat transfer from the flue gas to water. This is a more important influence in diminishing combustion efficiency than the increase in unburned pyrolysis gases. When there is a lack of secondary air, all of the gases are not burnt, resulting in higher emissions and a drop in efficiency. (Johansson;Tullin;Leckner;& Sjövall, 2003)

3.4 Automatic feeder

Combining load management and combustion control allows for automatic running of pellet heating systems (Obernberger & Thek, 2004). The temperature of the flowing water in the boiler is used to manage with fuel load. (Johansson;Tullin;Leckner;& Sjövall, 2003) Load control can also be accomplished by sensing the temperature of the surrounding environment. (Fiedler;Persson;Bales;& Nordlander, 2004). Pellet boilers are frequently controlled by a thermostat, resulting in cyclical and continuous operation. In some more advanced boiler systems, the temperature outside of the building is also recorded and utilized to forecast the coming load. Power levels can be modulated between %thirty and %100 in complex systems. The boilers in these systems are fitted with drought fans rather than air fans. (Fiedler;Persson;Bales;& Nordlander, 2004)

In complex systems, combustion control is dependent on the use of a lambda sensor and/or temperature measurements from the combustion chamber. These boilers are popular throughout Central Europe. Frequency converters are used to give input signals for feeding screws, air fans, and draught fans in systems that employ modulating power levels. It is possible to specify an oxygen value below which the process should not function at a certain power level by using an oxygen/lambda sensor for combustion control. Thus, it is feasible to conduct air feed in such a way that the oxygen remains at such a level that emissions are limited, and efficiency is good owing to the avoidance of surplus air feed. However, because these oxygen limit values are equipment and power level dependent, the limit value should be redefined for each power level. (Eskilsson;Rönnbäck;& Samuelsson, 2002).

The air supply to the boiler can be accomplished by operating a fan depending on the under pressure measurement from the boiler, and the main and secondary air division is accomplished by controlled flaps. Another option is that the primary and secondary air feeds are handled by two different air fans. In these circumstances, the primary air feed is regulated according to the fuel feed (through load control), and the secondary air feed is utilized to trim the oxygen level to a desirable value based on the oxygen measurement. In boilers with separate fans, it is likely that there's a separate draught control as well. (Obernberger & Thek, 2004).

Because temperature measurement is a good indication of the heat power gained, and therefore showing the stability of the fuel feed, combustion control with temperature measurement from the combustion chamber may be used to make the pellet feed as even as possible. Because the oxygen level in pellet combustion normally has a strong negative association with the temperature in the combustion chamber, the temperature measurement may be used as an oxygen measurement by employing a soft sensor technique. (Korpela,, 2005) Temperature monitoring can also be used to manage flue gas recirculation in boilers. Adaptive control is a technology used by some boiler manufacturers (Obernberger & Thek, 2004).

Pellet producers now sell automated pellet transporters that carry pellets from larger storage areas to the boiler's fuel hopper. Screw conveyors are the most common conveyance devices, however, pneumatic conveyors are also available. Pellets are transferred from the storage chamber to the intermediate silo by air suction in these pneumatic conveyors. In order to make the heat transmission as efficient as possible, modern boilers contain automated cleaning of the heat exchanger surfaces. In addition, the ash is automatically evacuated from the combustion chamber. Grate sweeping, which evens the fuel bed and moves ash to the ash pan from the grate, if necessary, is also part of the automated maintenance routines. Moveable rods that are operated at predetermined intervals can be used to sweep the grate.

4 Analysis Method

4.1 Data Analysis

Data analysis is the systematic application of statistical or logical procedures to describe and illustrate, compress, recapitulate, and assess data. According to Shamoo and Resnik (2003), various analytic processes offer a way of generating inferences from data and discriminating the signal from the noise contained in the data.

Statistical processes may possibly be used in data analysis. The analysis is often a continuing process in which data is acquired and examined concurrently. Generally, there is looking for patterns in observations throughout the data gathering process (Savenye, Robinson, 2004).

4.1.1 Regression Analysis

Regression analysis is used in statistical modeling to predict the correlations between two or more variables. The dependent variable is the primary component you are attempting to explain and estimate. The elements that might impact the dependent variable are known as independent variables. Regression analysis explains how the dependent variable changes when one of the independent factors changes, and it allows you to calculate which of those variables has the most influence.

A regression analysis model is technically based on a mathematical method for determining the dispersion of data. A model's purpose is to obtain the least feasible sum of squares and to draw a line that is closest to the data. Linear regression uses a linear function to model the relationship between a dependent variable and independent variable. Multiple linear regression is the process of predicting the dependent variable using two or more variables. Use nonlinear regression in place of linear regression if the dependent variable needs to be modeled as a nonlinear function because the data relationship is not linear. (Cheusheva, n.d.)

5 Venect Boiler System

The experimental work for this thesis topic was carried out at the labs of Häme University of Applied Science in Valkeakoski. The boiler utilized was a VETO Oy commercial boiler from a Finnish boiler company. The boiler was also used to test biomass pellets derived from various sources. However, because the testing of these pellets was not part of this thesis, this work is not included in the thesis. Sensors and custom-made switchboard electronics were created in the same section of instrumentation and control engineering as the measuring equipment. The next chapters comprehensively present all of the used equipment.

5.1 System Components

The studied heating system was composed of biomass boiler, three hot water tanks and three pumps. In addition, the system had a pellet feeder, ignition unit, various sensors, valves, and actuators. There were also two fans for supplying primary and secondary air into the combustion chamber. The heating system is demonstrated in figure 2.

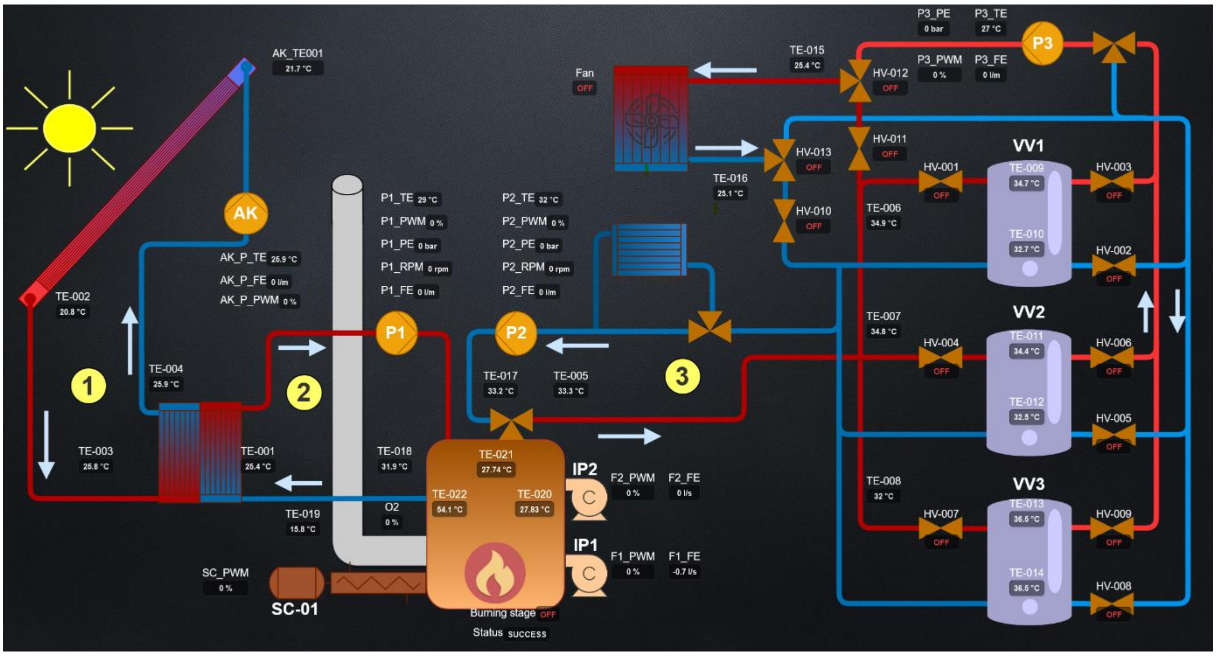


Figure 2: VeneCT control panel

5.1.1 Fuel properties

Pellet specification and fuel properties according to the manufacturer' datasheet were as follows (Versowood Oy, 2015);

- Manufacturer: Versowood Oy from Finland.
- Raw material: wood biomass.
- Wood species: spruce and pine.

- Characteristics: Diameter 8 ± 1 mm, length 3.15 ≤ l ≤ 40 mm, pellets longer than 40 mm can be max. 1% by weight. Mechanical resistance ≥ 97.5%, heat value: ≥ 4.6 kWh/kg, specific weight: 650 kg/loose m^3±5%, standard minimum density ≥ 600 kg/loose m^3.

- Moisture content: ≤ 10% (m 10) ash: ≤ 0.5% by weight chlorine: ≤ 0.02% by weight sulfur: ≤ 0.03% by weight (s 0.03) type: ≤ 0.3% by weight additives: binders ≤ 2% by weight.

- Quality criteria: SFS-EN ISO 17225-2 solid biofuels. fuel quality requirements and grades.

5.1.2 Boiler Design

The boiler utilized was a Veto 60 with a rated thermal output of 60 kW. The boiler was an integrated boiler. The boiler was intended to burn both biomass and fuel oil. The boiler's rated efficiency was 92 percent when using wood pellets as fuel. The boiler was intended for pellets with a diameter of 6,8 mm and a standard fuel input of 5,6 kg/h at rated output. (Veljekset Ala-Talkkari Oy, n.d.)

Figure 3: Veto 60 biomass boiler

The burner is horizon-fed, and the fuel is delivered by a screw conveyor. The conveyor transports pellets from the storage container to the vent via a hole on the side wall of the combustion chamber. Pellet is fed into the system at predefined intervals by a control unit. The screw rolling phase and the idle state are two of these times. The boiler is outfitted with two electric air fans that was initially impulse-controlled and cannot be adjusted to different air flow speeds. The air fan in the experimental configuration, on the other hand, is now operated by manually with adjusting the cover on the inlet. The fan circulates combustion air through the combustion chamber. The boiler's flue gases are sent to a chimney. There is no draught fan in the flue gas duct, therefore the boiler runs in natural atmospheric circumstances.

5.2 Measurement and Control

The positions of measuring sensors were also included in the experimental setup, which included four thermocouples. Temperatures were monitored in the combustion chamber, after the first heat exchanger, in the flue gas, and in the outgoing water. A standard thermometer inserted into the ingoing water tube was used to measure the temperature of the input water. In addition to the thermocouples, a gas analyzer was used to measure the amounts of CO and O2 in the exhaust gas. The gas analyzer was of the sample-taking variety, and the analyzer portion was made up of electro-chemical cells.

The flow rate of water was read via a meter inserted in a tube supplying the water into the water circuit. The combustion chamber temperature was measured from the end of the grate. After the first heat exchanger, the second thermocouple was situated downstream the flue gas duct. At this stage, the gas flow may be presumed to be adequately mixed, i.e. no substantial channeling occurs, implying that the derived temperature value accurately represents the condition.

The thermocouple monitoring the temperature of the flue gas was placed right before the gas analyzer probe, around the flue gas exited the boiler. The temperature of the incoming water was quite near to the boiler wall. The gas analyzer probe was situated after entering flue gas duct into the boiler. The gas analyzer is made up of a sample probe, a sampling pump, sample pre-processing components, and electro-chemical cells that do the actual analysis. The analyzer can measure many gas components, and each gas component has its own cell in the analyzer.

Fuel feed or air feed were supposed to be the process's inputs. However, at the very beginning of the tests, the initial values and adjustments were not read properly. Furthermore, neither the location of the air staging valve, nor the fuel feed were an input to the process, because they were not controlled in a reliable way and fluctuations on their values were high, so none of them was not examined further.

A Testo 350 boiler kit was utilized for analyzing the flue gas as a result of the combustion process. This device is a robust emissions and combustion analyzer designed for testing boilers and burners in industrial and commercial applications.

Figure 4: Testo flue gas analyzer

5.2.1 Combustion efficiency

Combustion efficiency is calculated with following formula. (Testo AG, 2014)

$$qA = (FT - AT) \times \left[\frac{A_2}{(21 - O_2)}\right] + B \qquad (1)$$

FT: Flue gas temperature

AT: Ambient air temperature

A_2 , B: Fuel specific factors

O_2: oxygen level in flue gas

With that the formula have been simplified to the so called Siegert Formula. (Testo AG, 2014)

$$qA = f \times \frac{FT - AT}{CO_2} \qquad (2)$$

Pellet-specific factor (f) used in the formula as 0,74 according to testo manual.

6 Analysis of the Test Results

Data was collected for ten minutes at 2 second intervals in each test. After ten minutes the load level and fan speed were adjusted to a new preset value and the data collection started again with the same duration and interval.

A Regression analysis was carried out for determining which parameters have a higher influence on combustion efficiency. Linear regression was used to develop a regression model to evaluate the data. CO_2 concentration was chosen as a dependent variable. The load level and fan speed were independent variables in this project.

The fuel feeding capacity was critical in order to achieve the expected efficiency. It was also required to configure the air supply to provide air to the burner. At early stage of these combustion tests, five experiments were conducted with three different combinations of setup. Main idea is to get better combustion efficiency.

This analysis' factors, and combustion efficiency are recorded and shown in Table 1. The correlation investigated using statistical analysis, and the results are summarized in Table 2.

Table 1: Test measurements

Test No	CO2 % in flue gas	Load Level %	Fan Speed %
1	1.41	70	25
2	1.60	70	25
3	1.92	70	25
4	2.03	70	25
5	3.30	50	50
6	6.17	50	50
7	9.25	50	100
8	11.53	50	100
9	12.64	30	25
10	13.24	30	100
11	13.65	30	100
12	14.16	30	100
13	14.46	30	100
14	14.83	30	100
15	16.30	30	100

Table 2: Summary of statistics

Variable	Min	Max	Mean	σ
CO_2 % in flue gas	1.41	16.30	6.64	5.50
Load level %	30.00	70.00	43.09	16.65
Fan speed %	25.00	100.00	57.43	34.72

Table 3 shows a scatter plot for two parameters and the combustion efficiency, indicating that CO_2 concentration in the flue gas and combustion efficiency have a non-linear relationship in general.

Table 3: Scatter plot of combustion efficiency

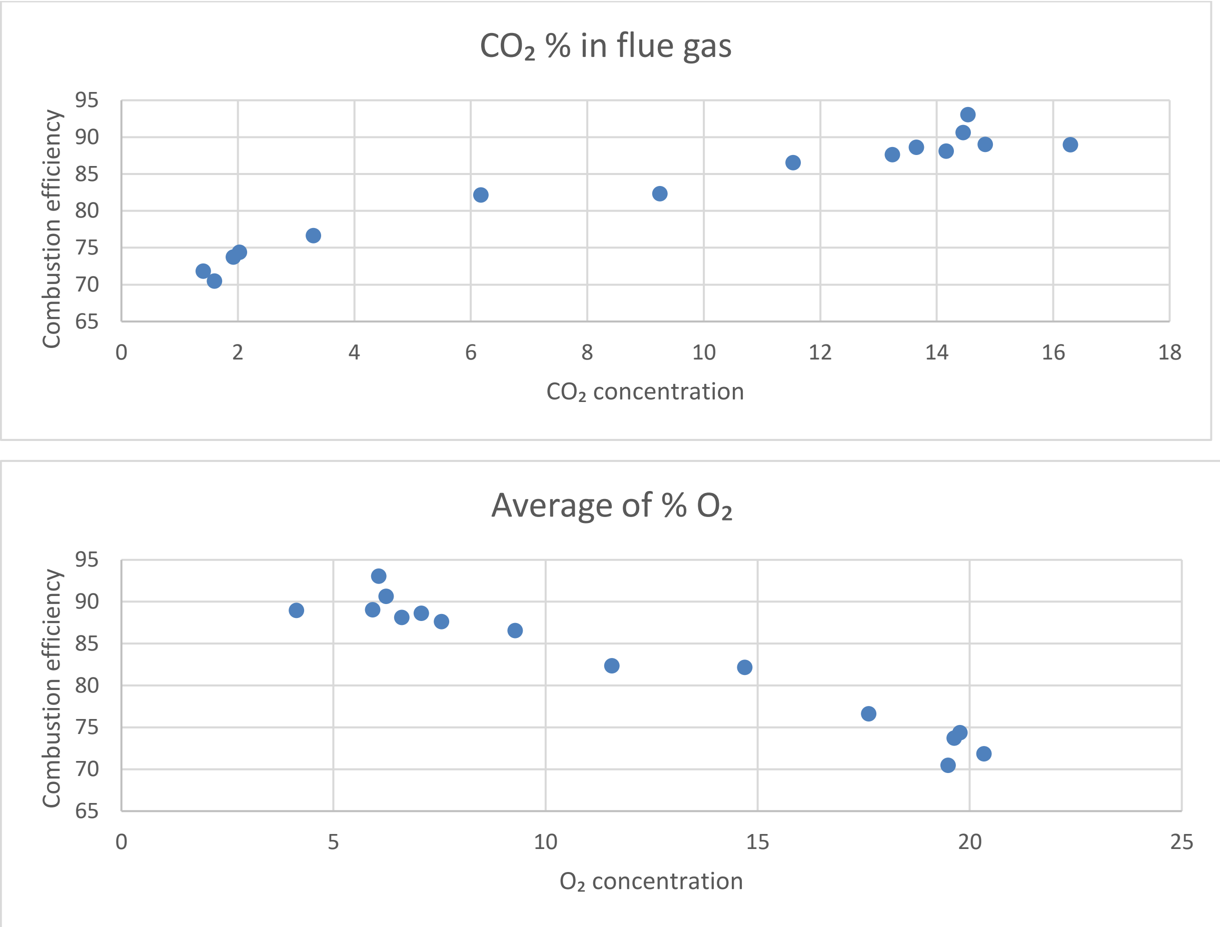


Table 4 depicts the correlation between O_2 and CO_2 in flue gas and combustion efficiency. There is a strong correlation between CO_2 and O_2 concentration in flue gas and combustion efficiency. The efficiency of combustion has a positive relationship with CO_2 concentration in flue gas. As the number of CO_2 concentration increases, so does the efficiency of the combustion as well.

Table 4: Correlation matrix

Variable	**CO_2 concentration in flue gas**	**Load level %**	**Fan speed %**
CO_2 concentration in flue gas	1	-0,946	0,830
Load level %	-0,946	1	-0,738
Fan speed %	0,830	-0,738	1

7 Results and Discussion

Based on load level and fan speed, a regression analysis was performed on CO_2 concentrations in the flue gas. The goodness of the fit was assessed using the coefficient of determination (R Square).

Multiple R	0,966
R Square	0,933
Adjusted R Square	0,921
Standard Error	1,597
Observations	15

Table 5: Statistics of regression analysis

	df	SS	MS	F	Significance F
Regression	2	423,89856	211,94928	83,12393919	9,30982E-08
Residual	12	30,59757977	2,549798314		
Total	14	454,4961398			

Table 6: Analysis of variance

The processes outlined in the preceding section were followed with a calculation of the model's coefficients, which are listed in Table 7.

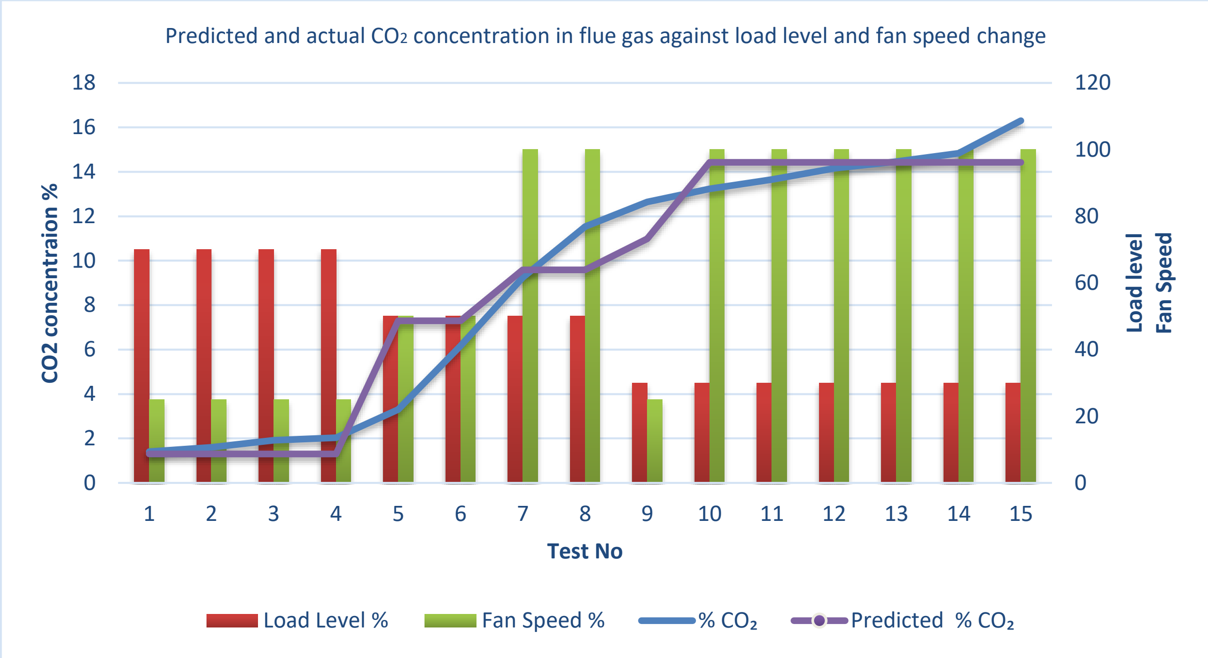
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	17,097	2,731	6,261	0,000	11,148	23,047
Load level	-0,242	0,037	-6,598	0,000	-0,322	-0,162
Fan Speed	0,046	0,018	2,608	0,023	0,008	0,084

Table 7: Model parameters

Based on the regression analysis the following model was derived.

$$\text{CO2 \% in flue gas} = 17.097 - 0.242 \times \text{Load level} + 0.046 \times \text{Fan speed}$$

Figure 5: Predicted CO_2 concentration influence depending load level and fan speed.



8 Conclusion

The main problem with domestic pellet boilers is that there are practically no measurements related to them at all. Therefore, a practical implementation on the optimization of pellet boilers would require predefined parameters in order to reach the optimal combustion efficiency. In this project we came to the conclusion with a Venect boiler system that the fan speed of the primary air feed should be 100 %.

Inadequate combustion air reduces fuel efficiency and produces a large volume of carbon monoxide. Extra combustion air is given to ensure that there is adequate oxygen to thoroughly react with the pellets. This additional air is stated as a percentage of what is required for full combustion.

One of the main causes of poor combustion efficiency is the usage of too much extra air. Most of the pellet boilers reach the highest efficiency at around %7 of oxygen concentration in flue gas. (Kirsanovs, et al., 2014) As a result, minimizing excess air utilization might be one of the most effective methods of achieving extra fuel savings.

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