Diploma thesis No. 3582

Mr.cand. Mach. *Alexios-Vasileios Papandreou (ERASMUS)*

Matr.-Nr. 3197525

Application of an electrical ignition system for cold start up using hard coal

Date of issue: 1.10.2018

Date of submission: 1.04.2019

Supervising tutor: MSc. Reyhane Youssefi

Submitted at University of Stuttgart

Institut für Feuerungs- und Kraftwerkstechnik

Acknowledgement

I would like to express my gratitude to the director of the Institute of Combustion and Power Plant Technology (IFK) Prof. Dr. techn. G. Scheffknecht for providing me with the opportunity to conduct this study, and my supervising tutor MSc. Reyhane Youssefi for the guidance and support during the course of the study.

Dedication

For their unconditional love and support through this study I would like to dedicate this work to my parents, Andreas Papandreou and Eleni Nikolakarou, as well as my brother Dipl.-Ing. Ioannis Papandreou.

Task Description

1. Problem Definition

To develop the plasma assisted ignition and combustion system for power plants, the technology need to be first tested in pilot scale in order to identify the limitations and boundary conditions. These conditions are directly related to the burner design and fuel characteristics. Therefore, the electrical ignition system need to be investigated comprehensively for each fuel quality

2. Objectives

Two types of hard coal with high and low volatile contents will be used for investigation and development of the plasma ignition system. Different experimental conditions will be tested to evaluate the ignition behavior. A parametric study on the effect of the air ratio, the position of the plasma lance inside the coal burner and the thermal load of the burner will be performed. The ignition and following combustion process are recorded with a visual system and a dedicated flame scanner

3. Task Description

1. Literature review about ignition and combustion process, flame characterization and plasma assisted combustion

2. Ignition test performance for 2 types of hard coal in a 500kWth combustion facility

3. Evaluation of recorded data

Kurzfassung

Aufgrund der Notwendigkeit von Kraftwerken, ihre Flexibilität zu erhöhen, wird derzeit eine neue Startmethode mit einem Plasmabrenner entwickelt und untersucht. Ziel dieser Studie war experimentell die Anwendbarkeit des Plasmabrennersystems, um eine Zündung von Hartkohlen unter kaltem Ofen zu erreichen, und die Fähigkeit, diese Zündung aufrechtzuerhalten, nachdem der Plasmabrenner ausgeschaltet wurde. Mehrere Betriebsparameter wie thermische Belastung, Primärluftstrom, Luftverhältnis, Position des Plasmabrenners, verschiedene Düsen wurden an zwei verschiedenen Arten von Hartkohle mit unterschiedlichen physikalischen und chemischen Eigenschaftsunterschieden untersucht. Die Tests wurden an einer 500-kW-internen Anlage mit einem 3,5-kW-DC-Plasmabrenner durchgeführt. Die Tests werden mit den Kriterien der für diese Studie verwendeten Zündgrade verglichen und bewertet. Die Ergebnisse und Ergebnisse der beiden Steinkohlen zeigten für die Zwecke dieser Studie einige optimistische Ergebnisse, jedoch nur unter bestimmten Bedingungen, die durch die vorgenannten Parameter festgelegt wurden.

Abstract

Due to the need of power plants to increase their flexibility, a new start-up technique using a plasma torch is being developed and studied. The objective of this study experimentally the applicability of the plasma burner system to achieve ignition of hard coals under cold furnace conditions and the ability of sustaining said ignition after the plasma burner has been turned off. Multiple operational parameters such as Thermal Loading, Primary air flow, air-ratio, position of the plasma burner, different nozzles were studied on two different types of Hard coals with distinct physical and chemical property differences. Tests were conducted on a 500kWth in-house facility with a 3 kW DC plasma torch. The tests are compared and evalu-

ated with the criteria of ignition grades that were used for this study. Results and findings on the two hard coals showed some optimistic results for the purpose of this study but only under specific conditions set by the aforementioned parameters.

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List of Abbreviations

IFK	Institute of Combustion and Power Plant Technology
KSVA	Kohlenstaubverbrennungsanlage
ISO	International Organization for Standardization
TL	Tragluft
SL	Sekundarluft
DC	Digital Current
SA	South African
EC	El Cerrejon

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1 Introduction

The last few years it has been noticed an increase of use of renewable energy to generate power in order to reduce the environmental problem that exists in the world due the high amount of pollutants that fossil fuels produce. For that reason a new Plasma technology is being developed to increase the flexibility of the power plants and replace the conventional oil/natural gas burners. Renewable Energy provides a high quota of the weekly energy market however due its unreliable state it is needed for the power plants to be ready to provide any excess in energy needed if the renewable energy methods fail to adhere to the requirements. Below is shown a graph depicting the Energy consumption for a week in Germany and the sources it derives.

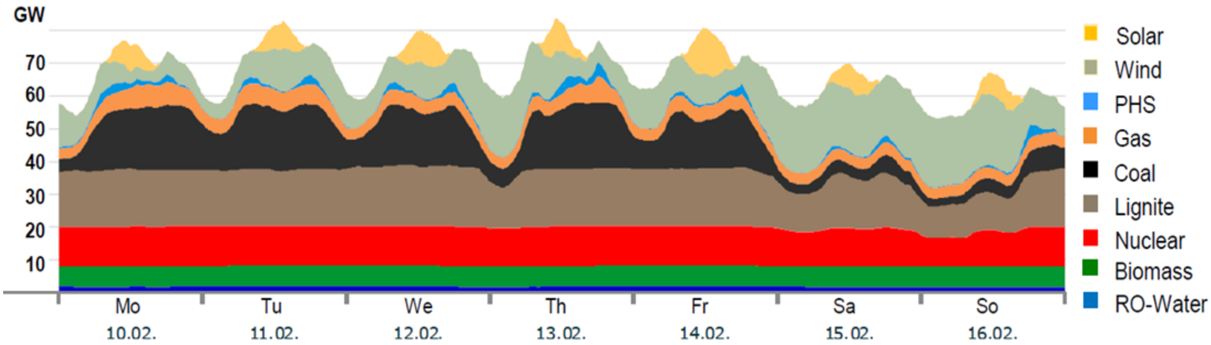

Figure 1.1 Weekly Energy Consumption for Germany 2014 (1)

In the following thesis, a detailed parametric study is conducted in a 500 kW pilot-scale pulverized fuel combustion plant at the Institute of Combustion and Power Plant Technology (IFK). A burner with an integrated plasma ignition system is used for providing initial ignition energy to solid fuel particles. The parameters such as air-fuel ratios, thermal loading, plasma torch positions are varied to study and investigate the ignition and combustion behavior of two different types of hard coals with distinct chemical and physical properties, El Cerrejon with a medium volatile count and South African hard coal with low volatile count.

The combustion is observed through video recording during the test for detailed evaluation. The results of the tests are then evaluated according to the extent of combustion achieved against different operating parameters. The results are used to define the suitable operational range for each specific fuel.

2 Literature Review

2.1 Ignition

The coal undergoes the ignition and combustion process after the moisture content has been extracted and it has undergone thermal decomposition, in order to form volatile gases and residual char substances.

The difference between the volatile gases and the char in terms of combustion is that the volatiles ignite and combust homogenously whereas the char leans towards the heterogeneous oxidation and combustion (2) Volatiles released in a gaseous phase begins to mix and diffuse in the oxidizer medium while at the same time the gaseous phase volatiles are being heated by the external source of thermal energy. As this heat and mass transfer of gaseous volatiles and oxidizer continues the exothermic reaction rate increases which also increases the chemical heat release rate.

This chemical heat release rate further accelerates the exothermic reaction and finally, a flash point is achieved where the thermal ignition begins. (3) This point is classified as the point where the chemical heat release by the volatiles exceeds the heat dissipated to the surrounding and hence the point of ignition. (4) Thermodynamically speaking the ignition is driven by convective and radiative mode of heat transfer between the gaseous volatiles and the oxidizer. The radiative mode of heat transfer is highly dominant, exponentially two orders of magnitude higher. (5) The ranges of ignition temperature for volatile content is between 500 °C to 700 °C while the char is ignited above 700 °C (4). Ignition of the hard coal particle is influenced as well by the size of the coal's particles as well as the rate of provided heat. In the following Figure 2.1 the three modes of ignition are observed for coal particles.

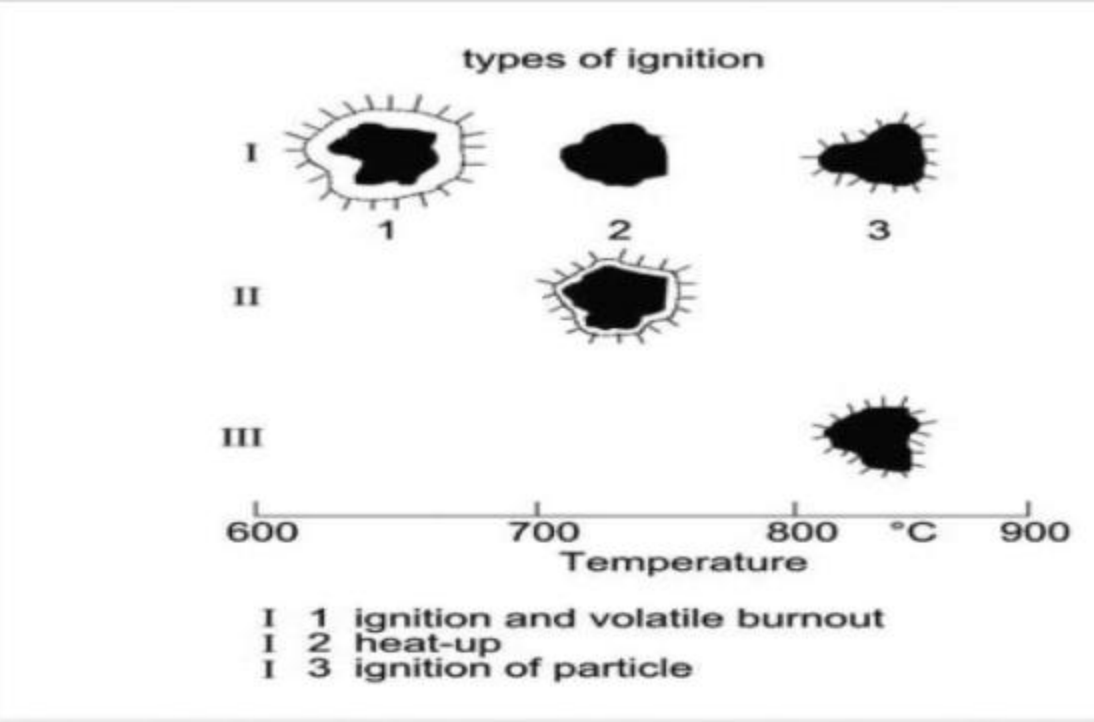

Figure 2.1 Ignition mechanism of coal particles (4)

- Mode I

When the rate of heating the particles is relatively slow, the ignition of the larger particles leads to the extraction of volatile matters and their ignition in the surrounding areas of the coal particles. Therefore a combustible mixture of light volatile gases is built and ignited which then forms a wrapping of gases around the coal particles. This inhibits the diffusion and mixing of oxygen with the rest of the coal particle. Therefore, ignition of the residual char is only possible after the burn out of the volatile gases around it. (4) (6)

- Mode II

When the rate of heating the particles is higher, the ignition of the larger particles lead to the concurrent and synchronous ignition of the volatiles as well as the coal particles. The heating rate helps in quick diffusing of the oxygen molecules into the surface of the coal particles without being restricted by volatiles envelope. Because of that, devolatilization times are slightly increased and hence, the complete ignition of the coal particle is a possibility before the burn out of the volatiles. (4) (6)

- Mode III

The smaller particles, when ignited with a higher rate of heating, can lead to the ignition directly on the surface of the coal particles. This is since as the particle diameter decreases the effective area available for the chemical reaction greatly increases. Hence, the particles are promptly heated and ignition condition for the solid particle is achieved even before an ignitable mixture of volatiles is formed around the particle. (4) (6)

Figure 2.2 shows a linear trend line of the increasing ignition temperature, increasing by 10.7, 6.0, and 2.4 ^{o}C at the heating rates of 10, 20, and 30 ^{o}C*min^{-1} , respectively, as the particle diameter increased by 1 mm. It is notable that the variation tendency in the ignition temperature of different particle sizes at higher heating rates was not as severe as that at lower heating rates (7)

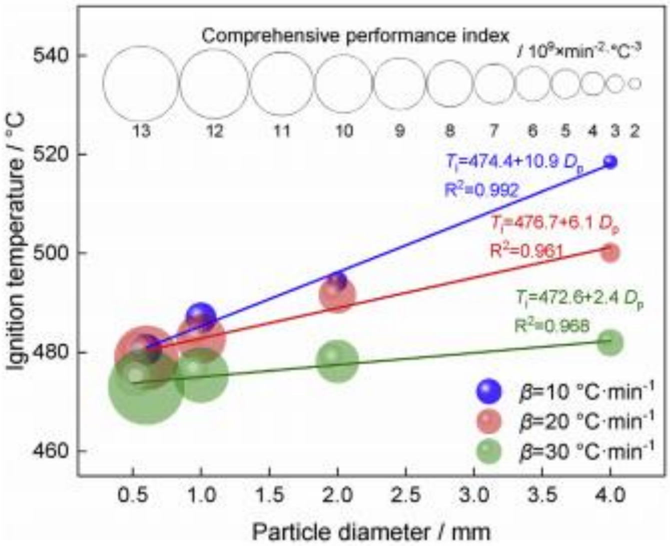

Figure 2.2 Ignition temperatures and comprehensive performance indices of samples of four diameters at three heating rates

In the following section the different parameters affecting the ignition of the coal particles are going to be discussed.

a. <u>Coal Rank</u>

The coal's rank has an impact on the ignition characteristics of its particles. Bituminous coals proceed towards typical homogenous ignition of volatiles followed by heterogeneous ignition of char. On the other hand, Anthracite coals show primary fragmentation before homogenous ignition. Lignite coals undergo direct fragmentation prior to homogenous ignition. (8). The rank of the coal also affects the ignition temperature of coal. As higher rank coals have low volatile matter, the ignition temperature increases with the rank of the coal. (9)

b. <u>Particle Size Diameter</u>

The reactivity of coal particles decreased as the particle size increased. The ignition and burnout temperatures of coal particles rise linearly with the increase in particle size. The comprehensive combustion performance index is reduced with increasing coal particle size. The diversity of activation energies between different diameters is magnified with the increase of particle size within the range of ignition temperature and become far greater than that after the ignition. In addition, the effect of particle size on the ignition of large coal particles decrease with the increase in heating rate, while the effect on the burnout is enhanced (7)

c. <u>Oxygen Concentration</u>

According to studies that were conducted on different ranks of coals, the increase of oxygen in the system significantly decreases the ignition temperature (10). This is explained by an improvement in reaction kinetics of the fuel and oxidizer as the oxygen concentration is increased.

d. <u>Heating Rate</u>

As mentioned before, increase of heating rate results in the simultaneous heating of the volatiles and the char which leads into an improved ignition of the coal

e. <u>Moisture Content</u>

The amount and nature of the moisture content present in the coal particles directly affect the ignition of the coal. Studies conducted on Victorian brown coal (11) indicate that with the increase of inherent moisture content in the coal, drying overlaps with devolatilization. Therefore, a significant amount of energy that arises from the devolatilization is being consumed in the vaporization of the moisture. This leads to a delayed ignition with high ignition temperatures.

2.2 Plasma Technology

Plasma, which is the fourth state of matter is an ionized gas consisting of positive ions and free electrons in proportions resulting in more or less no overall electric charge, provides and unprecedented opportunity for combustion and emission control, owing to its unique capability in producing active species and heat and modifying transport processes. New Reaction pathways, such as Atomic O production from the collisions between high energy electrons/ions and oxygen molecules can be introduced into combustion systems to modify the fuel oxidation pathways considerably. (12)

In the last two decades, plasma has been demonstrated as a promising technique to enhance combustion, reduce emissions and improve fuel reforming.

Recent studies using plasma torch, (13) (14) filamentary discharge, microwave discharge, low frequency arc, discharge, streamer high frequency (HF) discharge, surface discharge, and nanosecond pulsed discharge (NSD) have shown that plasma can enhance ignition, flame stabilization, and fuel/air mixing via chemical, thermal and plasma induced aerodynamic effects. Recent studies (15) (16) have also demonstrated that plasma discharge in pulsed detonation engines (PDE) can shorten the ignition delay time and facilitate the transition engines, pulsed and steady plasma jets, gliding arc, DC electric field and HF streamer discharge have been tested to increase flame stabilization.

The results have showed that plasma discharge can extend lower lean blowout limit and lean flammability lament. In addition to combustion enhancement, plasma has also been used in emission control (17). By using a plasma jet (18), gliding arcs (17), pulsed corona discharge (19) (20), and dielectric barrier discharge (21) (22), extensive studies have shown that NOx emission can be effectively reduced. Recent studies have extended plasma emission control to remove SO_x (17) (23) (24) and unburned hydrocarbons (e.g., toluene and naphthalene) (25) (26) in flue gas.

2.3 Plasma Assisted Combustion

Instead of usual system of heavy oil burners for pulverized coal ignition and combustion stabilization in utility boiler furnaces, plasma torches are built in air–coal dust mixture ducts and applied for the purpose, in order to achieve the savings of liquid fuel (27)

Plasma assisted combustion is a unique way to increase flexibility of the solid fuel power plants regarding the startups. Plasma-fuel systems procedure is based on plasma thermo-chemical activation of coal for burning. It consists in arc plasma heating of air-fuel mixture up to the temperature of coal devolatilization and carbon residue partial gasification (28). The plasma torch is integrated into the combustion chamber in order for the fuel to come in contact with the plasma flame before entering the combustion chamber. A picture depicting how a setup might look is located below.

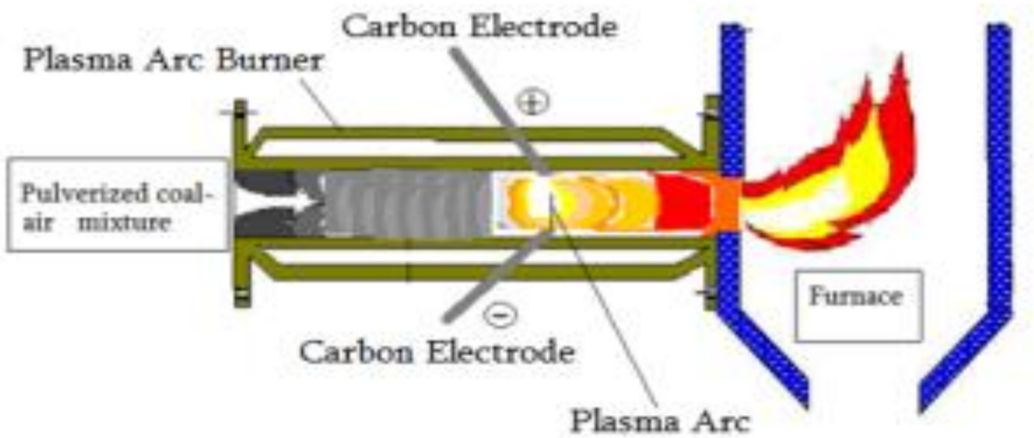

Figure 2.3 General scheme for a plasma arc burner system for pulverized coal combustion (28)

Figure 2.4 and Figure 2.5 present experimental results for NO_X reduction and the decrease of unburned carbon during plasma fuel system operation versus specific power consumption for the plasmatron. It is seen that the NO_X concentration is halved, and the amount of unburned carbon is reduced by a factor of 4 (29) (28)

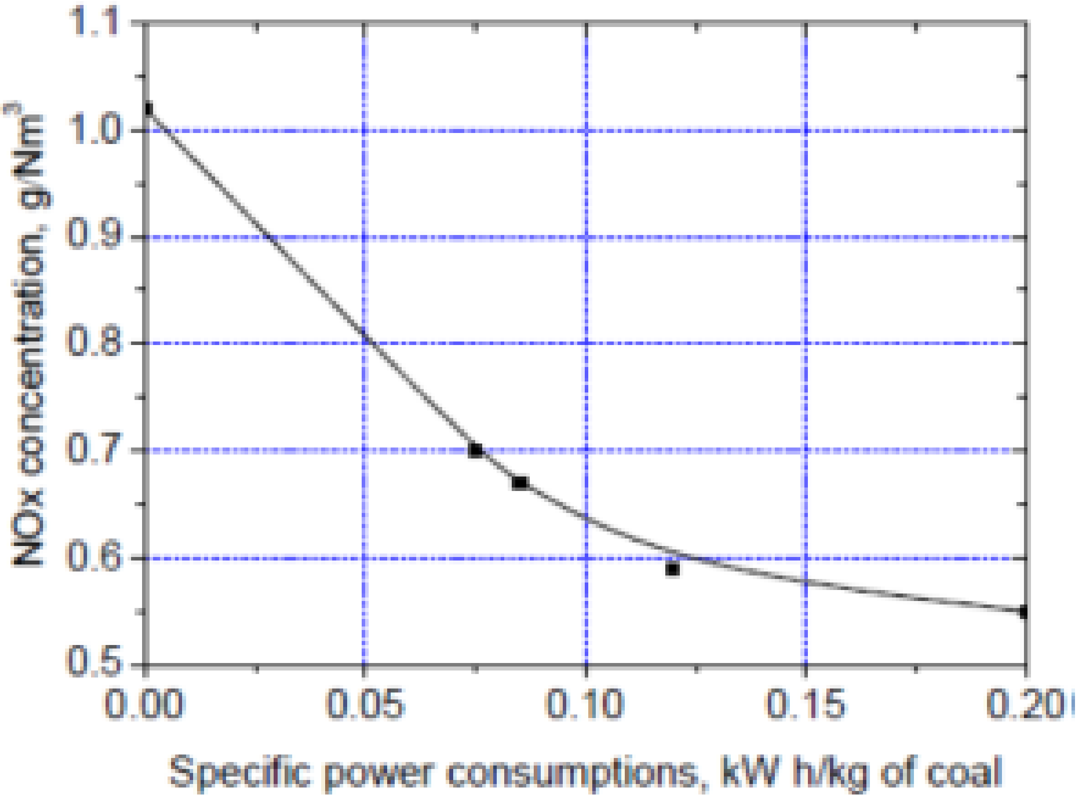

Figure 2.4 Specific power consumption influence onto reduction of nitrogen oxides concentration at plasma aided pulverized coal combustion (29)

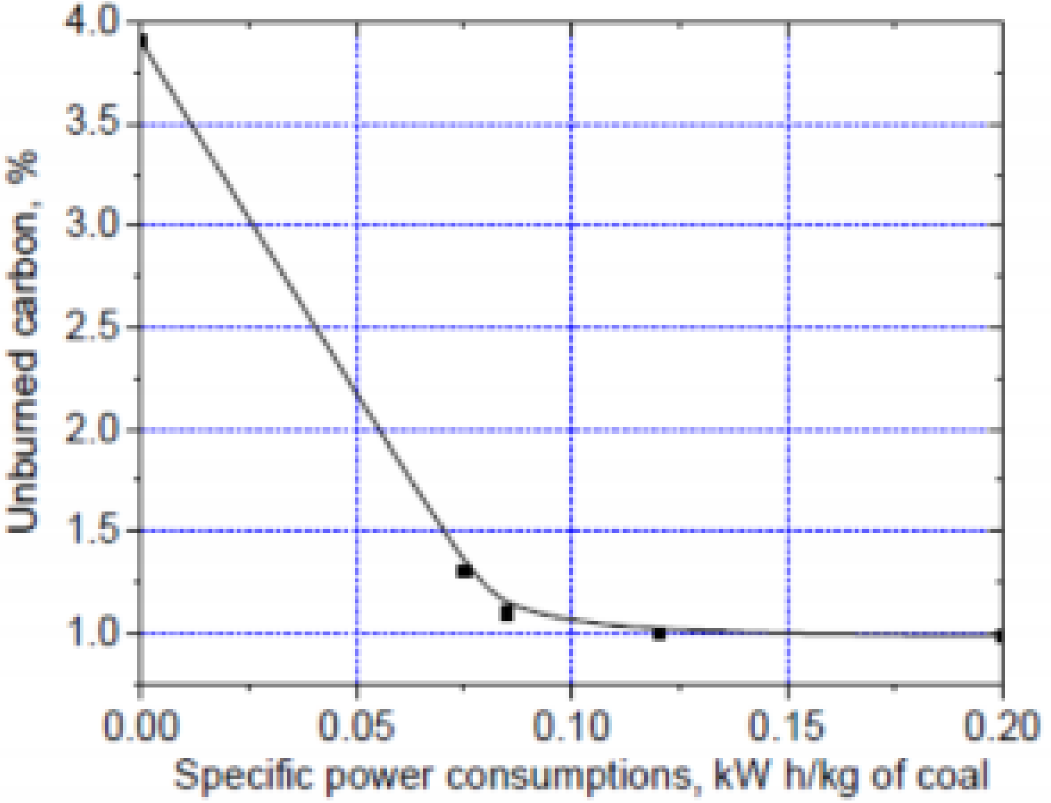

Figure 2.5 Specific power consumption influence onto reduction of unburned carbon at plasma aided pulverized coal combustion (29)

Numerous studies have shown and proved the ecological and financial efficiency of the use of plasma technology for coal combustion. By having more power plants integrate a plasma fuel system on their burners the decrease of the unburned carbon and nitrogen oxides will be allowed to the maximum permissible concentration according to regulations and maybe even less (28)

2.4 Thesis Statement

The infiltration of the renewable energies on the energy market has obligated the solid fuel power plants to become more flexible regarding the start-ups. That results in more frequent shut downs and so, having reduced efficiency and heavily increased costs.

The goal of this thesis is to test the viability of a plasma assisted combustion system that allows the cold start-up of the facility by using hard coals. For the extent of this thesis two different hard coals were selected, South African Hard coal, a low volatile content hard coal with small particle size distribution and the El Cerrejon hard coal, a medium volatile content hard coal with slightly larger particle size distribution. The success of these experiments would present the power plants with an opportunity to counter the problems that were stated earlier.

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3 Methodology

In the following section the experimental setup that was used for the tests will be discussed as well as the steps taken before each test was committed, and the method used to evaluate the results.

3.1 IFK's 500kWth combustion rig (KSVA)

In Figure 3.1 the combustion chamber is shown with the positions of the fittings numbered. The temperature measurements in the combustion chamber were built-in on the level 4+8 (Type B thermocouple from 400°C), levels 5, 6, 8, and on the level 11 (Type N thermocouple). The pressure sensor for detecting the combustion chamber pressure during the experiments was built on Level 22. The plasma torch is integrated as mentioned before inside the burner in order for the hard coal to come in contact with the plasma flame before entering the combustion chamber.

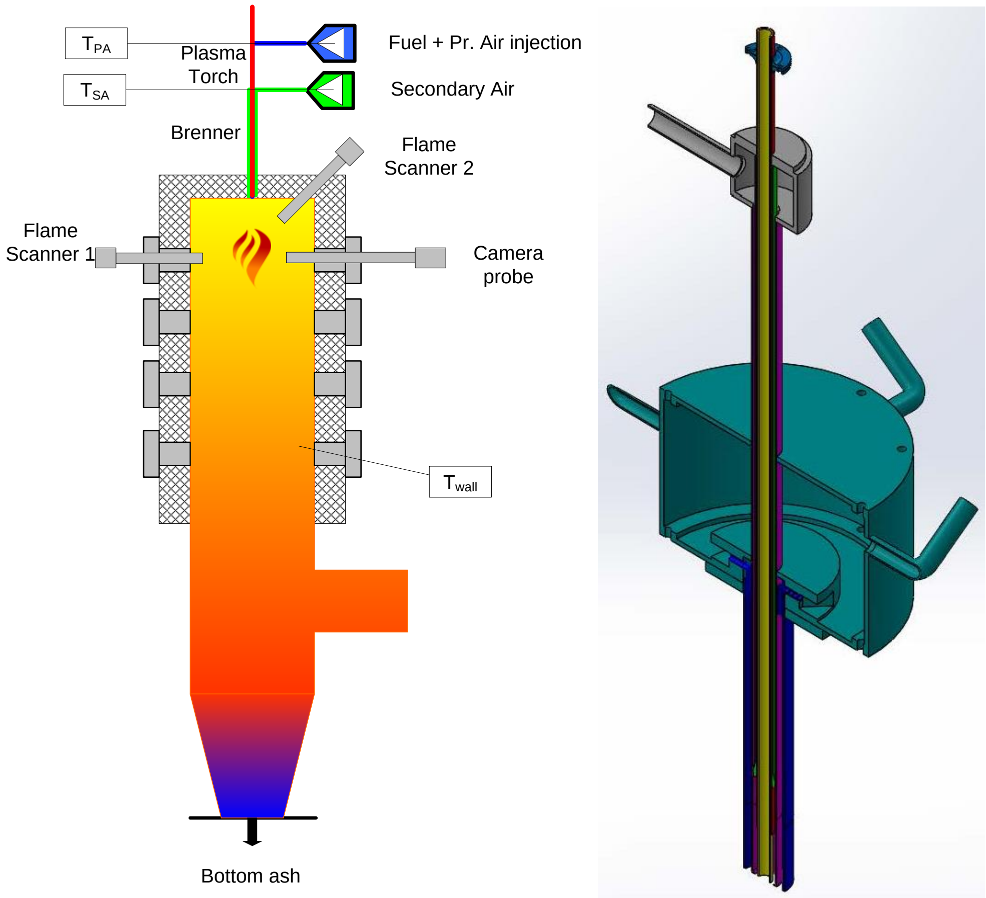


Figure 3.1: 500kWth test rig arrangement

3.2 Plasma Torch

The plasma torch that was used for these experiments can be seen on the Figure 3.2. It is a $3Kw_{th}$ direct current plasma air system that uses electrical energy and gas, in this case air, in order to conjure the stream of plasma.

The plasma flame being produced is measured at 10-15 cm in length and its temperature exceeds the 10.000K

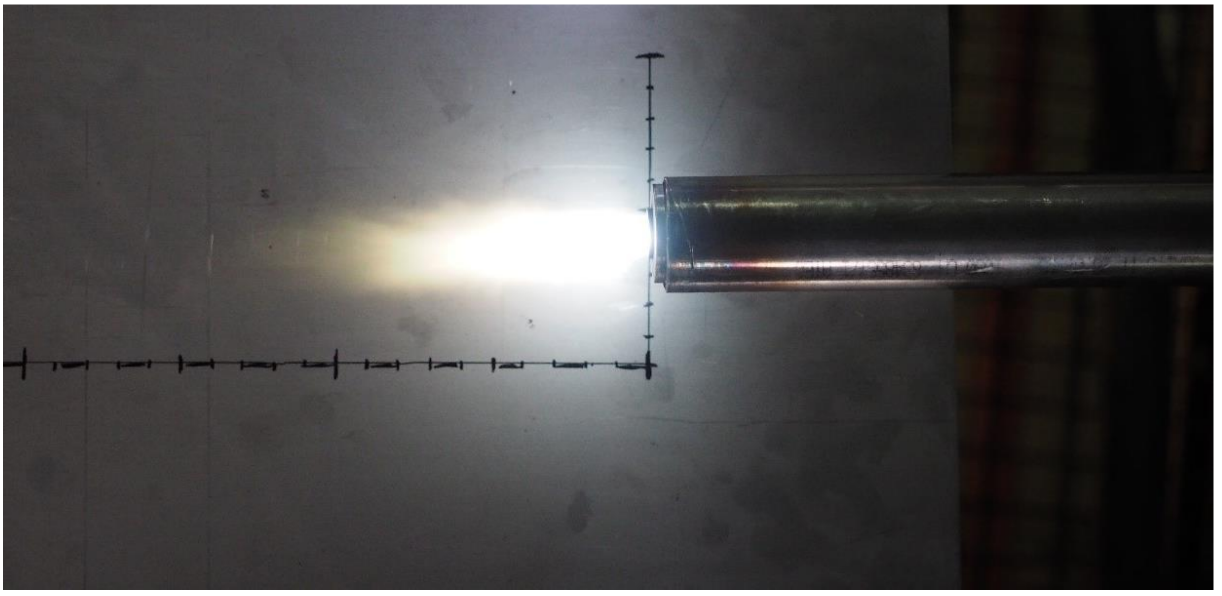


Figure 3.2 Plasma Torch

3.3 Plasma Setup

In the following section the different positions of the plasma burner are show depicting how the position of the plasma burner was changed for the purpose of these

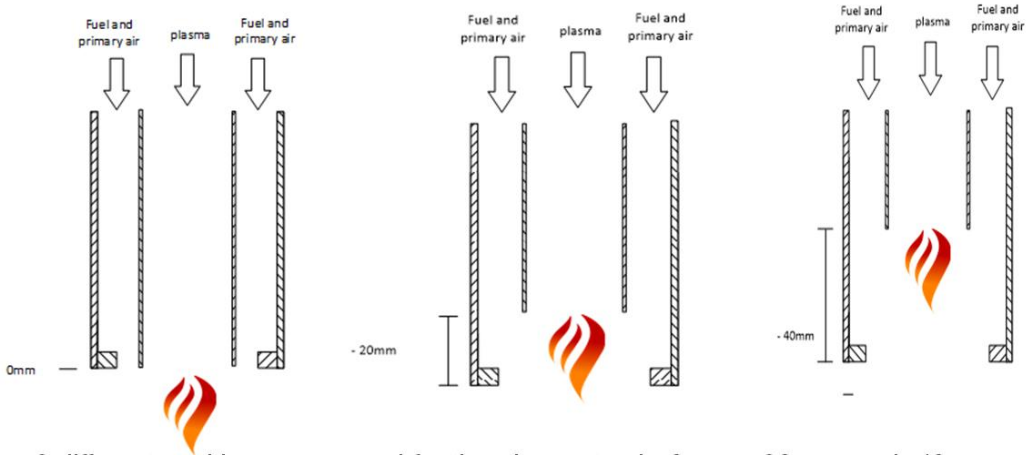


Figure 3.3 Different Plasma Torch Positions inside the burner

These Positions were chosen to be able to manipulate the velocity of the hard coal as it came in contact with the plasma flame and that of the coal flame as it entered the combustion chamber. When the plasma torch was at the position 0mm the velocity of the hard coal was at its peak whereas at -20 mm and -40 mm the velocity of the coal flame when it entered the combustion chamber was lower due to the bigger surface available for the hard coal when it came in contact with the plasma flame and the time needed to travel from the point of ignition to the combustion chamber.

$$V\left(\frac{m}{s}\right) = \frac{Q\left(\frac{m^3}{s}\right)}{A(m^2)}$$

By changing the positions we were able to test different velocities while keeping the secondary air and mass flow of the hard coal constant.

3.4 Camera

For visual control of the ignition a self-designed and constructed camera system was placed inside the combustion chamber and close to the burner. While it is operated using cooling air, only very little of it enters the combustion chamber (<1Nm^3/ h). This way its impact on the combustion or ignition process is negligible. Cleaning of the camera was required every 2 or 3 attempts in order to have good quality videos.

Figure 3.4: IFK's camera probe

3.5 Nozzles

The nozzles 1-4 as shown in the Figure 3.5 were used for tests that were completed to create a proof of concept using high quality pre-dried lignite (TBK). During those tests the results were analyzed and the conclusion was made that nozzle no3 had the best performance overall compared to the others. That nozzle was later improved and nozzle no5 was created, Figure 3.10, in order to proceed with the hard coal experiments

Figure 3.5: Nozzles 1-4 used for the TBK ignition tests

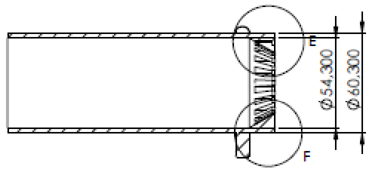
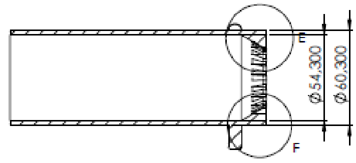
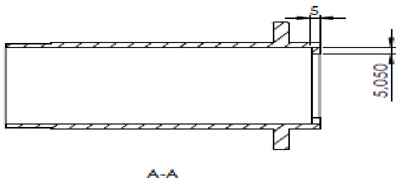
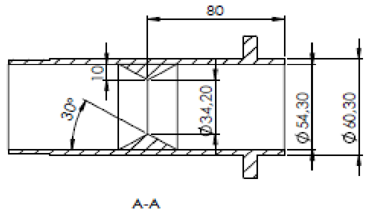
 **Figure 3.6 Nozzle 1**	 **Figure 3.7 Nozzle 2**
 **Figure 3.8 Nozzle 3**	 **Figure 3.9 Nozzle 4**

Table 3.1 Nozzle 1-4,sketches

A 5th nozzle was created for the hard coal experiments that is depicted in Figure 3.10

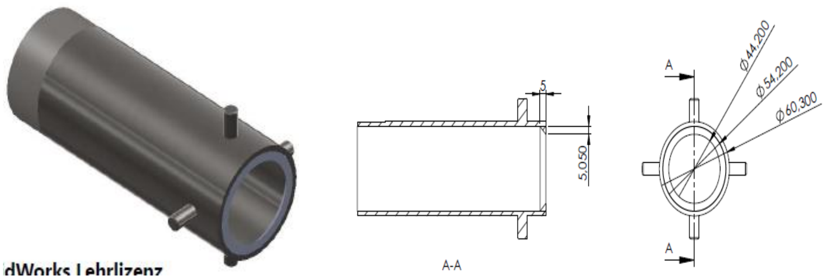


Figure 3.10: Nozzle 5

3.6 Flame scanners

For the purpose of these experiments the Flame scanners F-300K by Lamtec (Figure 3.11) were used to optically monitor the flame produced during the ignition tests. Below we can see an image of said Scanners.

Cooling air
pipe

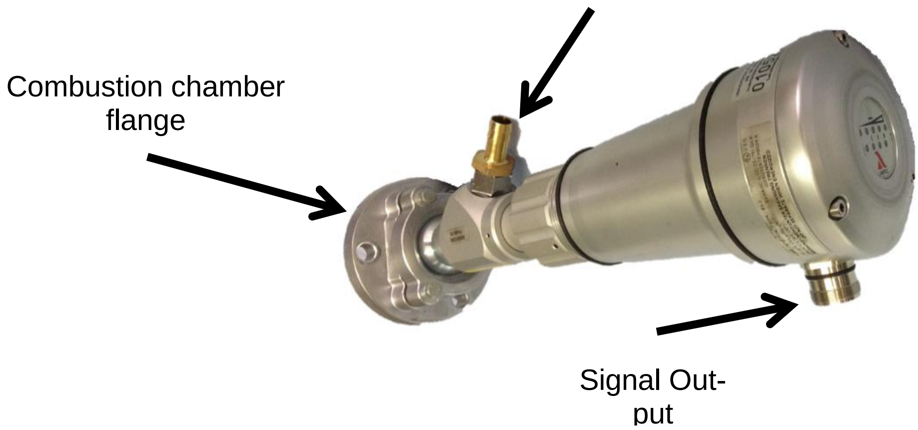


Figure 3.11: Lamtec F300K UV/IR flame scanners

These flame scanners were attached on the burner, with the combustion chamber flange and sent a signal, through cable, to a laptop where the ignition test was presented as seen below in Figure 4.17 and Figure 4.18. Because of the high temperatures it was needed to have the flame scanner cooled to avoid malfunction as well as permanent defects in the device. This was achieved by using cooling air and connecting it on the port as seen on the Figure 3.11 above. The flame scanner uses Ultraviolet and Infrared sensors to calculate the resulting intensity of the flame's frequency. Depending on the different conditions such as Loading, Air Ratio, type of fuel and flame stability the intensity of the different frequencies vary. At Figure 3.12 the program that was used to interpret the results provided by the flame scanners. When the intensity of each frequency is above the 70% threshold (green line) the flame scanner reads the flame as "on".

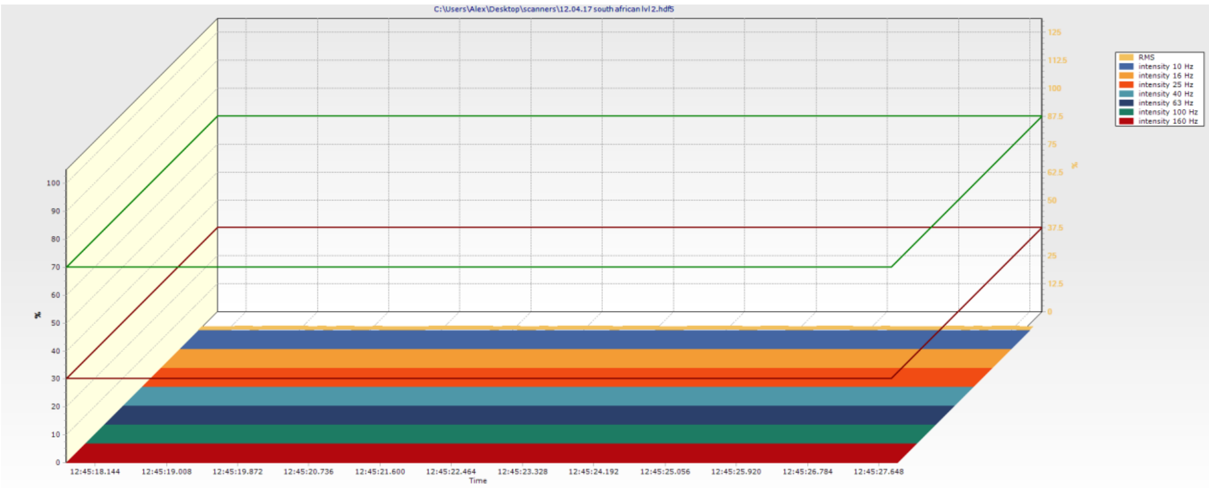


Figure 3.12 Flame Scanner Program

3.7 South African Hard Coal

On the table below is shown the chemical composition of the South African hard coal along with a graph depicting the particle size distribution of it

	Water [%]	Ash [%]	Volatiles [%]	Cfix [%]	C [%]	Htot [%]	H [%]	N [%]	S [%]	O [%]
waf	2.63	15.66	**31.96**	68.04	83.41	4.45	4.45	1.81	0.62	9.71

Table 3.2 South African hard coal Fuel Analysis

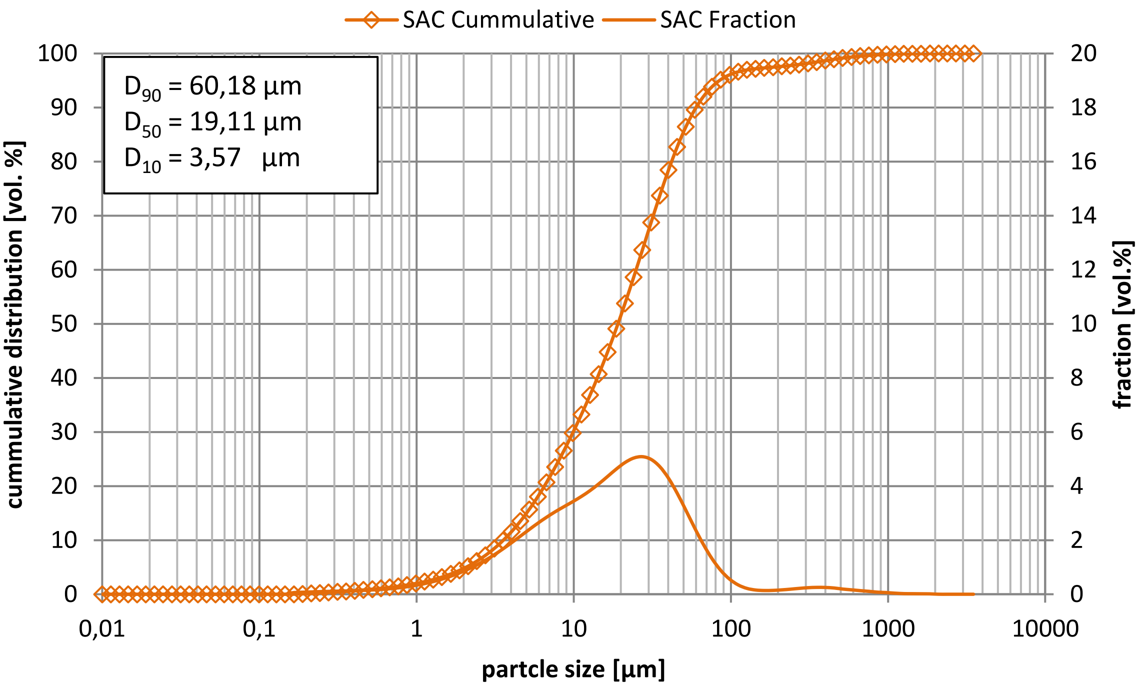
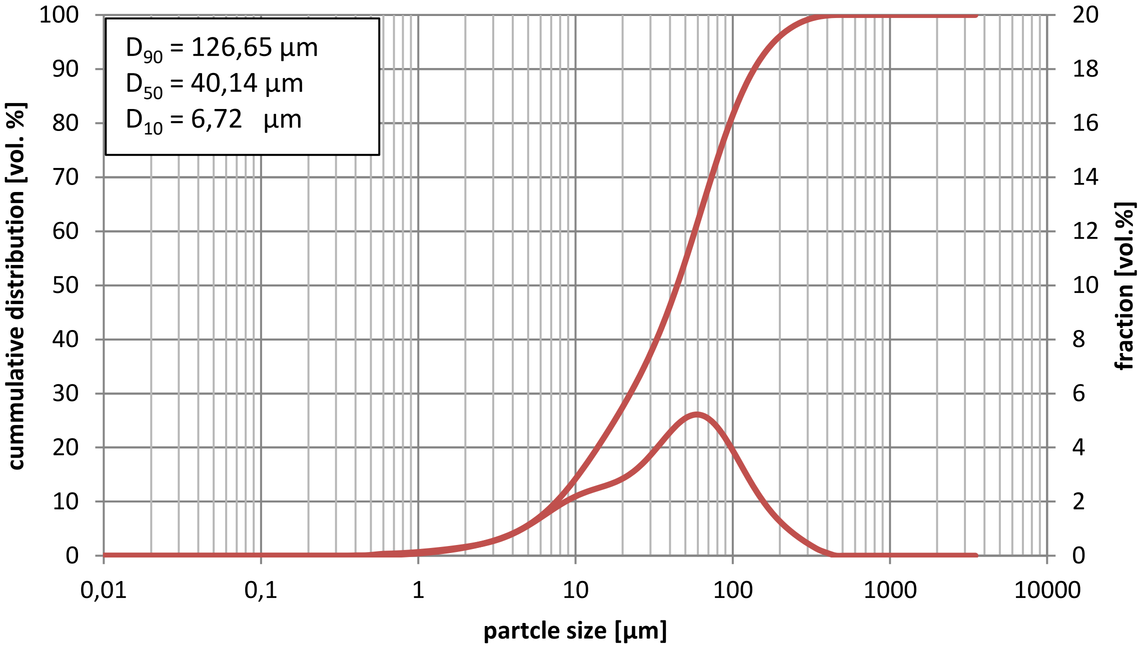


Figure 3.13 South Arican hard coal PSD

South African coal was used as one of the hard coals for the ignition tests performed at the KSVA unit of the IFK. Its low amount of volatiles and high percentage of ash compared to the others, made it difficult to achieve ignition, let alone stable flame without the support of the plasma torch.

3.8 El Cerrejon hard coal

	Water [%]	Ash [%]	Volatiles [%]	Cfix [%]	C [%]	Htot [%]	H [%]	N [%]	S [%]	O [%]
waf	1.63	11.99	**37.63**	62.37	85.79	5.22	5.01	2.00	0.84	6.35



El Cerrejon hard coal was the second hard coal that was used in the experiments at the KSVA 500kWth unit at the IFK power plant. It's higher amount of volatiles as well as low content of ash differentiates it from the South African hard coal depicted above and because of that reason provided better results.

The El Cerrejon hard coal has a higher content of volatiles than the South African hard coal. However its particles are slightly larger, we can see that for the South African hard coal the D_{50} =19.11 µm whereas for the El Cerrejon D_{50} = 40.14 µm. During the course of these experiments it was seen which of the two parameters has a greater effect on the ignition of the coal, and it was the higher volatile content.

3.9 Test Procedure

In the following Section the steps taken before each test was committed will be discussed along with the equipment used in the IFK Power Plant to carry out the experiments and the hard Coals used in the experiments

The experimental procedure for each ignition process took place as follows:

1. Calibration curves were created, by using data from older experiments in order to adjust the frequency of the dosing system.
2. The ignition was visually monitored via the IFK camera at level 2.
3. Flushing and cooling the combustion chamber through the secondary air
4. Secondary air adjusted to the desired value
5. Adjusted position of the plasma torch and switching it on
6. Start the coal dosing system
7. After approx. 5 seconds in most cases an ignition took place, after more than 15 to 20 seconds of no ignition the operation was stopped for safety reasons.
8. In case of an ignition, the plasma torch was switched off to determine whether the flame was stable without plasma support.
9. The regular stop of the ignition test has been obtained by cutting off the fuel supply.
10. After ignitions, there was a waiting period to be sure that cold conditions are reached in the facility. The wall temperature had to be kept at <90°C before each ignition attempt.
11. Cleaning of the camera was necessary after 3 – 4 ignitions to have good quality videos.

For the plasma ignition tests, an experimental matrix was created. On these matrices symbols were used to describe the different stages of success for each ignition test, these were:

1: No Ignition

2: Ignition is not very stable

3: Stable Flame with Plasma

4: Flame is not stable without plasma

5: Flame is stable without plasma

For the purpose of this thesis the goal was to achieve the highest amount of Grade 3 ignitions as possible.

After the tests were performed **Ω** was calculated and implemented into the matrices. **Ω** is defined as the ratio of the oxygen available during the ignition phase to the oxygen required for combustion of the released gaseous volatile components

4 Results And Discussion

Detailed matrices with all of the results have been made. In the following section, the effect that different parameters had on the experiments will be discussed and assessed in order to better understand the behavior of the hard coals in the environment of a plasma assisted combustion. The parameters that were examined were the Loading, which is the mass flow of the fuel versus the Primary air flow (kg_F/Kg_{PA}), which translates into different power levels, different Air ratios that were modified by adjusting the secondary air and the three different positions that we mentioned before.

- The Loadings that were tested ranged from 0.13-0.81 or 50-300 kW_{th}.
- The air ratios that were tested were 0.7, 0.9 and 1.1
- The positions tested as mentioned before were 0 mm, -20 mm and -40 mm

The aforementioned parameters will be examined for the tests conducted with two different nozzles, nozzle 3 and nozzle 5

4.1 Pictures of Ignitions

	TBK	South African Coal	El Cerrejon

Fuel Dosing Begins			
Ignition			
Flame with Plasma on			
Flame with plasma turned off			

Figure 4.1 Pictures of Ignitions

At Figure 4.1 pictures of the different stages of the ignition are shown taken from the camera that was installed at the second level of the KSVA approximately 350mm down from the burner. The pre-dried lignite was used to establish a proof of concept. It is noticed that for the South African hard coal during the ignition the flame is highly concentrated and after a few seconds it weakens, however for the El Cerrejon hard coal the flame is more consistent although a bit weaker at the point of the ignition. The differences between the flame's different intensities for the two hard coals tested will be later reviewed at the Flame scanner results section of this thesis.

4.2 Influence of Air ratio and loading, Nozzle 5

In the following Figures we see the effect that the Loading has between different air ratios on the grade of ignition achieved by the experiment while using nozzle 5 and the primary air kept constant at 40 Nm^3/h. The position chosen for the evaluation of the different air ratios was the -40 mm one.

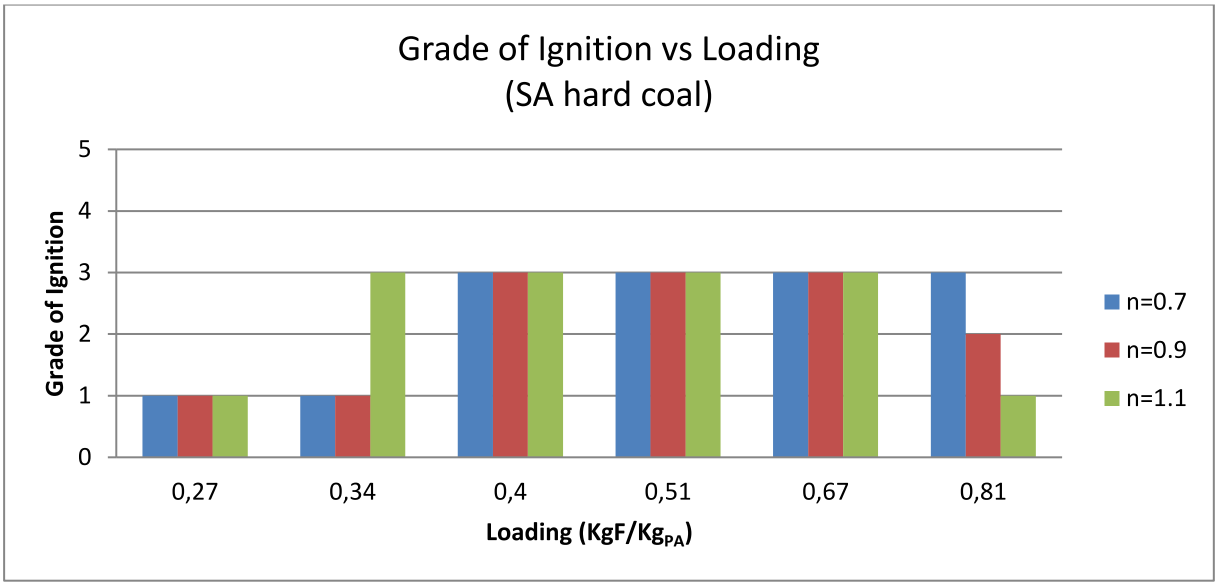


Figure 4.2 Influence of Air ratio, South African Hard coal nozzle 5

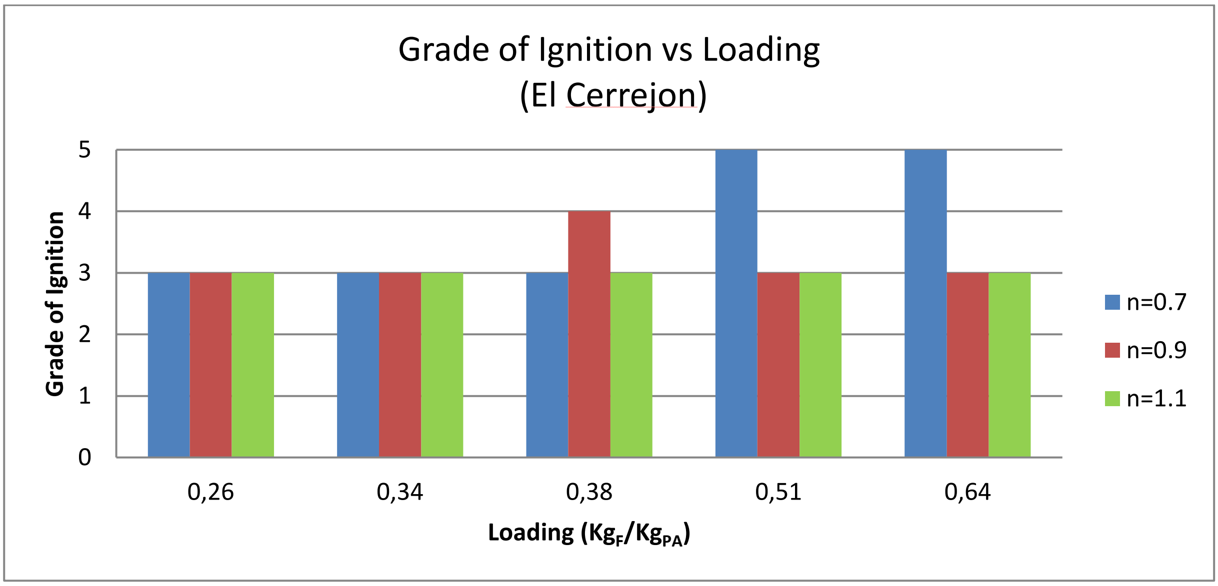


Figure 4.3 Influence of Air ratio, El Cerrejon hard coal nozzle 5

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After testing the effect that loading and air ratio has on the grade of ignition at a specified position, -40 mm, it was discovered that after achieving ignition, increasing the loading does not have a big effect on the grade of the ignition. Looking at Figure 4.2 we can see that while using low loadings, 0.34, we could only have grade 3 ignition at n=1.1 . On the higher loads, 0.81, the exact opposite occurred. Grade 3 ignition was achieved at n=0.7. The explanation for that effect would be that during low loads the velocity of the coal is not high enough for the ignition to take place and while using higher loads, if the secondary air is adjusted high, (0.9 and 1.1 air ratios) it is presumed that the coal is being flushed down too quickly for an ignition to take place. On the other hand, while using the El Cerrejon hard coal and using low loads, the air ratio did not affect the grade of ignition. However, while using higher loads, 0.51 and 0.64, only when the secondary air was adjusted as to have air ratio of 0.7 we could achieve ignition grade 5. Both graphs are for plasma torch positioning -40 mm so when the loading is such as to provide an increased velocity of the fuel and the plasma torch positioned in a way to reduce the velocity of the coal flame as it enters the combustion chamber there is an improvement on the grade of the ignition achieved by using lower air ratio as for the coal not to be flushed down too quickly down the combustion chamber.

4.3 Influence of Position

In the following section the influence that the position of the plasma torch in the burner will be investigated while the air ratio will remain constant at 0.7, 0.9 and 1.1. As stated before, adjusting the plasma position enables the manipulation of the coal's velocity as it comes in contact with the plasma torch and the coal flame's velocity as it enters the combustion chamber, without changing the secondary air or the mass flow of the hard coal. Two different nozzles were tested and the results of both have been evaluated and examined in order to determine the best position the plasma torch can be at in order to achieve grade 3 ignition or above.

4.4 Influence of Position South African hard coal Nozzle 5

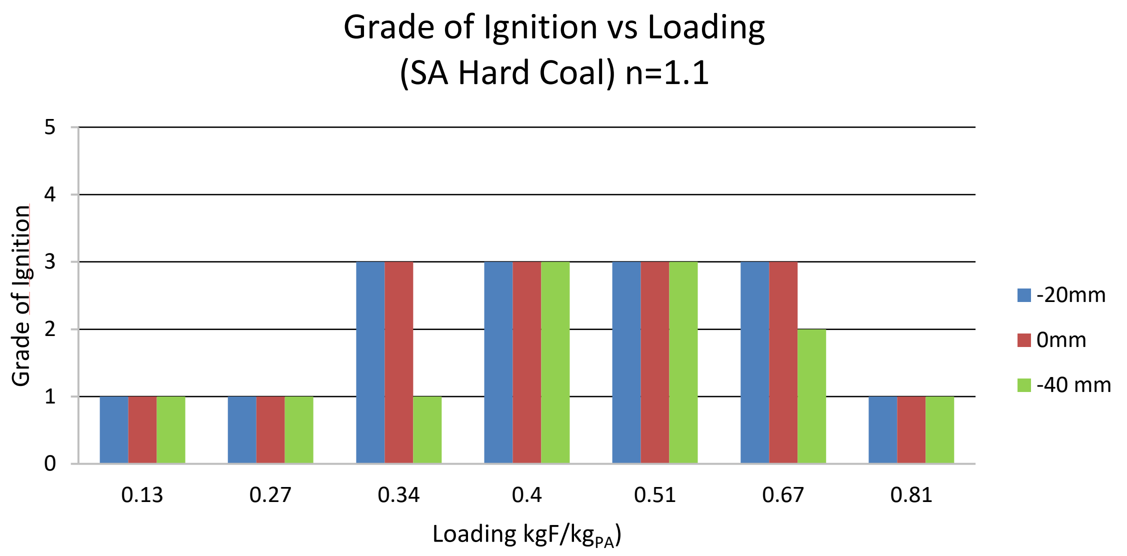

Figure 4.4 Influence of Position SA Hard coal, n = 1.1 nozzle 5

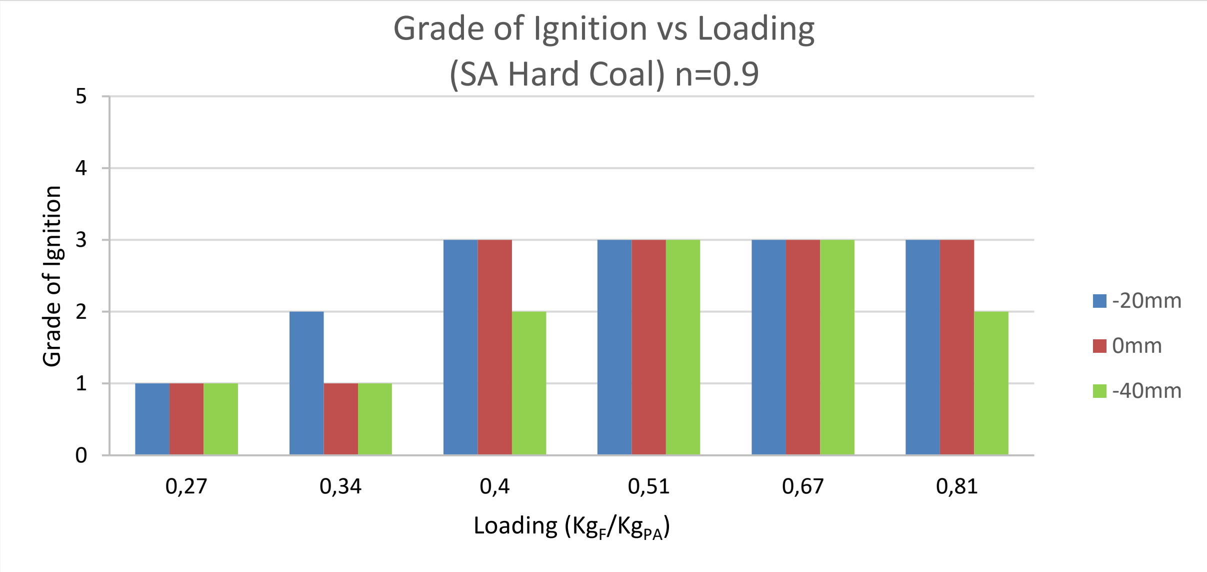

Figure 4.5 Influence of Position SA Hard coal n = 0.9 nozzle 5

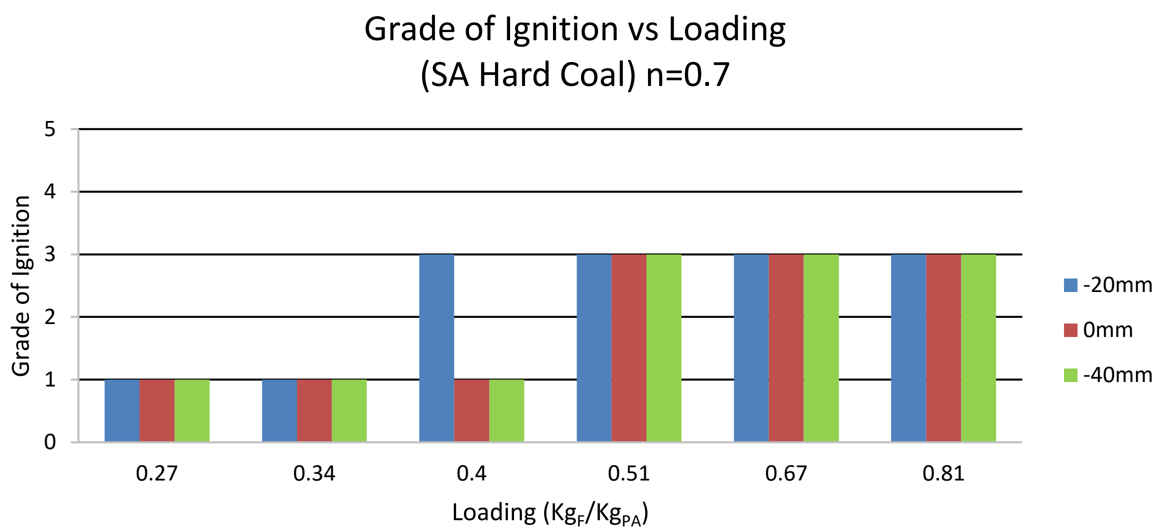

Figure 4.6 Influence of Position SA Hard coal n = 0.7 nozzle 5

The Influence the position of the plasma burner has on the grade of ignition for the South African Coal is shown on the Figure 4.4-Figure 4.6. For the loadings 0.27-0.34 ignition was scarce but was only achieved when the plasma burner was at the -20 mm or 0 mm position. It can be noted that while using air ratio n=1.1 the amount of ignitions achieved was higher than using lower ones which is consistent with the results of the previous plots. We can conclude that for the South African hard coal having the plasma burner at the position of -20mm or 0 mm was the best choice as they provided the better results out of the three. That can be attributed to the chemical composition of the South African hard coal. Due to its lower volatile count, as mentioned in the bibliography, to achieve ignition the conditions had to be very specific. Having the plasma burner at the position of -20 mm and 0 mm provided ignitions of grade three even at the lower loadings and thus as mentioned before, the South African hard coal had less ignitions for the same amount of tests compared to the El Cerrejon, and the position of the plasma burner is important in order to achieve those ignitions

4.5 Influence of Position El Cerrejon hard coal Nozzle 5

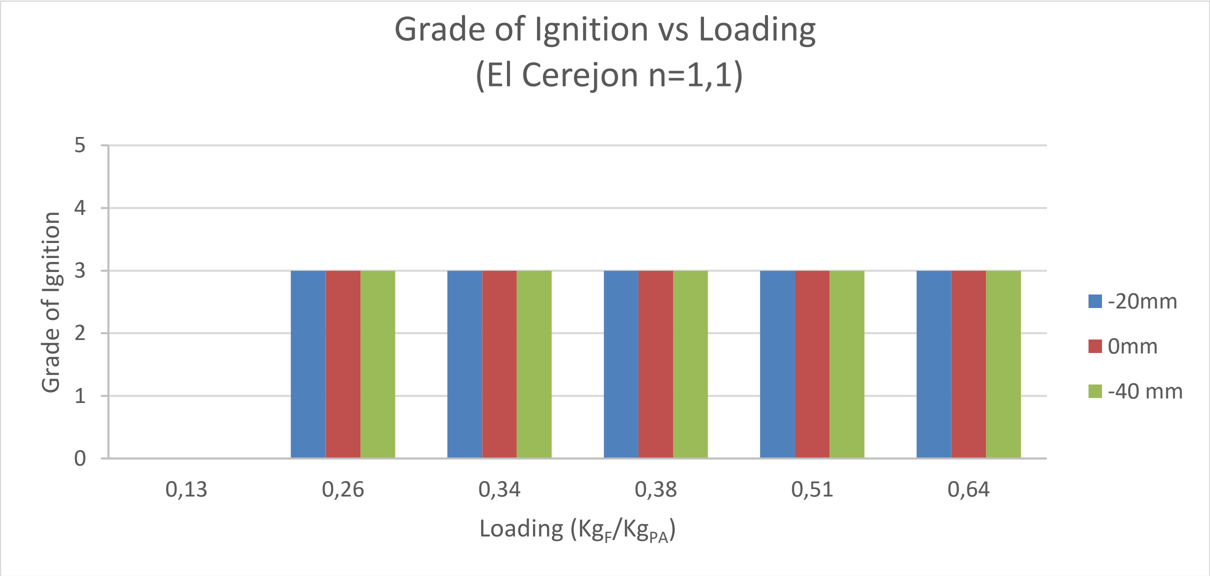

Figure 4.7 Influence of Position El Cerrejon Hard coal n = 1.1 nozzle 5

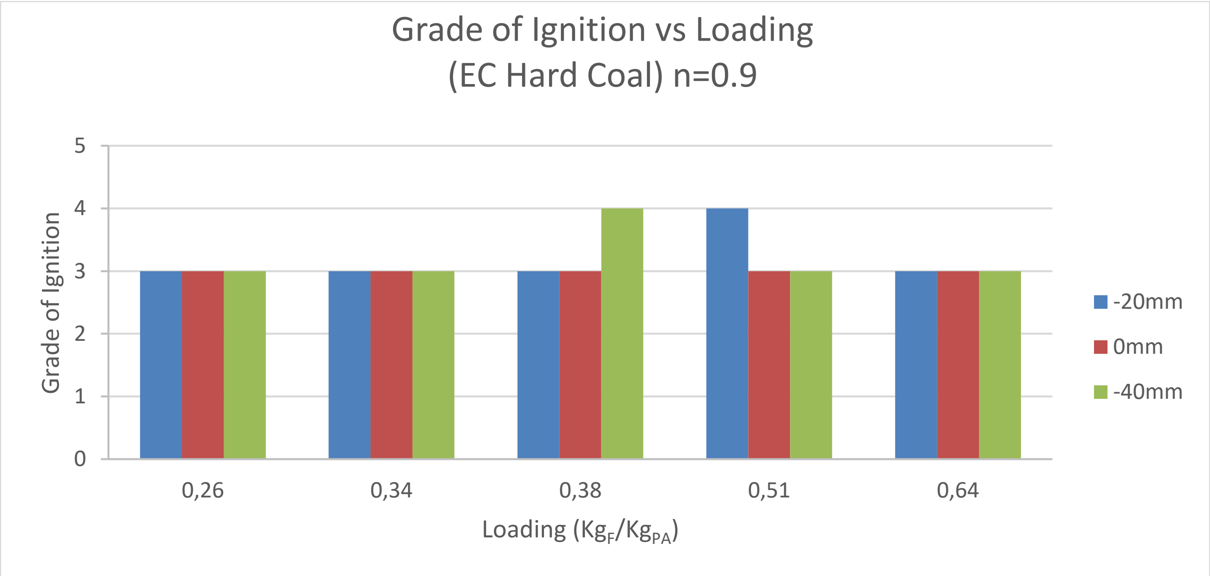

Figure 4.8 Influence of Position El Cerrejon Hard coal n = 0.9 nozzle 5

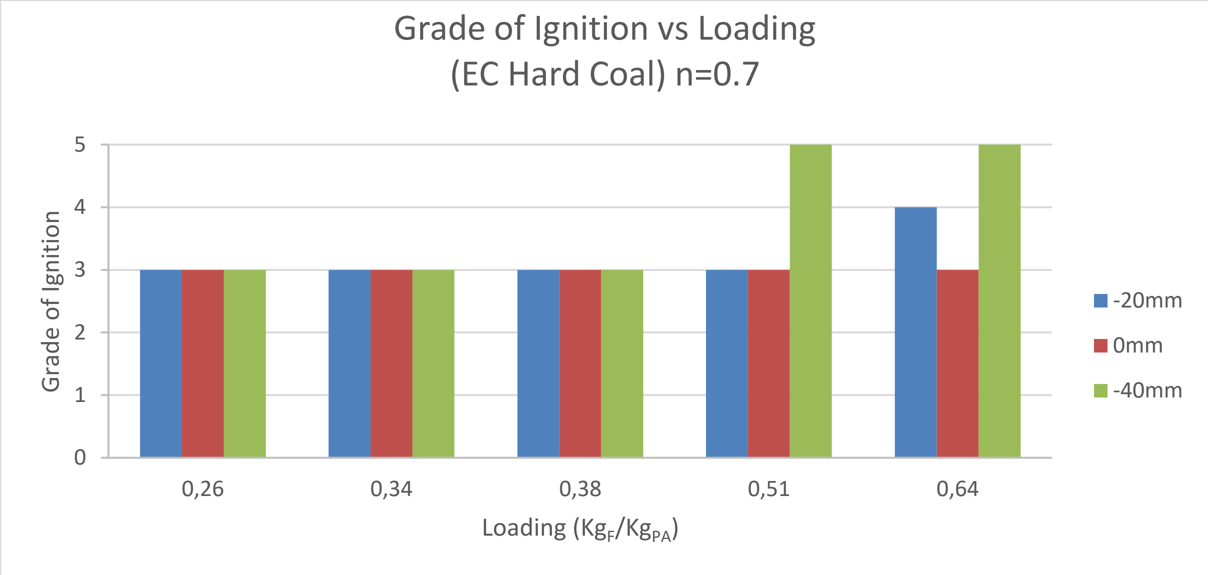

Figure 4.9 Influence of Position El Cerrejon Hard coal n = 0.7 nozzle 5

In the Figures above it is shown the influence the position of the plasma burner had on the El Cerrejon hard coal tests that were conducted. Compared to the South African hard coal results it is seen that having the plasma burner at lower positions, -20mm and -40mm, provided the best results. That can be attributed to the fact that because of its higher volatile count, El Cerrejon hard coal required a lower velocity of the coal as it became in contact with the plasma torch in order to ignite. It is worth noting that for the El Cerrejon hard coal the air ratio that produced the best results, is n = 0,7 on higher loadings, 0.51 - 0.64

4.6 Influence of Position Nozzle 3 South African hard coal

While using nozzle 3 in our experiments, the primary air was kept constant at 70 Nm^3/h

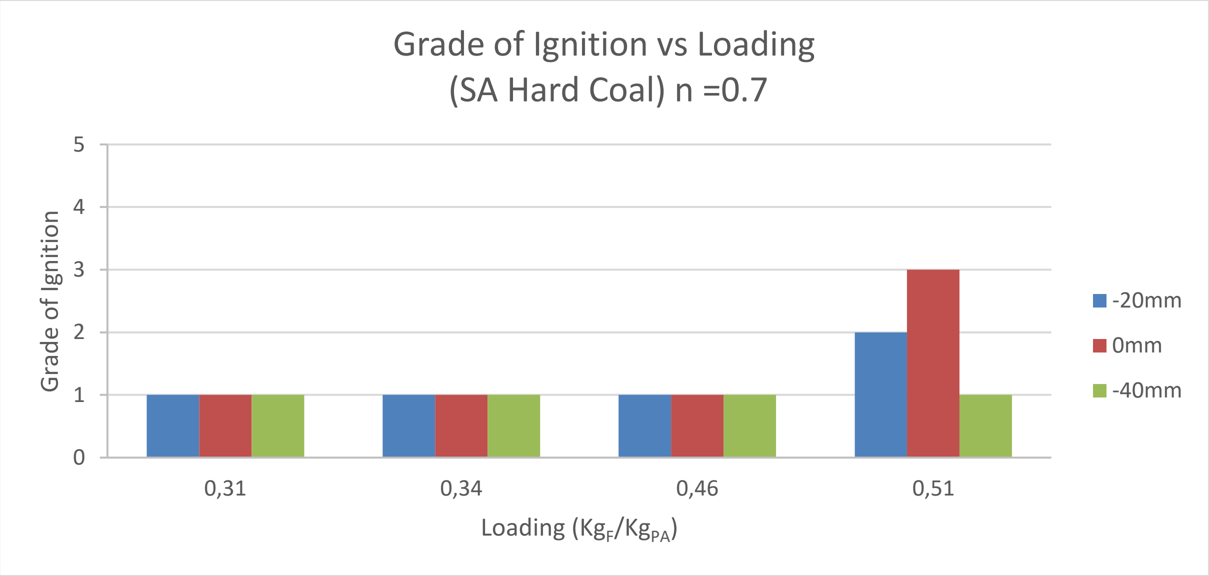

Figure 4.10 Influence of Position South African hard coal n=0.7 nozzle 3

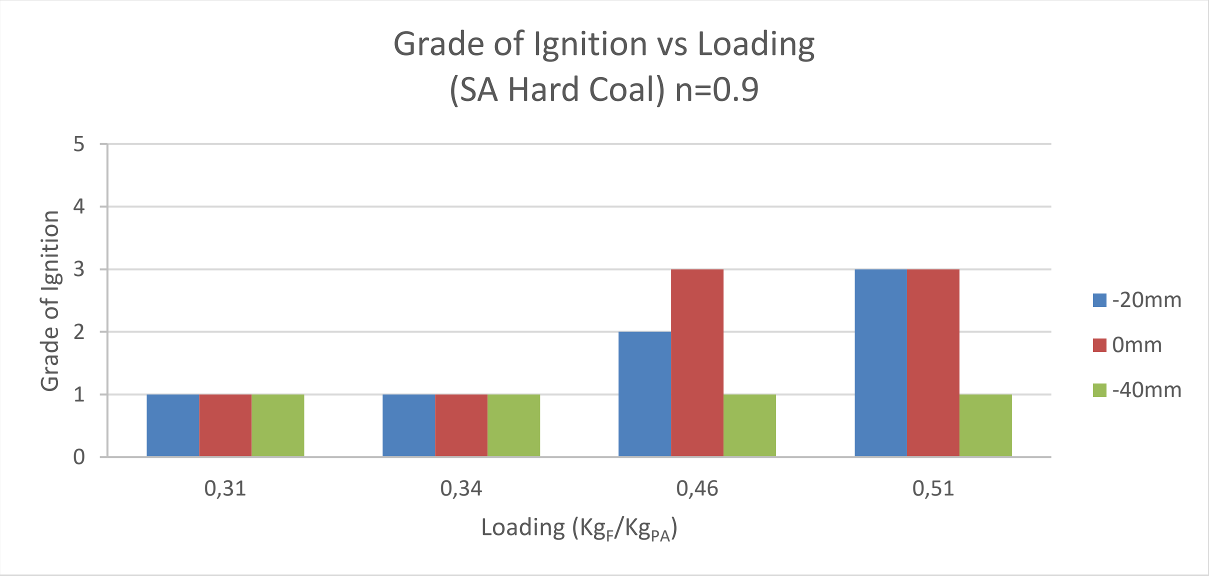

Figure 4.11 Influence of Position South African hard coal n=0.9 nozzle 3

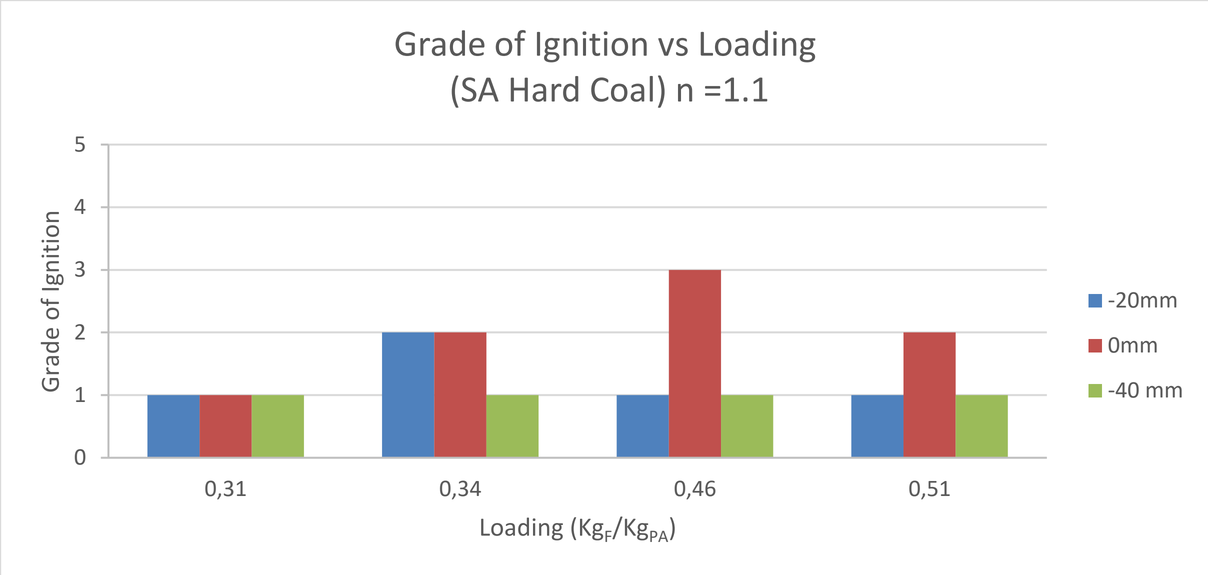

Figure 4.12 Influence of Position South African hard coal n=1.1 nozzle 3

During the course of the experiments with Nozzle 3 for the South African hard coal the results were not very promising. Grade 3 ignition was only achieved during high loadings and the plasma torch positioned at either 0 mm or -20 mm. From that fact we can assume that for the South African hard coal higher velocity of the fuel while it comes in contact with the plasma flame is important in order to achieve positive results.

4.7 Influence of Position Nozzle 3 El Cerrejon Hard coal

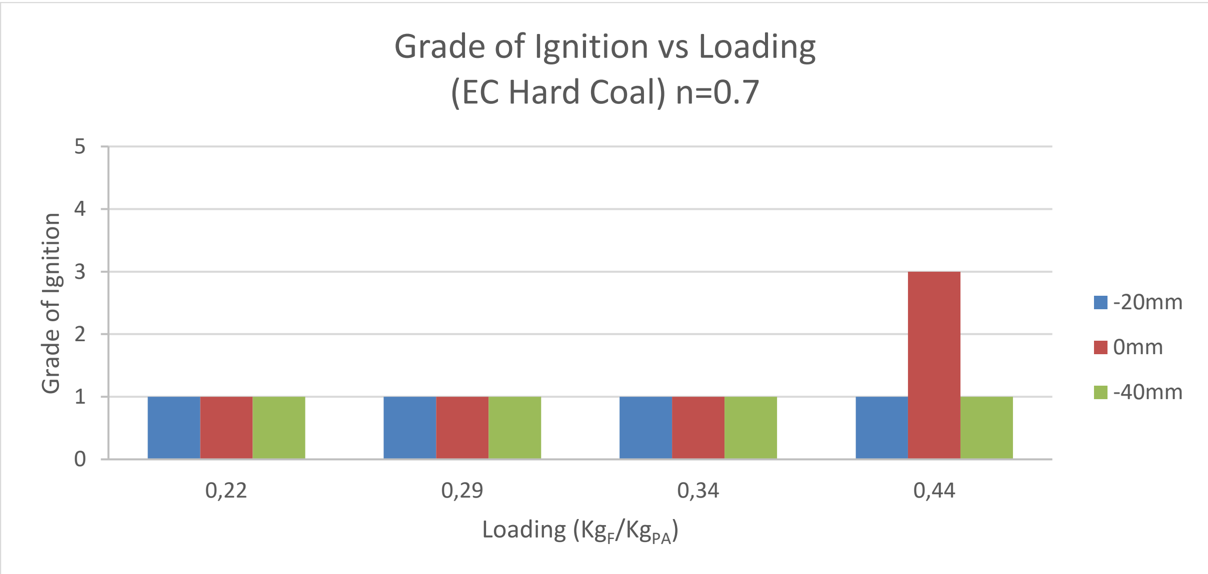

Figure 4.13 Influence of Position El Cerrejon hard coal n=0.7 nozzle 3

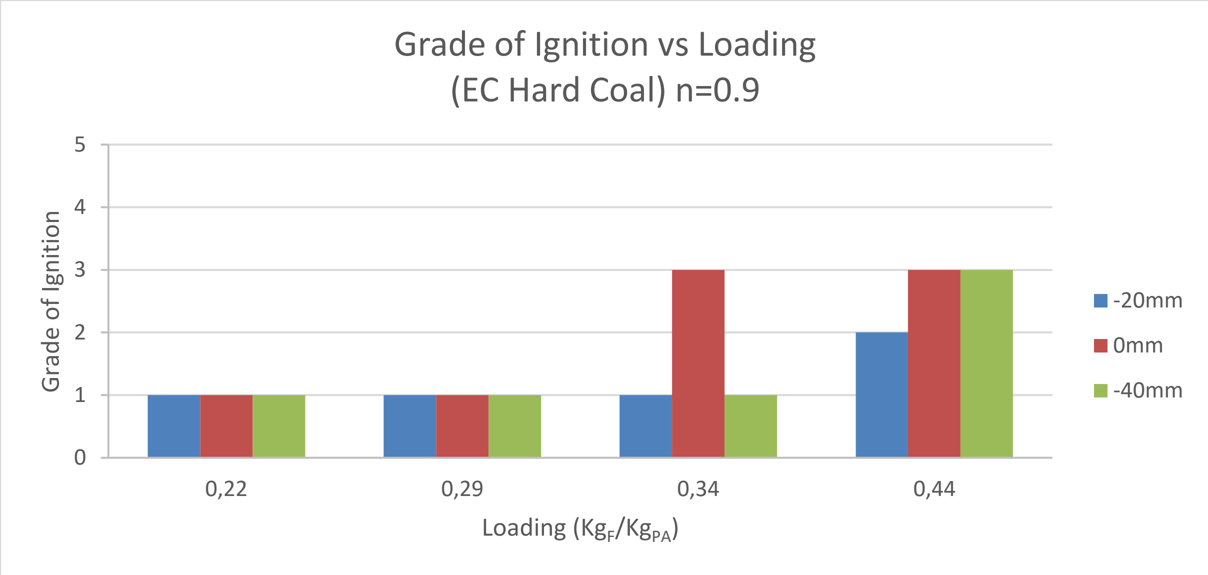

Figure 4.14 Influence of Position El Cerrejon hard coal n=0.9 nozzle 3

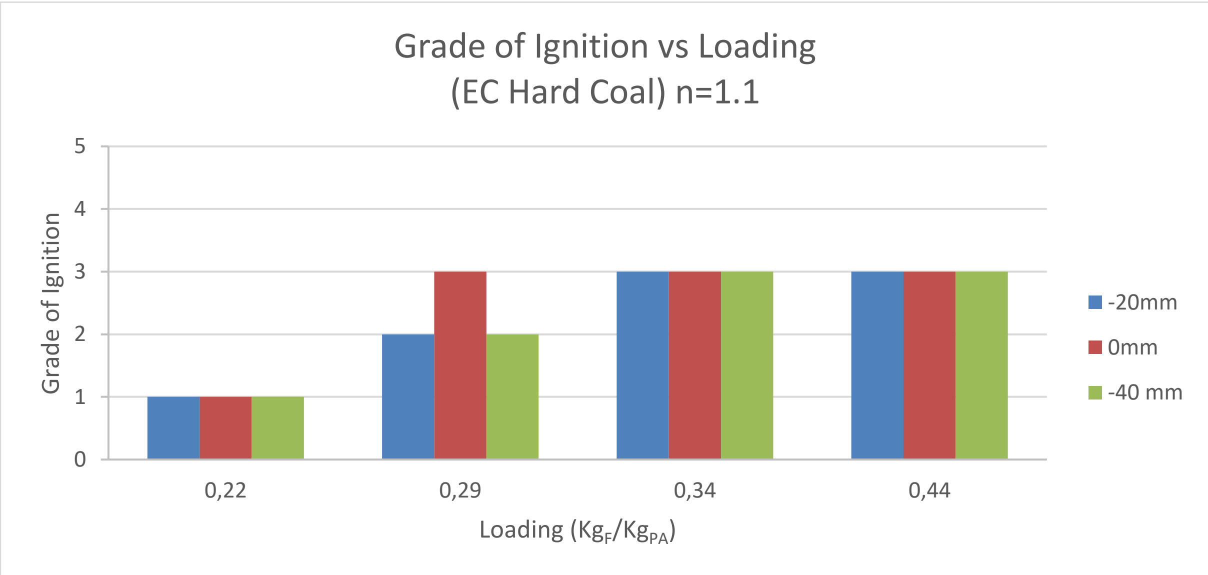

Figure 4.15 Influence of Position El Cerrejon hard coal n=1.1 nozzle 3

While testing the Nozzle 3, with the primary air kept constant at 70 Nm^3/h with the El Cerrejon hard coal we can see that positioning of the plasma torch is not as important as is Loading and air ratio. Positioning plays a bigger role when the air ratio is low we can see at Figure 4.13 that Grade 3 ignition could only be achieved at high loadings and position 0 mm. On the other hand looking at Figure 4.15 positioning of the plasma torch is not as impactful. We were able to achieve grade 3 ignitions for all three of the positions during high loads and one grade 3 ignition for medium load (0.29Kg_F/Kg_{PA}) for the position of 0 mm. We can conclude that for nozzle 3 position 0 mm provided the better results especially during lower air ratios (n=0.7). This result is in contrast with the nozzle 5 results that we saw earlier.

4.8 Nozzle Comparison

Because of the different amount of experiments performed with each nozzle, in order to evaluate which nozzle provided better results we calculate the percentages of successful ignitions for each nozzle, meaning grade 3 or higher.

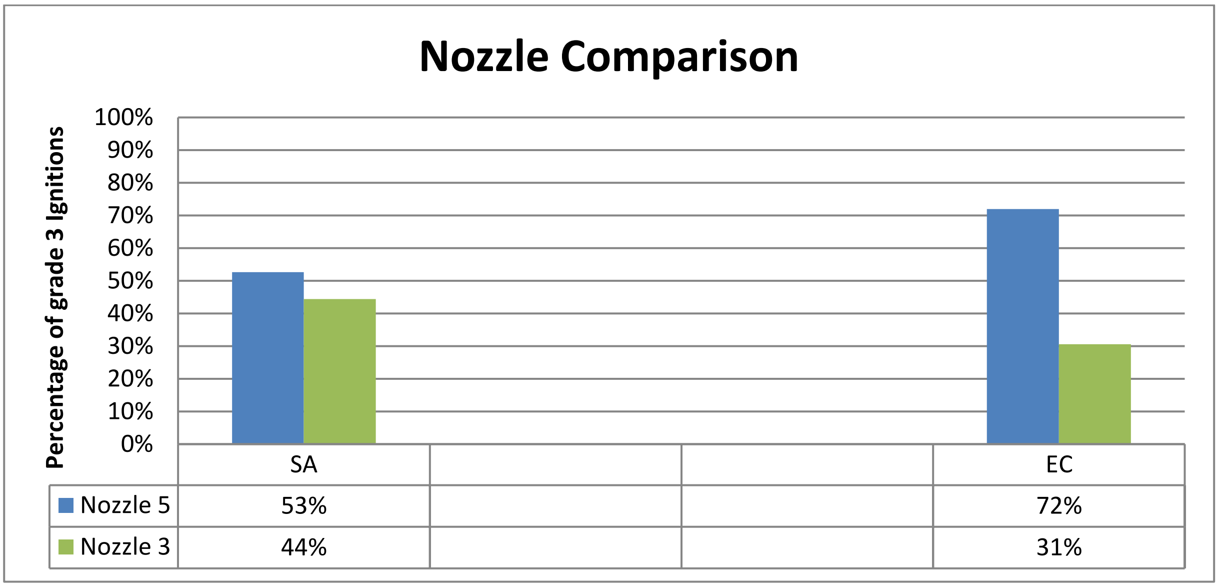

Figure 4.16 Nozzle comparison for the two different hard coals

Looking at Figure 4.16 we can clearly see that nozzle 5 provided better results, as it was expected considering it was created for that exact purpose. The highest impact is seen at the El Cerrejon hard coal where the success rate with Nozzle 5 is over 70% whereas using nozzle 3 the success rate was 31%.

4.9 Flame Scanner Results

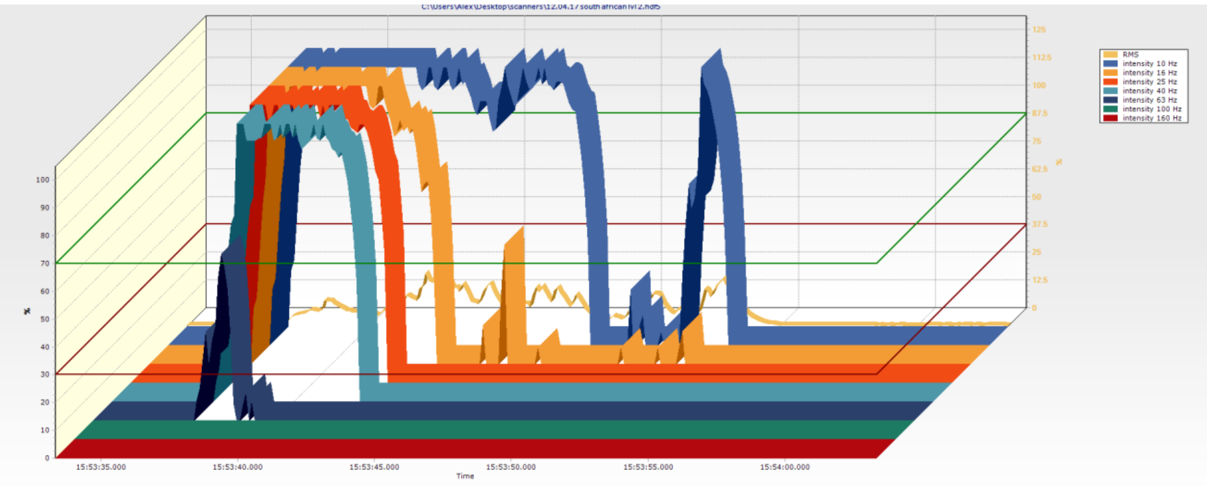

Figure 4.17 grade 3 ignition of SA hard coal. Air Ratio n=0.7 Position 0 mm, Loading 0.67

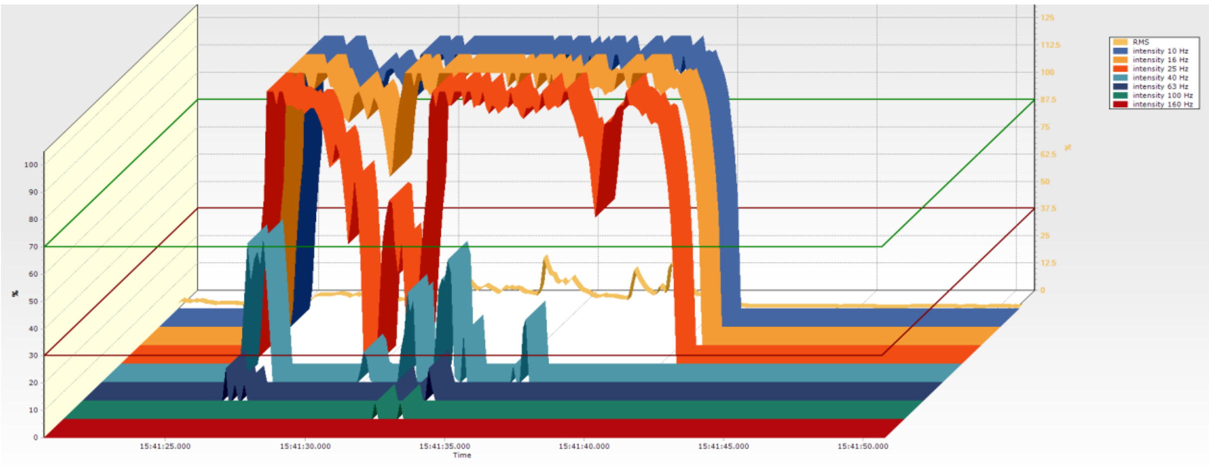

Figure 4.18 Grade 3 ignition of El Cerrejon hard coal Air Ratio n=0.7 Position 0 mm, Loading 0.64

Above we can see two different grade 3 ignitions for the two hard coals used in the experiments, South African hard coal and El Cerrejon hard coal. The flame scanner as is mentioned before measures the intensity of each frequency the flame emits. Figure 4.17 shows the flame produced by using the South African hard coal with nozzle 3. The flame's frequency is high at start but after 5 seconds the flame diminishes in strength and is completely off when the plasma torch is switched off after about 15 seconds. On the other hand Figure 4.18 depicts the El Cerrejon's hard coal flame's frequency. It is clear that even though the flame does not have the intensity of that of the South African's hard coal at start it maintains a consistent intensity throughout the whole course of ignition making it more stable and valuable for the goal of these experiments.

By using the Flame Scanners as an optical method to review the different flames the correlation between each graph provided by the flame scanner and the grade of the ignition as well as the type of hard coal used was able to be achieved.

5 Conclusion

A series of plasma ignition tests took place in IFK's 500kWth facility using a 3 kW DC plasma torch, to test the ignition capabilities of hard coal. The fuels used were 2 different hard coals, El Cerrejon and South African hard coal. In total, 5 different nozzles were designed, manufactured and tested for the scope of those tests. The first 4 were used for the TBK and out of those a best choice was picked (Nozzle Nr.3). For the tests with the hard coal, a 5th nozzle was designed and manufactured in order to examine if the performance could be improved. While testing the hard coals it was discovered that they were difficult to ignite and that was especially true in the case of South African hard coal with a low volatile content. The main focus of this series of tests was to find the loading at which each coal ignited. Different parameters were examined, namely the Loading of the fuel, the air ratio and the position of the plasma burner, as well as the two different nozzles, Nozzle 3 and Nozzle 5 in order to evaluate in what degree each parameter affected the grade of the ignition.

As seen from the figures and tables above, the parameter that had the most effect was the Loading. While using low loading the success was limited in achieving the preferred results due to the chemical composition of the hard coals making it difficult for the ignition to take place if the mass flow of the fuel was not enough.

The success rate with the loading increase is not linear. As expected by using very high loads the coals were being fed too quickly in order for the ignition to take place. For that reason, different air ratios and positions of the plasma burner were tested to achieve a better understanding of the conditions required for the ignition to take place for each Coal.

After examining the graphs designed, the conclusion was made that while using lower loads, having a bigger air ratio, namely n = 1.1 provided better results and while using higher loads, the best results were achieved by using air ratio of 0.7, which can be attributed to the difference in velocities of the coal, where in lower loads the velocity of the fuel was not enough as it came in contact with the plasma torch to achieve ignition and during higher loadings it was being flushed down too quickly for the ignition to take place.

Furthermore, the position of the plasma burner played a significant role in the experiments. For each coal the position of the plasma burner had to be different in order to achieve the better grade of ignitions, for the SA hard coal it was discovered that the best position is -20mm and 0 mm considering that by having the plasma torch at these two positions procured grade 3 ignitions for the South African hard coal at lower loads. For the EC hard coal the position that procured the better results was the -40mm and -20 mm where we had two of the only sustained flames after the plasma burner was turned off, grade 5 ignitions. The position of the plasma plays a pivotal role in the experiments as it directly affects the time and intensity in which the coals are exposed to the plasma flames and their different chemical and physical characteristics require a different exposure for the ignition to take place.

Moreover, as discussed previously, Flame scanners were used to measure the intensity of the flame's produced frequencies provided by the hard coals ignitions. From the data of the scanners we were able to correlate every ignition grade to a graph that depicted the frequencies of the flame, as it is seen on Figure 4.17and Figure 4.18.

Future studies could select to further investigate the parameters that were discussed in this thesis and creating opportunities to achieve higher grades of ignition while using hard coals.

6 Summary

To increase the flexibility of lignite power plants, a new start-up method with plasma ignition technology was studied and implemented in a pilot-scale facility. The goal of the study was to determine optimal ignition and combustion boundaries of a plasma integrated pulverized fuel burner under the cold furnace conditions. A detailed parametric study was conducted in-house in a 500 KW_{th} pilot-scale test facility at the Institute of Combustion and Power Plant Technology (IFK). Two types of Hard coals with distinct physical and chemical properties were used for the study, El Cerrejon with a medium volatile count and South African hard coal with low volatile count. Several parameters associated with pulverized coal combustion were varied under cold-start up environment and the results were evaluated individually and in comparison with each other based on the grade of ignition, a metric that was perceived during these tests and is used to evaluate the ignitions achieved by the Hard coals.

Increasing the Loading led to a better grade of ignition for both hard coals. Five different loadings were used for these tests ranging from 0.13 to 0.81 Kg_F/Kg_{PA}. It was noticed that the best results were achieved between the loadings 0.34 - 0.64 Kg_F/Kg_{PA}. The reasoning for that is because on higher loadings the coal is being fed too quickly therefore making it harder for the ignition to take place.

Furthermore, two other parameters were examined with the loading of the fuel, air ratio and the position of the plasma burner.

In total three different air ratios were used for the tests, n = 0.7, n = 0.9, n = 1.1 , as well as three different positions of the plasma burner, 0 mm, -20 mm, -40 mm. The air ratio was changed by adjusting the secondary air flow while the primary air flow was being constant at 40 Nm^3/h or 70Nm^3/h. The results concerning the air ratios showed that during lower loadings, it was best to have higher air ratios, while using n=1.1 we achieved the better results, whereas in higher loadings the air ratios that were used to achieve grades 4 and 5 of ignition was n = 0.7. That can be attributed to the fact that the air flow had to be balanced in order for the hard coal to ignite.

Position of the plasma was also a deciding factor. Results showed that for the South African hard coal the optimal position was -20mm and 0 mm and for the El Cerrejon hard coal it was -40mm and -20 mm.

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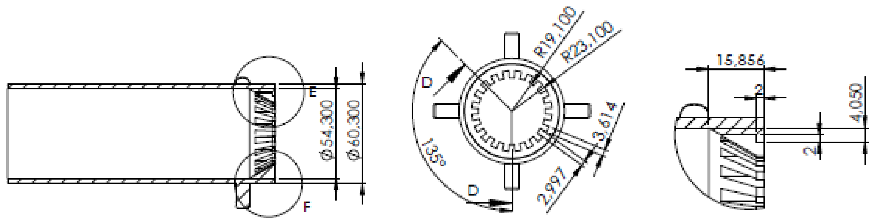
8 Annex

8.1 Nozzle Pictures and Drawings

8.1.1 Nozzle 1

Characteristics:

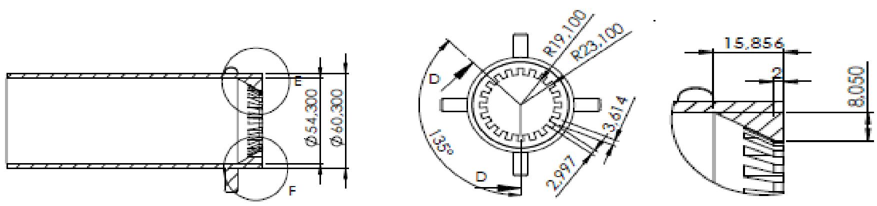
- Fuel nozzle -- toothed (DS®- Burner eleme for a sufficient ignition and a stable flame)
- Baffle ring to slow down the PF for better i tion and for deflection of the PF



8.1.2 Nozzle 2

Characteristics:

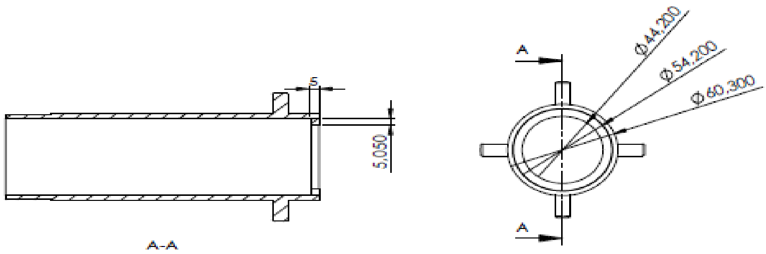
- Fuel nozzle -- toothed (DS®- Burner elements for a sufficient ignition and a stable flame)
- Another kind of nozzle (slightly different type of the teeth) for deflection of the PF



8.1.3 Nozzle 3

Characteristics:

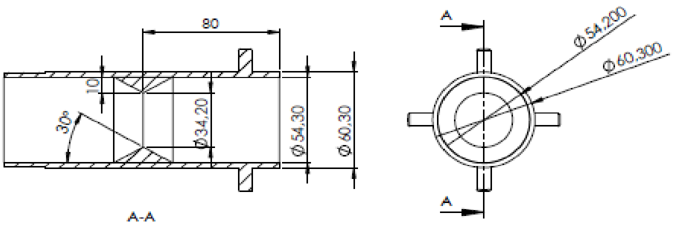
- Baffle ring to slow down the PF for better ignition and for deflection of the PF



8.1.4 Nozzle 4

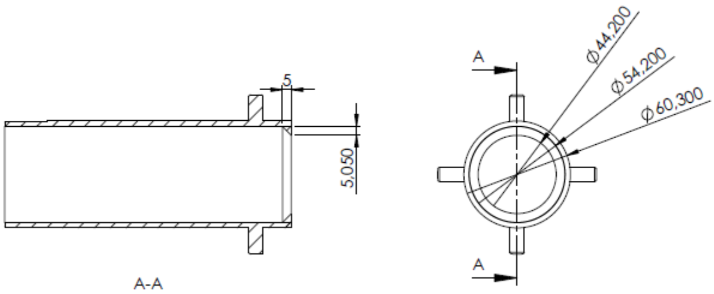
Characteristics:

- PF deflector like a "venturi contraction" for deflection of the PF



8.1.5 Nozzle 5

Characteristics: Nozzle 5 is an improved version of nozzle 3, it was designed for the purpose of achieving better results on the hard coal tests.



8.2 Experimental Matrices

8.2.1 South African Hard Coal

Nozzle 5 normal TL

Loading [kgF/kgL]	MF [kgF/h]	TL (Nm3/h)	Thermal Power (KWth)	Plasma Power (KWth)	λ	Ω	Secondary Air velocity(m/s)	SL (Nm3/h)	Plasma position								
									0			(-)20mm			(-)40mm		
0,13	6,95	40	50	3,0	0,7	2,27	-	-									
					0,9	2,91	0	3									
					1,1	3,56	1	13	1			1			1		
0,27	13,90	40	100		0,7	2,27	3	27	1			1	1		1		
					0,9	2,91	5	46	1			1	1		1		
					1,1	3,56	7	65	1			1	1		1		
0,34	17,58	40	126		0,7	2,27	5	45	1			1			1		
					0,9	2,91	7	69	2			1			1		
					1,1	3,56	10	93	3			3			1		
0,40	20,86	40	150		0,7	2,27	7	60	3			1			1		
					0,9	2,91	10	89	3			3			2		
					1,1	3,56	13	118	3			3			3		
0,51	26,38	40	190		0,7	2,27	9	87	3			3			3		
					0,9	2,91	13	123	3			3	3	3	3		
					1,1	3,56	17	159	3			3			3		
0,67	34,76	40	250		0,7	2,27	14	127	3	3		3	3		3	3	3
					0,9	2,91	19	175	3	3		3	3		3	3	
					1,1	3,56	24	223	3	3	3	3	3		2	3	
0,81	41,71	40	300		0,7	2,27	17	161	3			3	3	1	3		
					0,9	2,91	23	218	3			3	3		2	1	
					1,1	3,56	29	275	1			1	1		1		

Nozzle 5 High TL

Loading [kgF/kgL]	MF [kgF/h]	TL (Nm3/h)	Thermal Power (KWth)	λ	Ω	Sec-ondary Air veloci-ty(m/s)	SL (Nm 3/h)	Plasma position								
								0			(-)20mm			(-)40mm		
0,08	6,95	70	50	0,7	2,27	-	-									
				0,9	2,91	-	-									
				1,1	3,56	-	-									
0,15	13,90	70	100	0,7	2,27	0	3									
				0,9	2,91	2	24									
				1,1	3,56	4	45									
0,23	20,86	70	150	0,7	2,27	3	40									
				0,9	2,91	6	71									
				1,1	3,56	9	102									
0,31	27,81	70	200	0,7	2,27	7	76									
				0,9	2,91	11	118									
				1,1	3,56	15	160									
0,34	30,77	70	221	0,7	2,27	8	92	1			1			1		
				0,9	2,91	13	138	1			1			1		
				1,1	3,56	17	184	1			1			1		
0,38	34,76	70	250	0,7	2,27	10	113	1			1			1		
				0,9	2,91	15	165	1			1			1		
				1,1	3,56	20	217	1			1			1		
0,46	41,71	70	300	0,7	2,27	14	150	1			1			1		
				0,9	2,91	20	212	1			1			1		
				1,1	3,56	26	275	1			1			1		

Nozzle 3 Normal TL

Loading	MF	TL	Ther-	λ	Ω	Sec-	SL	Plasma position

								0			(-)20mm			(-)40mm		
0,13	6,95	40	50	0,7	2,27	-	-									
				0,9	2,91	0	3									
				1,1	3,56	1	13									
0,27	13,90	40	100	0,7	2,27	3	27	1			1			1		
				0,9	2,91	5	46	1			1			1		
				1,1	3,56	7	65	1			1			1		
0,34	17,58	40	126	0,7	2,27	5	45	1			2			1		
				0,9	2,91	7	69	1			2			1		
				1,1	3,56	10	93	3			3			3		
0,40	20,86	40	150	0,7	2,27	7	60	3	2		3	3		3		
				0,9	2,91	10	89	3			3			3		
				1,1	3,56	13	118	3			3			3		
0,51	26,38	40	190	0,7	2,27	9	87	3			3			3		
				0,9	2,91	13	123	3			3			3		
				1,1	3,56	17	159	3			3			3		
0,54	27,81	40	200	0,7	2,27	10	94									
				0,9	2,91	14	132									
				1,1	3,56	18	170									
0,67	34,76	40	250	0,7	2,27	14	127	3			3			3		
				0,9	2,91	19	175	3			3			3		
				1,1	3,56	24	223	3			3			3		
0,81	41,71	40	300	0,7	2,27	17	161	3			3			3		
				0,9	2,91	23	218	3			3			2		
				1,1	3,56	29	275	3			3			1		
0,78	40,32	40	290	0,7	2,27	16	154									
				0,9	2,91	22	209									
				1,1	3,56	28	265									

Loading [kgF/kgL]	MF [kgF/h]	TL (Nm3/h)	Thermal Power (KWth)	λ	Ω	Secondary Air veloci-ty(m/s)	SL (Nm3/h)	Plasma position								
								0			(-)20mm			(-)40mm		
0,13	6,60	40	50	0,7	1,81	-	-									
				0,9	2,32	0	136	2			2			2		
				1,1	2,84	2	175	2			2			2		
0,26	13,19	40	100	0,7	1,81	2	234	3			3			3		

AirDos input (Hz)	TL (Nm3/h)	Thermal Power (KWth)	λ	Ω	Secondary Air veloci-ty(m/s)	SL (Nm3/h)	Plasma position											
							0			(-)20mm			(-)40mm			(+)20mm		
3,47	70	50	0,7	2,27	-	-												
			0,9	2,91	-	-												
			1,1	3,56	-	-												
6,94	70	100	0,7	2,27	0	3												
			0,9	2,91	2	24												
			1,1	3,56	4	45												
10,42	70	150	0,7	2,27	3	40												
			0,9	2,91	6	71												
			1,1	3,56	9	102												
13,89	70	200	0,7	2,27	7	76	1			1			1					
			0,9	2,91	11	118												
			1,1	3,56	15	160	1			1			1					
15,37	70	221	0,7	2,27	8	92	1			1			1					
			0,9	2,91	13	138	1			1			1					
			1,1	3,56	17	184	2			2			1					
17,36	70	250	0,7	2,27	10	113												
			0,9	2,91	15	165												
			1,1	3,56	20	217												
20,83	70	300	0,7	2,27	14	150	1			1			1			2		
			0,9	2,91	20	212	3			2	2		1			3		
			1,1	3,56	26	275	3			1			1			3		
22,92	70	330	0,7	2,27	16	171	3			2			1					
			0,9	2,91	23	240	3			3			1					
			1,1	3,56	29	309	2			1			1					

Nozzle 3 High TL

8.2.2 El Cerrejon

				0,9	2,32	5	312	3			3			3		
				1,1	2,84	7	390	3			3			3		
0,34	17,58	40	133	0,7	1,81	6	325									
				0,9	2,32	8	429									
				1,1	2,84	11	533									
0,38	19,79	40	150	0,7	1,81	7	371	3			4			3		
				0,9	2,32	10	488									
				1,1	2,84	13	605									
0,51	26,38	40	200	0,7	1,81	11	508									
				0,9	2,32	15	664									
				1,1	2,84	19	820									
0,64	32,98	40	250	0,7	1,81	14	644									
				0,9	2,32	20	840									
				1,1	2,84	25	1036									

Nozzle 3 Normal TL

Nozzle 3 High TL

Loading [kgF/kgL]	MF [kgF/h]	TL (Nm3/h)	Thermal Power (KWth)	λ	Ω	Secondary Air velocity(m/s)	SL (Nm3/h)	Plasma position								
								0			(-)20mm			(-)40mm		
0,07	6,60	70	50	0,7	1,81	-	-									
				0,9	2,32	-	-									
				1,1	2,84	-	-									
0,15	13,19	70	100	0,7	1,81	0	70									
				0,9	2,32	2	110									
				1,1	2,84	4	150									
0,22	19,79	70	150	0,7	1,81	4	140	1						1		
				0,9	2,32	7	200				1			1		
				1,1	2,84	10	260	1			1			1		
0,29	26,38	70	200	0,7	1,81	7	210	1						1		
				0,9	2,32	12	290	1			1			1		
				1,1	2,84	16	370	3			2			2		
0,34	30,77	70	233	0,7	1,81	10	256	1			1			1		
				0,9	2,32	15	350	3			1			1		
				1,1	2,84	20	443	3			3			3		
0,36	32,98	70	250	0,7	1,81	11	280									
				0,9	2,32	17	380									
				1,1	2,84	22	480									
0,44	39,58	70	300	0,7	1,81	15	350	3			1			1		
				0,9	2,32	21	470	3			2			3		
				1,1	2,84	28	589	3			3			3		

Nozzle 5 Normal TL

Loading [kgF/kgL]	MF [kgF/h]	TL (Nm3/h)	Thermal Power (KWth)	λ	Ω	Secondary Air velocity(m/s)	SL (Nm3/h)	Plasma position								
								0			(-)20mm			(-)40mm		
0,13	6,60	40	50	0,7	1,81	-	-									
				0,9	2,32	0	136									

				1,1	2,84	2	175	1	1	1	1	1	1	1	1	1
0,26	13,19	40	100	0,7	1,81	2	234	3			3			3		
				0,9	2,32	5	312	3			3			3		
				1,1	2,84	7	390	3			3			3		
0,34	17,58	40	133	0,7	1,81	6	325	3			3	3		3		
				0,9	2,32	8	429	3			3			3		
				1,1	2,84	11	533	3			3			3		
0,38	19,79	40	150	0,7	1,81	7	371	3			3			3		
				0,9	2,32	10	488	3			3			4	3	
				1,1	2,84	13	605	3			3			3		
0,51	26,38	40	200	0,7	1,81	11	508	3			3			5	3	
				0,9	2,32	15	664	4			3			3		
				1,1	2,84	19	820	3			3			3		
0,64	32,98	40	250	0,7	1,81	14	644	4			3			5		
				0,9	2,32	20	840	3			3			3		
				1,1	2,84	25	1036	3			3			3		

Nozzle 5 High TL

Loading [kgF/kgL]	MF [kgF/h]	TL (Nm3/h)	Thermal Power (KWth)	λ	Ω	Secondary Air velocity(m/s)	SL (Nm3/h)	Plasma position								
								0			(-)20mm			(-)40mm		
0,07	6,60	70	50	0,7	1,81	-	-									
				0,9	2,32	-	-									
				1,1	2,84	-	-									
0,15	13,19	70	100	0,7	1,81	0	70									
				0,9	2,32	2	110									
				1,1	2,84	4	150									

				0,7	1,81	4	140									
0,22	19,79	70	150	0,9	2,32	7	200									
				1,1	2,84	10	260	1			1					
				0,7	1,81	7	210	1								
0,29	26,38	70	200	0,9	2,32	12	290	2			1					
				1,1	2,84	16	370	3			5			1		
				0,7	1,81	10	256	2			1			1		
0,34	30,77	70	233	0,9	2,32	15	350	3			3			1		
				1,1	2,84	20	443	3			4			4		
				0,7	1,81	11	280									
0,36	32,98	70	250	0,9	2,32	17	380									
				1,1	2,84	22	480									
				0,7	1,81	15	350	3			1			1		
0,44	39,58	70	300	0,9	2,32	21	470	5			5			5		
				1,1	2,84	28	589	3			3			3	3	