energies

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Pilot-Scale Experiences on a Plasma Ignition System for Pulverized Fuels

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Abstract: The need for flexible power generation is growing worldwide as the energy transition is altering the operational regimes of thermal power plants. Plasma ignition systems, as an alternative technology to the conventional start-up method with natural gas or oil firing, offer a cost- and energy-efficient start-up process in pulverized fuel power stations. The application of plasma ignition systems for cold start-ups using different qualities of pre-dried lignite is investigated in a pilot-scale combustion facility. A plasma integrated swirl burner is developed and validated using highly ignitable lignite dust. Eight pre-dried lignite qualities with a moisture content of up to 30% and a broad particle size distribution are investigated for this application to determine the applicability and limitations of the plasma ignition system with regard to the fuel quality. The performance of lignites for cold start-up in the plasma ignition system are categorized based on their ignition and combustion performance. All lignite qualities were ignited under the cold-start-up condition with a plasma power of 4 kW to 7 kW. Lignite qualities with a moisture content of up to 20% and a median particle size of below 450 µm form a self-sustained flame with short-time plasma-supported combustion, while flame blow-out is observed for lignites with lower qualities.

Keywords: plasma ignition system; coal-fired power plants; ignition; self-sustained flame; cold start-up

Citation: Youssefi, R.; Maier, J.; Scheffknecht, G. Pilot-Scale Experiences on a Plasma Ignition System for Pulverized Fuels. *Energies* **2021**, *14*, 4726. https://doi.org/10.3390/en14164726

Academic Editor: Nikolaos Koukouzas

Received: 18 June 2021
Accepted: 30 July 2021
Published: 4 August 2021

1. Introduction

The energy transition has brought new operational principles for the fossil fuel energy sector [1]. This transformation has, in particular, impinged the solid fuel power stations such as bituminous coal and lignite power plants [2]. These plants need to cope with new operational regimes, where flexible operation is a key component. Low-cost and energy-efficient solutions are therefore required to reinforce the flexibility [3]. In the last years the plasma-assisted coal combustion technology has drawn attention as an alternative start-up process for solid fuel power plants [4,5].

The plasma-assisted combustion technology has been widely applied for different types of liquid and gaseous fuels for enhancing the ignition and thermal efficiency [6,7] . The application of plasma-assisted combustion for the coal industry was further developed to utilize coal for start-ups and concurrently to increase the combustion stability and fuel flexibility. In plasma-assisted ignition and combustion the coal particles undergo a thermochemical activation and consequently are ignited with the help of plasma, eliminating the need for gas and oil for the start-up [8,9]. Thermochemical plasma preparation of a portion of the coal stream produces a partially gasified coal flow, which is used to ignite the main pulverized fuel flow. Simulations on the thermochemical activation showed an increase in the reactivity of the treated coal flow, which is related to enhancements in the volatile extraction [10]. Experimental data from the real-scale implementation of the plasma fuel systems reveal that plasma stabilization is applied from 30 min up to several hours [11–13]. The most frequently used plasma systems for this application are DC arc plasma torches. Since the electrodes applied for generating a DC arc plasma jet are subjected to erosion and have a limited lifetime [14], prolonged plasma-supported combustion can necessitate increased maintenance and reduce the system robustness.

Given the increased number of plant start-ups compared to the originally designed number, the operational costs are considerably reduced when the coal is directly used for this purpose instead of costly start-up fuels [15]. Economical evaluations and real-scale experiences showed that plasma-assisted combustion not only reduces the energy consumption of the plant during start-ups but also a lower thermal power input is required for the start-up process to reach a stable condition [16,17]. A techno-economic evaluation on plasma-assisted combustion, considering only the economic benefits associated with the minimum thermal load reduction, proved the economic viability for an investigated 200 MW power station [18].

Different firing systems are designed and constructed based on the plasma-assisted ignition technology for cold, warm, and hot start-ups using different types of fuel qualities [15,17,19,20]. Investigations on coal devolatilization with plasma showed that particle size, volatile content, and residence time represent strong influence on the devolatilization process [21,22]. Coal ignition, under cold start-up conditions with no additional heat available in the boiler, is a challenge, particularly when fuels with low ignitability and large particle sizes are used.

A promising approach is to use a highly reactive pulverized fuel quality, which can be ignited rapidly when it comes into contact with a plasma jet [19]. In this configuration, a plasma torch is integrated into a burner system which brings the fine lignite dust particles to ignition within a few seconds and the resulting flame is stabilized after several minutes [23]. Due to the high reactivity and ignitability of the fuel, the plasma system can be switched off shortly after the flame formation which considerably reduces the operating time of the system and, consequently, increases the life-time of plasma electrodes and lowers the associated maintenance cost. The development of such systems requires detailed investigations on the boundary conditions of the firing system and the fuel qualities required to ensure ignition and stable flame formation. However, there is limited experience for implementing different fuel qualities in short-time plasma-assisted ignition systems under cold start-up conditions.

The presented work studies the performance of several pre-dried lignite qualities with distinct characteristics in a 400 kW pilot-scale plasma-assisted ignition system. The plasma-ignition system was developed and validated in this study. It aims to characterize the ignition and combustion performance of these fuels under cold start-up conditions, where only short-time plasma-assisted ignition and combustion is applied, and to evaluate the limitations and required boundary conditions of the system with regard to the fuel quality. This investigation provides a better understanding of the ignition and self-sustained flame formation process for the short-time plasma-assisted ignition under cold start-up conditions.

2. Materials and Methods

2.1. Fuel Properties

Eight types of pre-dried lignites originating from Germany were investigated for the application of the plasma ignition system under cold furnace conditions with short-time plasma support. To study a variety of fuel properties for this application, lignites with distinct chemical and physical characteristics were selected. Tables 1 and 2 show the lignites' composition and characteristic particle sizes of *D10*, *D50* and *D90*, respectively. The lignites were sieved with a sieve size of 2 mm, to eliminate operational and technical problems related to the fuel dosing, considering that fuels larger than 2 mm do not contribute to the initial ignition process. Lignite A was a finely milled lignite from the Lusatia region (*D50* of 46 µm) that was dried to a moisture content of 10%. This lignite, which had similar properties as the one used in the industrial-scale implementation of the plasma ignition system [19], served as the reference fuel for this study due to its high reactivity and ignitability. Lignite B and Lignite C also originated from the Lusatia region and were dried to 15% and 20% moisture, respectively. The raw lignites were milled to larger particle sizes, *D50* of 320 µm to 360 µm. These lignites were low in ash and sulfur content. Lignite D and Lignite F derived from a mine in East Saxony, containing high ash, sulfur, moisture, and correspondingly low heating values. These lignites underwent different preparation processes and had particles larger than lignites from the Lusatia region with *D50* of 420 µm to 667 µm. Lignite E, Lignite G, and Lignite H were lignites from Central Germany with high ash and sulfur content but high heating values. Lignite E and Lignite H had the largest particle sizes among the tested fuel qualities. Excluding Lignite A, the particle size distribution of the pre-dried lignite qualities were coarser than typical ones used in power stations, the coarse particle size was of interest to investigate if plasma-assisted ignition has the potential to shift the ignition towards larger particle sizes.

Table 1. Chemical properties of pre-dried lignite qualities.

Fuel	NCV	γ_{H_2O}	γ_A	$\gamma_{volatile}$	γ_C	γ_H	γ_N	γ_S	γ_O
	raw				**dry and ash free**				
	MJ/kg	**10^{-2} kg/kg (%)**							
Lignite A	20.8	10.5	5.0	48.5	66.3	4.9	0.8	1.2	26.9
Lignite B	20.2	14.5	4.7	46.4	66.4	5.0	0.8	0.7	27.2
Lignite C	18.8	19.4	4.0	43.8	66.7	5.2	0.8	0.9	26.5
Lignite D	15.8	20.2	12.5	42.6	63.3	4.9	0.8	5.5	25.5
Lignite E	18.2	21.3	10.5	41.3	71.0	5.7	0.7	4.3	18.3
Lignite F	12.2	29.3	19.6	32.5	67.3	5.4	0.9	6.5	20.0
Lignite G	19.6	12.6	15.5	44.7	70.1	5.8	0.7	4.7	18.8
Lignite H	15.8	26.6	14.9	36.4	69.7	5.8	0.7	7.9	15.8

Table 2. Particle size characteristics of pre-dried lignite qualities.

Fuel	*D10*	*D50*	*D90*
	2 mm Sieved		
	µm		
Lignite A	5	46	184
Lignite B	42	320	1500
Lignite C	31	366	1600
Lignite D	34	420	1726
Lignite E	190	1048	2247
Lignite F	73	667	1935
Lignite G	31	551	1143
Lignite H	135	907	2147

2.2. Experimental Facility

A 400 kW combustion test facility was used for the investigation of plasma-assisted ignition technology under cold start-up conditions. The test facility and the swirl burner are described and illustrated elsewhere [24]. The 7 m reactor consisted of 6 segments and was cooled by a water jacket, where the first three segments and the top plate of the reactor were covered with a refractory lining. The temperature at the furnace wall was measured via thermocouples at several distances from the burner outlet. The reactor was featured with several measurement ports along its length, allowing visual and optical observations of the ignition and combustion process. The ignition process was monitored visually at 0.18 m from the burner outlet, with a high-speed camera at a frame rate of 250 fps which provided detailed observations on the ignition initiation and flame formation. A movable block swirl burner was modified and integrated with a DC-arc plasma torch and was mounted centrally on the burner plate. The burner outlet was followed by a 0.1 m built-in quarl of the burner plate. The plasma torch was positioned co-axially in the central opening of the burner. The torch was vertically movable, allowing variable vertical torch positioning in the burner. Through a set of screening tests, selected boundary conditions were adjusted for different fuel qualities. The ignition tests for Lignite C were performed, where the plasma head was retracted 40 mm inside the burner, whereas the experiments for other lignites were performed under the configuration that the head of the plasma torch was located at the burner outlet. The fuel and primary air in the middle annulus of the burner were swirled by axial vanes with a swirl number of 0.9. The vanes were located 0.12 m upstream of the burner outlet. The primary air velocity was set to 15 m/s for Lignite A, B, C and E. The primary air velocity was reduced to 11.5 m/s during the experiments for Lignite D, Lignite F, Lignite G and Lignite H. The swirled particles were directed towards the plasma jet via a conical contraction at the outlet of the primary air duct. The movable block swirler, which was followed by a 0.6 m duct, produced a secondary air with a swirl number of 0.9. To monitor the combustion process, the flue gas emissions were measured at a 5.25 m distance from the burner outlet. To emulate the cold start-up condition, ignition tests were performed without preheating the combustion chamber. A wall temperature of 90 °C close to the burner zone was a prerequisite for the test initiation, to eliminate the impact of existing heat inside the furnace, generated from previous experiments, on the following ignition tests. The secondary air was also not preheated and was supplied to the burner at a temperature of approximately 40 °C. A 3 kW to 7 kW DC-arc plasma torch, using air as the medium gas, was utilized for this study. The plasma power was adjusted with the input current and the flow rate of plasma medium gas. The produced thermal plasma had a temperature of around 9500 K at the inner core of the plasma jet [25].

2.3. Test Procedure and Evaluation Methods

In this study, the plasma jet served as the ignition source, where short-time plasma-assisted ignition and combustion concept was applied. The plasma was therefore not used to stabilize the flame and was only applied for ignition initiation. The required heat for flame stabilization was considered to be supplied by the existing heat produced from the flame formed via the swirl burner. Consequently, fuel properties play a decisive role in flame stabilization and self-sustainability after the plasma is turned off. To evaluate the fuels' potentials to form a self-sustained flame, in case of ignition initiation via plasma, the plasma jet was turned off within approx. 30 s, and the flame behavior was observed afterwards. An evaluation method was developed to reveal the ignition and flame behaviors, which is illustrated in Table 3. A criterion named "Combustion Class" was defined, which represents the optical observations on cold start-up ignition tests. Combustion Class 1 stands for no ignition, whereas Combustion Class 3 denotes ignition and flame formation with plasma support. A stabilized and self-sustained flame after the plasma turn-off is shown with Combustion Class 5, a lifted flame detached from the burner outlet, and Combustion Class 6, a self-sustained attached flame formed at the burner outlet.

Table 3. Definition of Combustion Classes (CC).

CC	Definition
0	No ignition
1	Ignition and fast extinction (only spark)
2	Ignition and unstable flame with plasma
3	Ignition and stable flame with plasma
4	Ignition and flame blow-out in few seconds after plasma turn-off
5	Ignition and detached self-sustained flame after plasma turn-off
6	Ignition and attached self-sustained flame after the plasma turn-off

The Combustion Class is determined for each ignition using the profile of the flame brightness intensity. Figure 1 shows the flame brightness profile close to the burner zone. For Combustion Class 1, almost no brightness is detected, where only sparks are observed. The flame brightness for Combustion Class 2 shows unstable ignition with large fluctuations ranging from 0 to 120. Combustion Class 5 is characterized by a stable flame formation and as the plasma is turned off at 27 s, the flame is detached to lower levels, where it is out of the optical access of the camera and only a small fluctuating part of the flame is registered. For Combustion Class 6, the plasma turn-off at 20 s is associated with a transition zone to reach a stable flame without plasma support while attached to the burner mouth. Although the brightness level of the flame is reduced as the plasma support is removed, the flame propagates with slight fluctuation until the stop of the fuel feeding at 34 s.

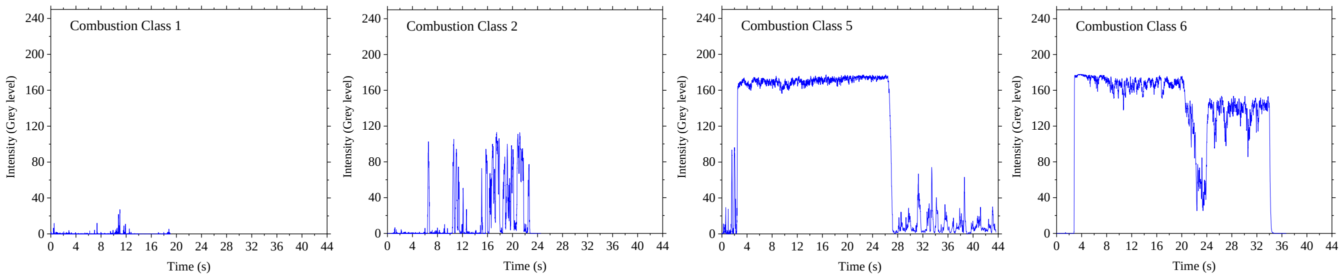

Figure 1. The flame brightness profile of different Combustion Classes.

Since the tests were demonstrated within short time frames, burnout measurements were not plausible. Hence, to evaluate the combustion process, a criterion was developed to provide quantitative information on the combustion reactions. “Combustion Degree” was defined as the share of burned fuel in the fuel stream calculated at a specific time after ignition. For these experiments, the amount of burned fuel 30 s after the ignition initiation was calculated based on the measured O_2 at the bottom of the reactor, 5.25 m from the burner outlet, and the total combustion air supplied. The ignition tests were performed at various air ratios, defined as the ratio of actual combustion air requirement to the stoichiometric air requirement, and several thermal loads, defined as the ratio of burner load to the full load of 400 kW.

3. Results

3.1. Validation of the System

The designed and developed plasma ignition system was first validated using a high-quality pre-dried lignite dust, Lignite A. Figure 2 compares the Combustion Class obtained at several thermal loads over the air ratio. Lignite A is ignited and develops a coherent flame at the thermal load of 25%, equivalent to 100 kW, which is indicated by Combustion Class 3. At this thermal load, as the air ratio is increased to 1.4, the Combustion Class further improves to Class 5. Once the thermal load is increased to 38%, the Combustion Class reaches Class 5 and 6. A further increase in the thermal load to 50% results in Combustion Class 6 for air ratios of 0.9 and 1.1. For the settings operated, the Combustion Class improves when the thermal load is increased. Besides, a positive influence of the air ratio on the Combustion Class is observed for each thermal load. The results of ignition tests using Lignite A conclude that this fuel quality can be ignited and can form an attached self-sustained flame with short-time plasma support under cold start-up conditions. Therefore, the system is validated for this application and can be further investigated for the applicability of lower quality lignites. Since promising results are obtained using Lignite A, it is deduced that aerodynamic parameters of the burner satisfy the required flow dynamic, to a large degree. Thus, only burner operational parameters e.g., burner load and air ratio, are used to study the performance of different lignite qualities in the plasma-ignition system.

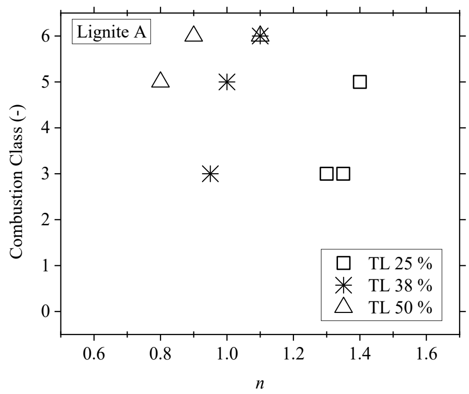

Figure 2. Combustion Class of Lignite A.

3.2. The Ignition Behavior

Figure 3a shows that Lignite B is ignited at 25% thermal load with Combustion Class 3. As the thermal load is increased to 38% and 50%, the Combustion Class improves to Class 5 and Class 6, respectively. A self-sustained flame is obtained over a wide operational range from sub-stoichiometric to over-stoichiometric conditions, under an air ratio range from 0.8 to 1.2, for the thermal loads above 38%. Although Combustion Class 6 is only obtained at an increased air ratio at 50% thermal load, no specific correlation between the Combustion Class and the air ratio is observed for Lignite B.

The ignition tests of Lignite C were performed at a retracted plasma position inside the burner (Results published by the authors [26] showed that a retracted plasma position can have a positive impact on the Combustion Class at higher thermal loads and a negative influence at the minimum thermal load that is required for ignition. However, no difference on the overall performance of the fuel in the cold-start-up plasma ignition system was obtained at the retracted and non-retracted plasma positions. Hence, these results can with high confidence be used for describing the overall behavior of the fuel), see Figure 3b. As can be seen, Lignite C cannot be ignited at 25% thermal load, and as the load is increased to 38%, coherent flames at Combustion Classes 4 and 5 are formed. A further increase in the thermal load to 50% results in similar Combustion Classes of 4 and 5. When the thermal load is increased to a higher value of 63%, the Combustion Classes conversely drop to Class 3 and subsequently to Class 1, when the air ratio is increased from sub-stoichiometric to the stoichiometric condition. The results of Lignite C suggest that self-sustained flames are obtained over specific thermal loads, 38% and 50%, and air ratios, from 0.9 to 1.1. The results also indicate that the Combustion Class at each thermal load behaves differently in relation to the air ratio. An increased air ratio has a beneficial influence on the Combustion Class at the thermal load of 50%, whereas it has negative effects on it at thermal loads of 38% and 65%.

Figure 3c illustrates that Lignite D, similar to Lignite C, reaches ignition at the thermal load of 38%. Further increase of the thermal load to 50% and 63% results in the formation of self-sustained flames under specific air ratios. Increasing the air ratio shows a positive impact on the Combustion Class for the thermal load of 63% with an air ratio range of 0.85 to 1.05. At 50% thermal load, the Combustion Class first increases and then decreases, as the air ratio is increased from 1.0 to 1.2. At the lowest thermal load of 38%, the ignition and formation of a coherent flame are hindered when the air ratio is increased to 1.45.

For both Lignite C and Lignite D, a self-sustained flame is obtained within a narrow operational range. This behavior highlights that these fuel qualities, due to their lower ignitability, are more sensitive to the burner boundary conditions and, thereby, optimized operational settings need to be identified through a series of experiments.

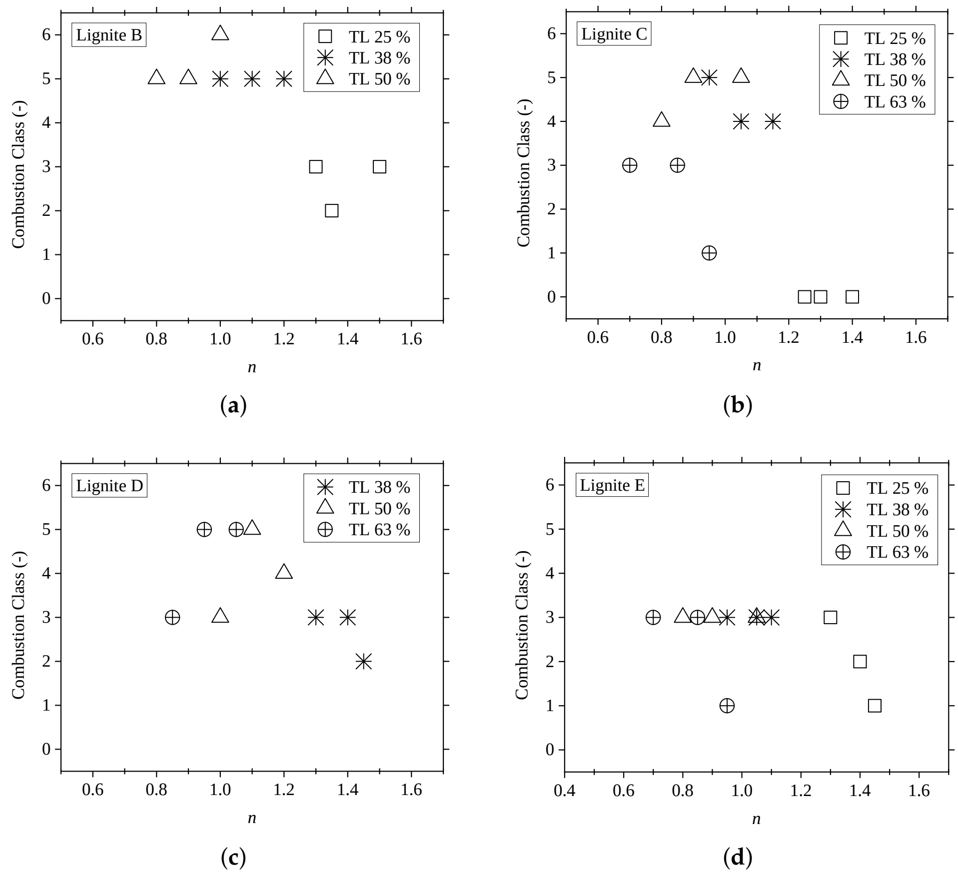

Figure 3. The Combustion Class versus air ratio obtained by four lignite qualities at several thermal loads (TL), (**a**) Lignite B, (**b**) Lignite C, (**c**) Lignite D, (**d**) Lignite E.

Combustion Class 3 is achieved for Lignite E at 25% thermal load, when the air ratio is reduced from 1.45 to 1.3, see Figure 3d. As the thermal load is increased to 38%, 50% and 63%, Combustion Class 3 is obtained under almost all operated air ratios from 0.7 to 1.1. The trend suggests that further increases in the dust concentration do not improve the ignition process to create a self-sustained flame for Lignite E, once the minimum thermal load required to form a coherent flame with plasma-supported ignition is reached. At the low thermal load of 25%, where high air ratios are applied, the lowest operated air ratio of 1.3 is the key parameter to reach Combustion Class 3. At higher thermal loads, where the value changes from 0.7 to 1.1, the air ratio does not notably influence the Combustion Class.

Similar behavior is observed for Lignite F, see Figure 4a. Ignition and flame formation is achieved at 50% thermal load under sub-stoichiometric conditions, and increasing the thermal load to 63% does not demonstrate any effect on the Combustion Class. Given the operating air ratios, ignition is mainly favored under highly fuel-rich conditions at the air ratios of below 0.7.

Figure 4b,c illustrates the results of Combustion Class for Lignite G and Lignite H when a 7 kW plasma power is used. These fuels cannot be ignited with a 4 kW plasma torch and hence the plasma power is increased to provide larger ignition energy. Lignite G is ignited at the thermal load of 38%, while a higher thermal load of 50% was required for Lignite H to reach Combustion Class 3. For these fuels, once the minimum thermal load for ignition is reached, increasing the thermal power and correspondingly the fuel quantity does not improve the Combustion Class to values higher than 3. Lignite G is ignitable over a broad air ratio range from sub-stoichiometric to over-stoichiometric up to the air ratio of 1.45, where at each thermal load operated a lower air ratio at the respective range was beneficial for ignition. On the other hand, Lignite H does not suggest an evident relationship between the air ratio and the Combustion Class.

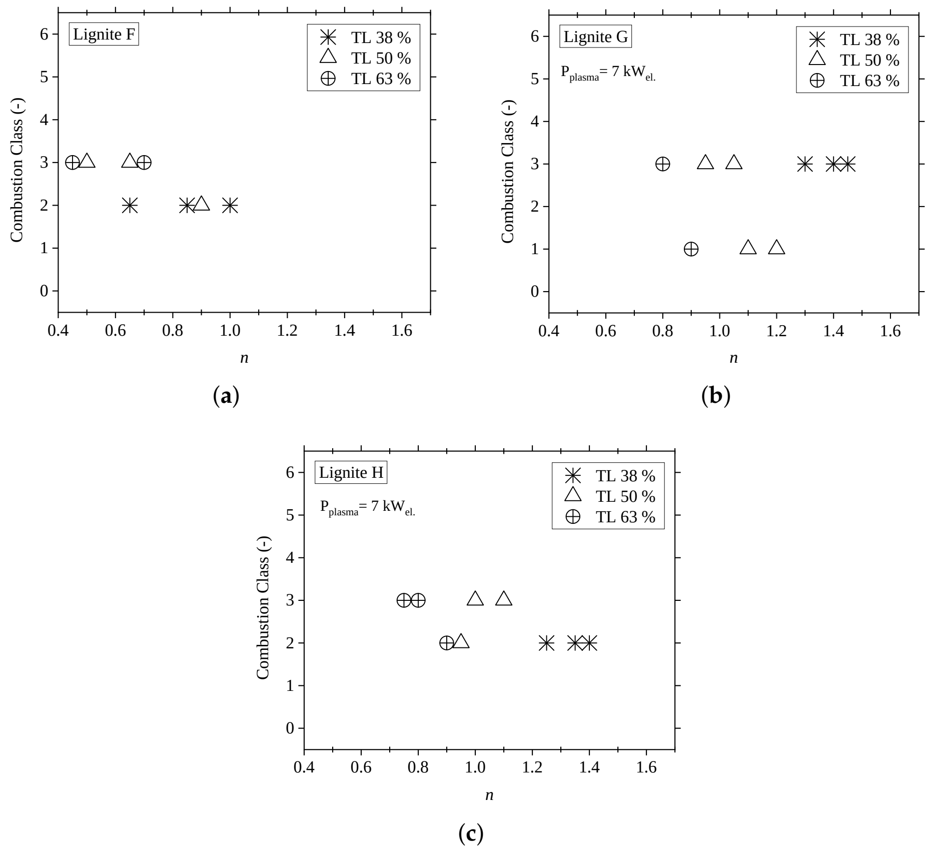

Figure 4. The Combustion Class versus air ratio obtained by three lignite qualities at several thermal loads (TL), (**a**) Lignite F, (**b**) Lignite G, (**c**) Lignite H, Lignite G and Lignite H are ignited with a 7 kW plasma torch.

3.3. The Combustion Behavior

The Combustion Degree parameter provides information on the combustion performance which allow a comparative evaluation on the behavior of lignite qualities in the plasma ignition system during the early stage of ignition.

Figure 5 illustrates the corresponding Combustion Degree obtained at each ignition test for Lignite B, Lignite C, and Lignite D. For Lignite B, the Combustion Degree increases with the thermal load. As the thermal load increases, the dust concentration grows accordingly, which consequently enhances the combustion process. Comparable behaviors are observed using Lignite C and Lignite D that increasing the thermal load improves the Combustion Degree. For Lignite C, Combustion Degree values at grows as the thermal load increases from 38% to 50%. However, at the thermal load of 63% the Combustion Degree drops, which is in-line with the Combustion Class behavior observed in Figure 3b. The behavior is assumed to be related to the high air velocity. For Lignite C, the most promising Combustion Degree values are obtained for an optimized burner load of 50%. Similarly, the Combustion Degree of Lignite D in Figure 5c is enhanced from the thermal load of 38% to the thermal load of 63%. For all three lignites the Combustion Degree values of flames with Combustion Class of at least 3 stays in the range of around 40% to 80%.

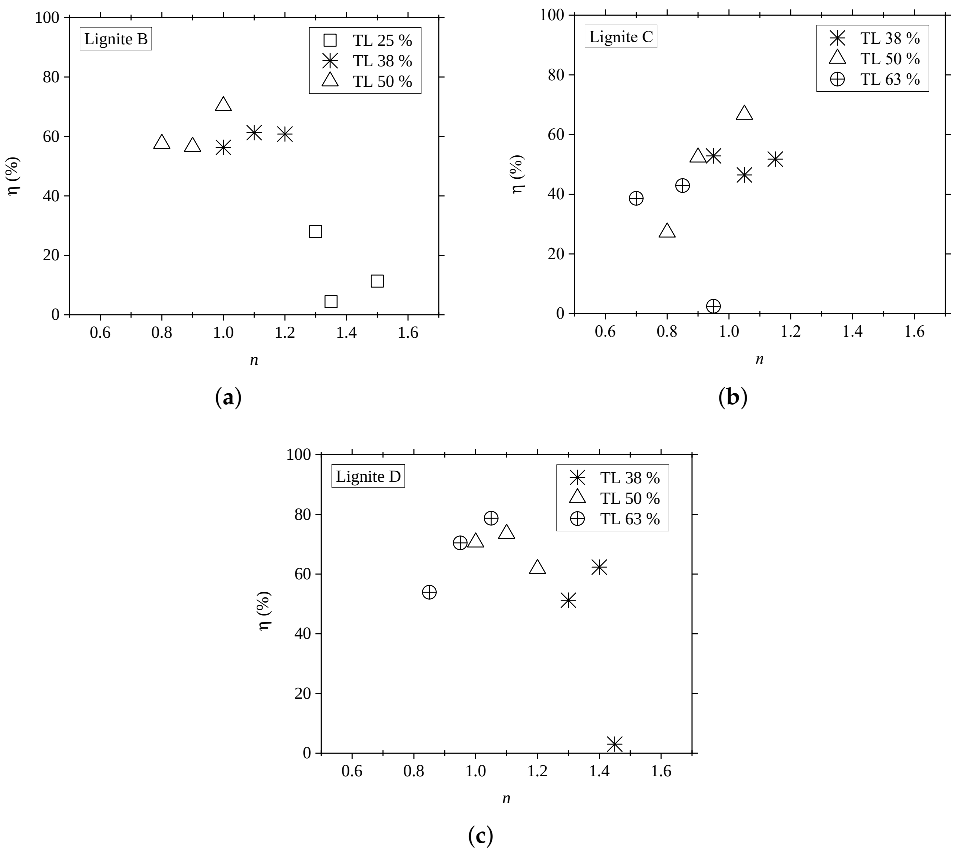

Figure 5. The Combustion Degree vs. air ratio at several thermal loads (TL) by (**a**) Lignite B, (**b**) Lignite C and (**c**) Lignite D.

The influence of the air ratio on the Combustion Degree varies depending on the thermal load. For Lignite B in Figure 3b, as the air ratio at the thermal load of 25% is increased, the Combustion Degree reduces. However, a different trend is observed for higher thermal loads of 38% and 50%, where increasing the air ratio either enhances the Combustion Degree or does not change it notably. This behavior is associated with the heat demand required for the ignition. When a low amount of heat is produced within the early stage of the combustion, i.e. at the low thermal load of 25%, increasing the air ratio, and correspondingly the secondary air enlarges the required heat demand and inhibits the ignition. Under low thermal loads, where mainly over-stoichiometric air ratios are applied and a limited amount of heat is produced by the ignition, increasing the secondary air serves only as a heat sink source. However, as the thermal load is increased to 38% and 50%, the Combustion Degree is significantly enhanced to values above 50%, which means a considerable quantity of heat is available from the combustion process. Thus, an increased air ratio under sub-stoichiometric and over-stoichiometric conditions yields an elevated amount of oxygen for the combustion and facilitates the combustion reactions and correspondingly eliminates the local oxygen depletion. Once the effect of improved oxygen availability for the combustion reaction overcomes the heat loss, the combustion process is enhanced and consequently, a higher Combustion Degree is achieved. Besides, taking the aerodynamic boundary conditions of the burner into account, the swirl intensity of the secondary air grows as the amount of air increases [27]. Hence, sufficient increased secondary air ensures proper mixing of the hot flue gas products with the fresh fuel stream and the combustion air.

This effect is more evident using Lignite C. For Lignite C, at the minimum thermal load required for the ignition (38%), high Combustion Degree values of around 50% are obtained, thus, increasing the air ratio does not have a strong adverse effect on the

Combustion Degree and the values stay relatively constant, despite a small drop at the air ratio of 1.05. At the higher thermal load of 50%, increasing the air ratio favors the Combustion Degree values from around 30% to 70%, indicating high degrees of combustion and devolatilization. Accordingly for Lignite D, as the air ratio increases at the thermal load of 38% and 50%, the Combustion Degree values of Lignite D first increases and then decreases. The heat production from the improved combustion, owing to a higher oxygen availability, competes with the heat loss associated with a larger heat demand and the net effect influences the Combustion Degree. Eventually, at the highest thermal load of 63%, the effect of enhancement in the combustion reaction overcomes the increased heat loss and hence the Combustion Degree of Lignite D increases as the air ratio is changed from 0.8 to 1.1. The heat sink effect of a larger air ratio is more pronounced in Lignite C and Lignite D compared with Lignite B. An improvement in the combustion efficiency of plasma ignition with the thermal load and the air ratio was also reported by others [16].

Figure 6a shows that the Combustion Degree values of Lignite E slightly improve, as the thermal load is increased from 25% to 38% and 50%, whereas no improvement is observed when the thermal load is further increased to 63%. It should be highlighted that the improvements in the Combustion Degree are limited to a narrow range with the minimum and maximum values of 10% and 30%, respectively. This behavior postulates that the devolatilization for this lignite quality is limited during the ignition and initial combustion, where an increased dust concentration does not have any significant impact on enhancing the combustion process. It is, therefore, considered that a low concentration of volatiles is the main parameter associated with flame blow-out when the plasma system is turned off.

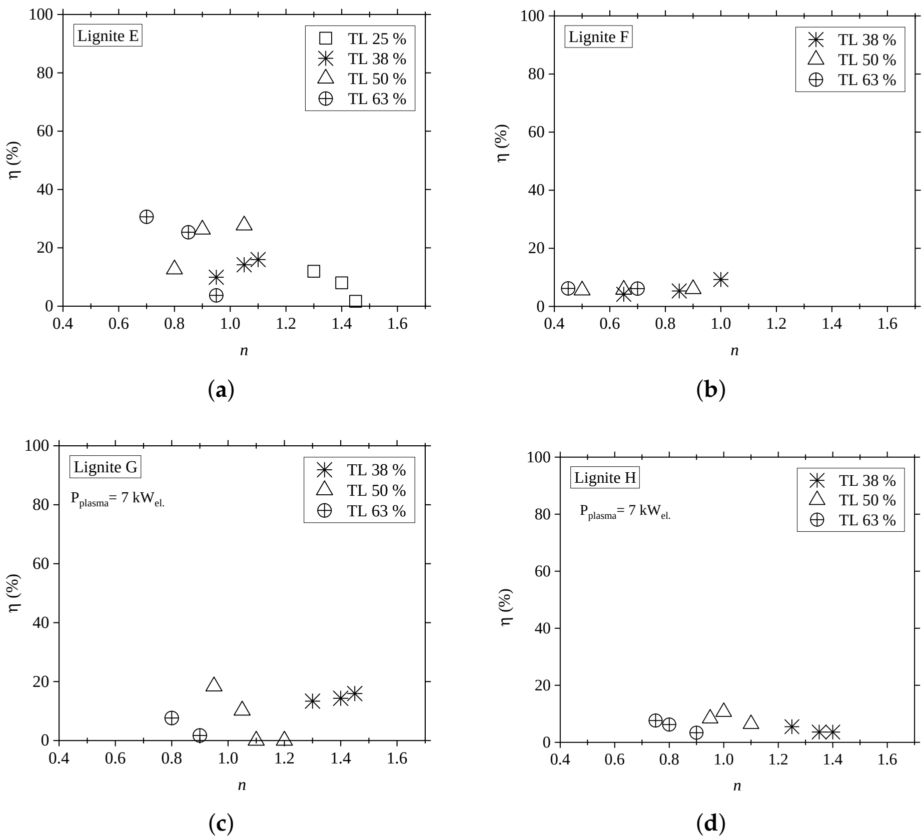

Figure 6. The Combustion Degree vs. air ratio at several thermal loads (TL) by (**a**) Lignite E, (**b**) Lignite F, (**c**) Lignite G, (**d**) Lignite H.

This behavior is also observed for Lignites F, G, and H. Figure 6b demonstrates that the Combustion Degree values obtained by Lignite F are not influenced by the thermal load and the values stay below 10% within the thermal loads of 38% to 63%. The devolatilization is not pronounced for this fuel quality and achieving an ignition with Combustion Class 3 at higher thermal loads is perhaps mainly associated with extended char combustion around the plasma jet due to a large fuel concentration. Figure 6c,d represents the Combustion Degree of Lignite G and Lignite H obtained using 7 kW plasma power. The values do not represent any correlation to the thermal load and they vary within the range of 8% to 18% for Lignite G and below 10% for Lignite H, indicating very limited degrees of devolatilization.

In Figure 6, improvements in the Combustion Degree by the air ratio is only observed with Lignite E. For Lignite E, an increased air ratio slightly improves the Combustion Degree values at 38% and 50%, while it impairs the combustion process at the lowest and highest thermal loads of 25% and 63%. Since the combustion cannot be further improved at the thermal load of 63%, the heat loss associated with the secondary air mainly dominates the heat production by the combustion process and inhibits the ignition when the air ratio is increased to near stoichiometric conditions.

For Lignite F, no correlation is found between the air ratio and the Combustion Degree, as very low Combustion Degrees are obtained. Considering Lignite G and Lignite H, the air ratio has a negative influence on the Combustion Degree for the thermal loads of 50% and 63%. The results suggest that a lower air ratio is beneficial to minimize the effect of heat loss and consequently to initiate an ignition. Since these fuel qualities have a low devolatilization degree and do not form a self-sustained flame, no positive impact neither on the Combustion Class nor on the Combustion Degree is observed by increasing the air ratio.

4. Discussion

The results of ignition tests performed for eight pre-dried lignite qualities outline the behavior of these fuels for short-time plasma supported ignition under cold start-up conditions. The behavior of these fuels concerning ignition, devolatilization and self-sustained flame formation can be classified into several categories. The categories are explained in Table 4. The performance of fuels is categorized based on the highest obtained Combustion Class and the required plasma power for ignition. Within each category similar behaviors with regard to Combustion Class, Combustion Degree and the influence of the air ratio are observed. The fuels that form an attached self-sustained flame, Lignite A and Lignite B, belong to the "very high ignitability" category and lignites with a detached self-sustained flame, Lignite C and lignite D, fit in the "high ignitability" category. These fuels reach high Combustion Degree values, indicating a high degree of devolatilization and high potentials for the formation of a self-sustained flame. While Combustion Classes 5 and 6 are obtained over a wide operational range for fuels within the "very high ignitability" category, optimization of burner parameters, with regard to the air ratio and the thermal load, becomes particularly crucial when the ignitability is reduced within the "high ignitability" category. The category of "moderate ignitability" describes the fuels that are ignited with short-time plasma-support but do not form a self-sustained flame without plasma, including Lignite E and Lignite F. The Combustion Class does not improve according to the thermal load, once the minimum load required for the ignition is reached. Low Combustion Degrees at high thermal loads highlight the incapability of these fuels to produce a highly-volatilized and consequently a self-sustained flame with short-time plasma support. The category of "low ignitability" includes Lignite G and Lignite H, where the ignition initiation is accomplished with a higher plasma power of 7 kW. These lignites have the lowest ignitability among the tested qualities, where ignition could not be accomplished with a 4 kW plasma power. Regardless of the thermal load, very low Combustion Degree values are obtained, which suggests these fuels cannot be considerably devolatilized by short-time plasma support and only a small portion of the fuel stream is combusted.

Ignition of eight tested lignite qualities with moisture contents of 10% to 30% and a wide range of particle sizes with a median diameter of 45 µm to 1159 µm using a

4 kW to 7 kW plasma jet is proven plausible within the developed system. The intensity and stability of the formed flame are governed by the fuel characteristics. To correlate the lignites' chemical characteristics to the ignition performance in the plasma ignition system and consequently to identify the suitable fuel qualities for this application, the volatile, moisture and ash content of fuels are correlated to the Combustion Class. Figure 7 illustrates the chemical and physical properties of the lignites, where the color of each lignite indicates the highest Combustion Class obtained using the 4kW plasma power under the investigated operational settings at different thermal loads and air ratios.

Table 4. Classification of the tested lignite qualities based on the observed behavior in the plasma ignition system for cold start-up.

	Very High Ignitability	**High Ignitability**	**Moderate Ignitability**	**Low Ignitability**
Lignite	A and B	C and D	E and F	G and H
Plasma power for ignition	4 kW	4 kW	4 kW	7 kW
Highest Combustion Class	Combustion Class 6	Combustion Class 5	Combustion Class 3	Combustion Class 3
Combustion Class behavior	Increases by thermal load Self-sustained flame over a wide operational range	Increases by thermal load Self-sustained flame over a limited operational range	No increase once the minimum thermal load is reached	
Combustion Degree behavior by the thermal load	Increases High devolatilization	Increases High devolatilization	Slight increase Low devolatilization	No increase Low devolatilization
Influence of air ratio	Principally positive influence on the Combustion Class and Combustion Degree	Stronger dependency on the heat production and heat loss	lower air ratio beneficial for ignition initiation	

In Figure 7a, the volatile content is plotted versus the median particle size. The volatile content of fuels, except Lignite F and Lignite H, stays in a narrow range of 41% to 49%. It can be seen that the fuels within the "very high ignitability" category have the highest volatile content and the smallest median particle size. These lignites have a median particle size smaller than approximately 450 µm. As the median particle size increases to above 500 µm, no relation between the volatile content and the ignitability can be found. This finding highlights the importance of particle size when rapid devolatilization is concerned. For this configuration, where the flame produced in the surrounding of the plasma jet is the only heat source for devolatilization and ignition, the particles need to be sufficiently fine to release volatiles within a short residence time in order to expand the flame and reach an adequately high Combustion Degree and consequently a self-sustained flame. For a typical lignite dust quality, the particle size corresponds to that of Lignite A. The results conclude no severe detrimental effect on the rapid devolatilization in the plasma ignition system when the median particle size is even increased to approximately 450 µm.

An evident correlation between the moisture content and the ignitability of lignites can be seen in Figure 7b. The fuels within the "very high ignitability" category have a moisture content between 10% to 15% and as the moisture is increased to 20%, the lignites fall to the "high ignitability" category. Although a higher moisture content and a larger particle size contribute to curbing the ignitability, an increase in the moisture from 10% to 15% and the median particle size from 50 µm to 150 µm does not alter the ignitability category of Lignite B. However, aggravations in the performance between Lignite A and Lignite B is pronounced as depicted in Figures 2 and 3a. Combustion Class 6 for Lignite B is obtained at defined boundary conditions, whereas Lignite A produces attached flames over a wider range of operational parameters. A further increase in the moisture content from 15% to 20% lowers the ignitability category to the "high ignitability". Flame detachment within this category is most likely related to an increased ignition delay time associated with a higher moisture content in the fuel. Given the lignites with a median particle size of below 450 μm, qualities with a moisture content of up to 20% show a satisfactory performance with regard to the formation of a self-sustained flame. As the particle size increases to above 450 μm, the performance of fuels cannot be directly correlated to the moisture content, which indicates the fuels within the “moderate ignitability” and the “low ignitability” groups.

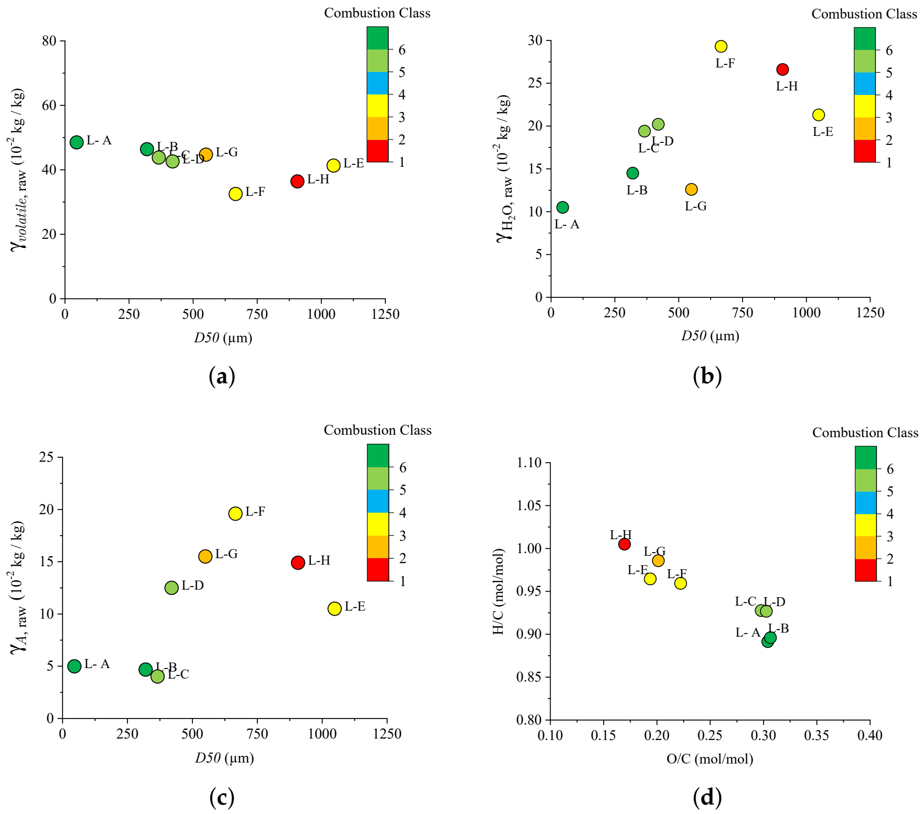

Figure 7. (**a**) fuel volatile share in the raw state, (**b**) fuel moisture content in the raw state, (**c**) fuel ash content in the raw state vs. median particle size of the samples sieved below 2 mm, (**d**) molar O/H/C diagram; “L” stands for Lignite (L-A: Lignite A), the color of each point represents the highest Combustion Class obtained by the 4 kW plasma jet within the tested experimental matrix.

Figure 7c outlines the ash content of the tested lignites and suggests that although Lignites A, B, and C have a low ash content of 5%, a self-sustained flame is also formed with Lignite D containing 12% ash. Even though it is expected that ash, as an inert material, reduces the ignitability of the fuel, no significant discrepancies in the ignition and self-sustained flame performance of Lignite D compared to Lignite C are observed. However, since the aerodynamic parameters of the burner differs for experiments performed with Lignite C and Lignite D (a different primary air velocity and a different plasma position), a solid conclusion on the ignition behavior cannot be drawn. However, it can be stated that lignites with 12% ash and 20% moisture and a particle size distribution corresponding to that of Lignite D can be implemented for the application of plasma-assisted ignition.

Given the differences in the moisture and ash content, it can be highlighted that moisture has a relatively high inhibiting effect on ignition and formation of a self-sustained flame. A 5%-variation in the moisture notably impacts the fuel performance in the plasma ignition system, whereas an increase of about 8% in ash content does not influence it considerably. This finding is related to the heat sink effect of ash and moisture as inert components. Moisture represents a considerably larger heat demand that is associated with a higher degree to the latent heat of evaporation and with a lower degree to a higher specific heat capacity of water compared with ash. Considering an ignition temperature of 600 °C, the heat demand of 1 kg of moisture is around 6 times higher than that of 1 kg of ash.

Figure 7d illustrates the properties of different lignite qualities within the Van-Krevelen diagram. The molar O/C ratio for fuels within "very high ignitability" and "high ignitability" categories is around 0.3. As the O/C ratio decreases, the quality of lignite gets closer to bituminous coal, where qualities of lignites belong to "moderate ignitability" and "low ignitability" categories are located. A higher O/C ratio facilities the ignition process by an early release of molecules with O–H bond [28] and by a higher CO yield during devolatilization [29], which produces an easily-ignitable mixture. The results suggest that a higher O/C ratio tends to improve the ignitability category of the investigated lignites from "low ignitability" to "very high ignitability" regarding their performance in the plasma ignition system.

To further discuss the sensitivity of the lignites' performance to the fuel quality, the average of min-max normalized Combustion Class for each lignite quality is identified in Table 5. The min-max normalized Combustion Class is calculated by considering 0 as the minimum Combustion Class and 6 as the maximum Combustion Class. Hence, for each lignite, the Combustion Classes presented in Figures 3 and 4 are normalized by the difference between the minimum and the maximum Combustion Class. An average of the normalized Combustion Classes under the investigated operational settings, e.g., different thermal loads and air ratios, is generated with the aim of showing the lignite potential in reaching Combustion Class 6. It should be mentioned that for Lignite A the average normalized Combustion Class is calculated by including three ignition tests with Combustion Class 6 obtained at 65% thermal load. Table 5 shows that these average values of min-max normalized Combustion Class are in good agreement with the fuel classification of "very high ignitability", "high ignitability", and "moderate ignitability" in Table 4. However, since the average Combustion Class for fuels within the "low ignitability" category is calculated based on the data presented in Figure 4b,c when a 7 kW plasma power is used, no notable difference is found between the average values of fuels in "moderate ignitability" and "low ignitability" categories. It indicates that contrary to the classification in Table 4, which considers the requirements for ignition initiation, the average Combustion Class represents the potentials of flame formation when the prerequisites for the ignition apply. This suggests comparable potential in self-sustained flame formation for lignites within the "low ignitability" and "moderate ignitability", once the ignition is initiated.

Table 5. The average of normalized Combustion Class.

Lignite A	Lignite B	Lignite C	Lignite D	Lignite E	Lignite F	Lignite G	Lignite H
0.83	0.72	0.63	0.61	0.43	0.42	0.39	0.41

The values in Table 5 are analyzed statistically using the Pearson correlation coefficient, r, and the p-value to realize any correlation to the four parameters of the median particle size, volatile content, ash content, and moisture content of the lignite. Table 6 shows the results of the analysis, where p-values and r are calculated by considering all eight lignites. The lignites are then divided in two groups, where p_1-values and r_1 are related to the lignites with a median particle size smaller than 450 µm and p_2-values and r_2 are related to the lignites with a median particle size larger than 500 µm. The p-value shows a significant correlation to the median particle size and the ash content with a high r-magnitude of above 0.86.

When lignites with a median particle size of below 450 µm are considered, including Lignites A, B, C, and D, a strongly significant correlation is observed for the moisture content with a p_1-value of 0.004 and a r_1-value of -0.99. The correlation is also significant for the volatile content and the median particle size with p_1-values of around 0.015 and similar r_1-values of 0.98 in magnitude, whereas no correlation is observed for the ash content within this group. When lignites with a median particle size above 500 µm are considered, including Lignites E, F, G, and H, p_2-values are larger than 0.17 and hence, no significant correlation is found. Similar to the conclusion obtained from Figure 7, the statistical analysis also shows a dominant influence of the particle size on the ignition and flame formation. The findings indicate that the moisture content and the median particle size have a strong impact on the performance of lignite for a cold start-up as long as the median particle size is sufficiently small. When the particle size is relatively large, the ignition and flame formation is worsened and no correlation can be deduced between the fuel properties and their performance as the ignition and flame formation is notably hindered.

Table 6. Statistical analysis of normalized average of Combustion Class.

	γ_{H_2O}	$\gamma_{volatile}$	γ_A	***D50***
r	−0.62	0.72	−0.86	−0.87
p-value	0.103	0.042	0.006	0.006
r_1	−0.99	0.98	−0.55	−0.98
p_1-value	0.004	0.016	0.454	0.017
r_2	0.57	−0.39	0.83	0.78
p_2-value	0.432	0.614	0.170	0.221

5. Conclusions

The application of the plasma ignition system for cold start-ups using pre-dried lignite was validated in a pilot-scale facility. The performance of pre-dried lignites tested in the ignition system was characterized by several categories. Lignite qualities with 10% to 20% moisture content and a median particle size of approximately below 450 µm were ignited with a 4 kW plasma torch and formed self-sustained flames after 30 s of plasma-supported combustion. These lignite qualities, Lignite A, lignite B, Lignite C, and Lignite D, showed a high devolatilization degree and represent great potentials to be utilized for the application of plasma-assisted ignition for cold start-ups.

Lignites with a moisture content of 10% to 15%, were categorized as "very high ignitability", demonstrated self-sustained flames over a wide range of operational settings, where under optimized burner configuration attached flames were formed at the burner outlet. As the moisture content was increased to 20%, ignition was less favored due to the ignition inhibiting effect of moisture and flame detachment from the burner outlet was observed after the plasma turn-off. Due to the reduced ignitability at higher moisture contents, the self-sustained flame formation was accomplished only under specific burner parameters with regard to the air ratio and the thermal load. Variations in the ash content of up to 12% did not demonstrate notable inhibiting effects on the fuel performance. As the median particle size was increased to above 500 µm, lignite qualities did not form a self-sustained flame with 30 s of plasma support. These qualities were categorized as "moderate ignitability" and "low ignitability", where the latter category required a higher plasma power of 7 kW for ignition initiation. Besides a large median particle size, these qualities had compositions above the determined limit values of 20% moisture and 12% ash content for one or both criteria. Further statistical analysis revealed a significant correlation between the median particle size and the lignites' performance in the plasma ignition system. Considering the lignites with a median particle size of below 450 µm, significant correlations were determined with the moisture and volatile contents, whereas no correlation was found for lignites with larger median particle sizes.

Ignition tests showed that the air ratio enhanced the combustion reactions as long as sufficient amount of heat was produced at the early stages of the ignition. The thermal load was also a key parameter to the ignition and self-sustained flame formation. For lignite qualities within "very high ignitability" and "high ignitability", an increase in the thermal load, e.g., dust concentration, was required to reach an ignition and a self-sustained flame, whereas for "moderate ignitability" and "low ignitability" fuel qualities, once the minimum thermal load necessary for the ignition was reached, further increases in the thermal load did not contribute to the formation of a self-sustained flame.

Author Contributions: Conceptualization, R.Y. and J.M.; methodology, R.Y. and J.M.; validation, R.Y., J.M. and G.S.; formal analysis, R.Y.; investigation, R.Y.; writing—original draft preparation, R.Y.; writing—review and editing, R.Y. and G.S.; visualization, R.Y.; supervision, Y.M. and G.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Germany Federal Ministry of Economic Affairs and Energy (BMWi) with the reference number of 03ET7076A (Project FlexIgnite).

Acknowledgments: The authors would like to thank the project partners; Institute of Interfacial Process Engineering and Plasma Technology (IGVP) of the University of Stuttgart, Lausitz Energie Kraftwerke AG, Mitsubishi Power Europe GmbH and PlasmaAir AG. The authors would also like to take this opportunity to thank partners who participated in the experiments and measurements from the IGVP and IFK Institute of the University of Stuttgart.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following nomenclature are used in this manuscript:

Symbol	Unit	Quantity
D10	μm	The particle diameter where 10% of the distribution has a smaller particle size
D50	μm	Median particle size
D90	μm	The particle diameter where 90% of the distribution has a smaller particle size
n	-	Ratio of actual air to stoichiometric air demand (air ratio)
η	%	Combustion Degree
NCV	MJ/kg	Net calorific value
r	-	Pearson correlation coefficient
γ_i	10^{-2} kg/kg	Mass fraction of the material i in the fuel

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