Effect of Electric Field in the Stabilized Premixed Flame on Combustion Process Emissions

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Abstract. The effect of the AC and DC electrical field on combustion processes has been investigated by various researchers. The results of these experiments do not always correlate, due to different experiment conditions and experiment equipment variations. The observed effects of the electrical field impact on the combustion process depends on the applied voltage polarity, flame speed and combustion physics. During the experiment was defined that starting from 1000 V the ionic wind takes the effect on emissions in flue gases, flame shape and combustion instabilities. Simulation combustion process in hermetically sealed chamber with excess oxygen amount 3 % in flue gases showed that the positive effect of electrical field on emissions lies in region from 30 to 400 V. In aforementioned voltage range carbon monoxide emissions were reduced by 6 % and at the same time the nitrogen oxide emissions were increased by 3.5 %.

1. Introduction
Pursuant to the final draft of the EU Best Reference (BREF) document for large combustion plants (LCP), thermal plants over 50 MW have to comply with the new regulations by 2020 [1]. The new European Parliaments resolution of 13 September 2016 on an EU strategy on heating and cooling (2016/2058(INI)) implies European Unions strategy for innovative heating and cooling that requires intensive research, providing a basis for the creation of industries making environmentally-friendly equipment to serve this purpose [2].

The effects of the electrical field application for combustion process enhancement recently were extensively studied. Wide range of studies showed improvements with negligible energy consumption compared to the input thermal power, however it is difficult to explain the key factor which is responsible for flame stabilization improvement [3]. In the recent research [4] were proposed two mechanisms, which were responsible for electrically induced instability: hydrodynamic instability initiation with ionic wind and thermodiffusive instability through the modification of transport properties in burning process. The first method was explained as accelerated charged-particles transfer their momentum to neutral particles by random collision, resulting in the ionic wind effect [5].

The effect of electrical fields on flame includes combustion process stabilization, emissions reduction [6], flame propagation speed [7], flame front behavior and the combustion characteristics [8]. The
processed data results of electrical field distribution [9] showed that presence of charged species generated by flame reduced the dielectric field strength to one seventh comparing with air. The open question remained in the field of electrical field impact on burning process emissions in flue gases of gaseous fuels like a propane, emissions concentration change at different voltage potential on electrode. The special experimental setup for burning process investigation under the high voltage electrical field with emissions concentration registration was built in 2016. In the presented study the experimental equipment was adjusted to focus on the emissions concentration and retaining control over the flame shape and operation of the auxiliary elements.

2. Experimental setup

2.1. Experimental apparatus

In compliance with Figure 1 the experimental apparatus consists of the following main components: C\textsubscript{3}H\textsubscript{8}/air premixed flame burner, air supply and flow control equipment, pressure reduction set, electrical field intensifier, electrical igniter, water cooled copper ring, CCD monochrome camera and flue gases analyzer.

2.2. Burner and combustion chamber

Cylindrical C\textsubscript{3}H\textsubscript{8}/air premixed flame was produced utilizing bras tube with metal net for flame stabilization and homogenization, which could be moved in vertical direction relatively to the copper coil. The diameter of the open end of the burner is 10 mm. The figure 1 shows that combustion chamber (Fig. 2 (a)) consists of hermetically sealed burner surrounded by transparent quartz glass for flame shape registration via CCD digital camera. The air flow after control valve was split before the gas/air mixing valve into the two different flows. Thus the burning air was divided into primary and secondary air. The primary air was premixed with gaseous fuel in the mixing valve. Propane gas and air mixture after mixing valve was supplied directly to the burning zone through the burner head. The secondary air flow was separately organized around the burner pipe inside of the combustion chamber imitating the industrial burner. This technique was utilized in order to control the flame stability as well as to stabilize the initial oxygen level in flue gases in hermetically sealed combustion chamber, where additional (ambient) air leakage was prevented. The height of the transparent cylindrical quartz is 350 mm with internal diameter 100 mm and thickness of the glass wall 5 mm. In the bottom side of the combustion chamber (Fig. 2) was fitted hermetically sealed burner. The top part of the combustion chamber consisted of the metal sheet with diameter 150 mm, which is connected to the base plate of the combustion chamber with four threaded studs. In the center of top metal sheet of the combustion chamber is welded main tube for flue gas removal with height 500 mm. Close to the upper metal sheet of the transparent combustion chamber for flue gas analyzing is designed additional nozzle in main flue gases pipe in 45\degree angle to the flue gas flow. This nozzle is designed for flue gas analyzer connection. Additionally, in the combustion chamber is fitted coil of the copper tube (D = 4 mm) with three rings and overall height 30 mm. The internal diameter of the coil is 40 mm. The copper coil is connected to the DC diaphragm water pump with adjustable flow. The DC or AC current is connected to the bras tube of the base part of the burner and to the copper coil with water cooling. Copper coil was insulated from the upper metal sheet with rubber hoses.

For the air supply was utilized standard air compressor with capacity 150 l/min and adjusted outlet pressure from the compressed air receiver 2 bar(g). After air receiver were installed in parallel two membrane type pressure regulators with adjusted outlet pressure 36 mbar. In line with pressure regulators was installed gas flow rotameter with control valve (Fig. 2 (b)) after which additionally was installed Pitot tube for precise primary burning air flow control. Before Pitot tube is installed control valve for secondary burning air.

Flame shape registration was organized by CCD digital monochrome camera (ThorLab DCC3260M). For better image quality transparent combustion chamber was isolated from external sources of light during the experiment process. Within the experiment the images of the flame shape were directly
Figure 1. Experimental configuration for burner process analysis under electrical field.

processed on PC. For image processing was utilized rainbow function in the cameras image processing software. Thereby it was possible to identify the shape of the root of the flame and the shape of the hot end of the flame, which was visible for the camera, however, invisible for eyes.

Flue gas analyzing process was organized with TESTO 350 gas analyzer, which was connected to the probe nozzle of the upper element of the combustion chamber in order to control the emissions concentration in flue gases. The flue gas probe of the gas analyzer was connected via PVC hose to eliminate the impact of the high voltage field on the gas analyzer. Conducting the experiment the flue gas content was analyzed in online mode. All measured data was written to the logger of the device and simultaneously transferred to the workstation for further analysis.

2.3. Electrical field generator and auxiliary elements
The source of the electrical current is AC with constant frequency 50Hz and stabilized voltage 220 V. For voltage control and regulation was used laboratory type autotransformer with the peak current 5 Amp. To the output plug of the secondary winding of the autotransformer was connected digital voltmeter for
precise voltage registration. In parallel to the voltmeter was plugged a high voltage transformer with the peak voltage 2.4 kV in full transformer saturation. From the side of a high voltage winding was installed a fuse from 0.07 mm copper conductor for an experimental unit protection. The direct current rectifier was built from super-fast high voltage diodes (MUR 460). The rectifier scheme is based on a full-wave rectification in a bridge configuration utilizing four diodes in each line with overall amount of super-fast 16 diodes. This configuration allowed to use diodes with downrated voltage parameters. One pole (negative or positive) was connected to the copper water cooled coil, which was placed around flame, but the second pole was directly connected to the burner. The position of the negative and positive poles was changed during the experiment. In the electrical field generator were not used high voltage capacitors due to the increased risk of the residual charge in capacitors [10] which may have an impact of the electronic elements of the experimental unit.

For the flame ignition purpose in the hermetically sealed combustion chamber was designed an ultra-high voltage generator, which consisted from the high voltage flyback transformer (with nominal output voltage 15 kV), low voltage circuit driver and Cockcroft-Walton high voltage multiplier.

In order to prevent the copper coil from the overheating, it was occupied with the water cooling circuit utilizing DC diaphragm water pump. For the diaphragm water pump capacity elimination was applied an additional autotransformer, circuit breakers, bridge rectifier and the capacitor for stabilized low-voltage diaphragm pump feeding at 25% voltage level from the nominal. Due to this solution was limited the hot flue gases condensation on the copper coil during the process of the experiment.

3. Results

3.1. DC and AC influence on emissions
It was identified that in order to enhance the premixed propane and air mixture burning - necessary to provide an external electrical field around the flame and at the same time to exclude any external factors, which may impact to the flame stability. Therefore the experiment study of external field impact on premixed flame burning should be organized close to the full scale equipment, where chemical reactions and residues of the burning process are similar. It is estimated that the presented results could be related to the large scale burning equipment, taking into account the main dimensional characteristics of the experimental unit. The main existing problem for such technology implementation is heat distribution in boiler unit and burning velocities, which may impact on electrical field induction elements and its cooling components.

According to the experimental equipment composition, the burner biased positively and water cooled
coil biased negatively. In the first set of the experiment burner head was adjusted at 35 mm below the copper coil (Fig. 3), also in the second set of the experiment burner head was lifted 4 mm over the copper coil (Fig. 3). Simultaneously the poles were reversed from positive to negative from burner head side and from negative to positive from copper coil side.

Emissions concentration reduction under external DC and AC electrical field was organized in two steps - large scale phase and small scale phase. During the large scale phase was checked DC and AC impact on the flame behavior, and the flue gas composition analysis at voltage from 30 to 1800 V. Afterwards were identified potential points of the positive effect (voltage region and emission concentration reduction potential), which laid the basis for the second phase of the experiment.

![Figure 3. Burner head positions in the experimental composition.](image)

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![Figure 4. DC electrical field (0–1800V) impact on oxygen content in flue gases.](image)

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The analysis of the research demonstrated oxygen reduction tendency in flue gases. Adjusting different voltage levels oxygen content in the flue gases was being lowered during all studies variations. According to Fig. 4 oxygen concentration lowered in average by 23 percent comparing with the initial
measurements (without electrical field application). The highest oxygen lowering rate was registered during the application of the AC current. The set of the experiment with AC current was done in voltage range 0–1380 V and finished at the rate 1380 V due to high CO concentration in flue gases. In case of AC electrical field application the oxygen content decreasing process was more stable. Comparing AC and DC current during the experiment was identified that DC electrical field in various variations has less influence on oxygen concentration in flue gases. When the burner was positioned 35 mm below the copper coil and positive pole (DC electrical field) was connected to the burner head - volume part of the oxygen in flue gas content raised. The similar results were registered when the burner head was moved 4 mm above the copper coil and negative pole was connected to the burner head. In this two cases oxygen volume rate has raised in average by 7-10 percent. Oxygen volume rate has direct correlation on the carbon monoxide (CO) concentration in the flue gases, therefore the effect of the CO reduction is the opposite process to the oxygen content rising.

**Figure 5.** DC electrical field (0–1800V) impact on carbon monoxide in flue gases.

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**Figure 6.** DC electrical field (0–1800V) impact on NOx in flue gases.

Carbon monoxide concentration was divided into two groups. The first group corresponds to CO reduction under low-voltage electrical field influence and the second group corresponds to CO rising
along with the voltage increase over 400 V. In Fig. 5 was defined, that the most common CO reduction correlates to regimes, when oxygen concentration was being raised [11]. Another variations of the burner head position relatively to the copper coil and electrode position demonstrated the negative effect of the external electrical field application on the premixed burning process.

The results of the different experimental variations (Fig. 6) are witnessing about the nitrogen oxides (NOx) concentration rise in average by 5 percent. Only in the range of the dramatic oxygen volume part reduction in flue gases, NOx concentration was reduced [12] by 3 %.

**Figure 7.** DC electrical field impact on CO and NOx emissions with positive pole connected to the burner head.

Taking into account that external electrical field application has less effect on NOx concentration variations - the most interesting parameter is CO concentration reduction.

Analyzing the set of the large scale data was identified the voltage region (30 - 280 V), when emissions concentration in flue gases is less than without application of electrical field. According to this was conducted experiment in narrow voltage region. The results of the second part of the experiment are in good correlation with similar experiment setup [13], during which was defined that at voltage range over 300 volts CO and NOx concentration is higher than initial values. The second set of the experiment (Fig. 7, 8 ) was conducted with the burner head position 2mm above the copper coil and varying positive and negative pole connection to the burner head. During the additional sets of the experiment in voltage range (30 - 280 V) oxygen rate varied in range 3-4 %.

In defined voltage range the oxygen rate and CO concentration in flue gases witnessed about the more effective burning process, keeping CO concentration and oxygen rate at the lower level comparing with initial values. This data provided the information about the positive effect of the external electrical field for premixed combustion process. CO reduction was registered at the rate of the 150 V, when the negative pole was connected to the burner head (Fig.8). The higher recorded reduction constituted 6 percent comparing with initial values. NOx concentration for the aforementioned voltage increased by 3.5 %. As CO reduction rates are higher than NOx concentration changes, it is possible to conclude, that low voltage electrical field has a positive effect on emissions.
Figure 8. DC electrical field impact on CO and NOx emissions with negative pole connected to the burner head.

4. Conclusions
A relationship exists between electrical field intensity and flue gas emissions composition. According to the research results emissions reduce at low voltage rate rather than at high voltage. The flame shape changes recorded with CCD camera during external electrical field application were visible starting from 1000 volts. This effect has a direct correlation with ion wind, which become active at the mentioned voltage rate. The combustion process in this conditions becomes unstable, in some cases flame may start to rotate and CO emissions start to increase due to unburned fuel. The emission reduction at lower voltage range is more stable when the burner head position is in one level with the copper coil and the negative electrode is connected to burner. In this combination CO concentration in flue gases reduces by 6 %, but NOx emissions simultaneously increases by 3.5 %. Such technology integration to the full scale equipment should be done in several stages, finding the correlation between results presented in this work and burner with the higher capacity, ensuring the right equipment layout and some modifications towards experimental unit.

5. References
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